Springer Tracts in Additive Manufacturing

Damir Godec ·
Joamin Gonzalez-Gutierrez ·
Axel Nordin · Eujin Pei ·
Julia Ureña Alcázar *Editors*

A Guide to Additive Manufacturing

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Springer Tracts in Additive Manufacturing

The book series aims to recognise the innovative nature of additive manufacturing and all its related processes and materials and applications to present current and future developments. The book series will cover a wide scope, comprising new technologies, processes, methods, materials, hardware and software systems, and applications within the field of additive manufacturing and related topics ranging from data processing (design tools, data formats, numerical simulations), materials and multi-materials, new processes or combination of processes, new testing methods for AM parts, process monitoring, standardization, combination of digital and physical fabrication technologies and direct digital fabrication.

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Introduction

Project INEX-ADAM

Increasing Excellence in Advanced Additive Manufacturing (INEX-ADAM) is a 3-year European Union (EU) funded project to establish networking and synergy among the five research institutions through identification, planning and implementation of Additive Manufacturing (AM) research tracks. The project is coordinated by the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture (UNIZAG FSB) and supported by Brunel University London (UBRUN), Lunds Tekniska Högskola (LTH), Montanuniversität Leoben (MUL) and the Technology Institute on Metal-Processing, Wood, Furniture, Packaging and related industries (AIDIMME). The principle goal of this project is to widen the participation for collaborative research among the consortium partners and support the coordinating partner UNIZAG FSB with technical assistance and knowledge in the field of AM research.

This book represents the main deliverable of the project and is a compilation of the training materials for AM education which can be used for further teaching purposes.

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1.1 What is Additive Manufacturing

Modern markets place increasingly stringent requirements on development and production processes. Besides the requirements to improve product quality and the level of flexibility in development and production, additional requirements are being imposed to reduce costs, and in particular to shorten development and production times. A new trend that is increasingly visible in certain segments of the markets is the abandonment of mass production in favour of small-scale, and very often individual (personalized) production.

In order to meet such market demands, modern additive manufacturing processes have been developed and applied since the second half of the 1980s. The main feature of these processes is the addition of material, usually layer by layer, until the entire product is made. Such production principle makes it possible to create a complex product geometry that would be very difficult or impossible to make with other, traditional manufacturing processes. An additional feature of additive processes is manufacturing of products directly from 3D CAD model without the need for additional tools or fixtures.

Historically, modern additive manufacturing processes have undergone several stages with regard to their application and thus terminology has changed. Initially, these procedures were mainly used for rapid prototyping (RP). The term "rapid" should be understood conditionally, because the manufacturing time it takes to

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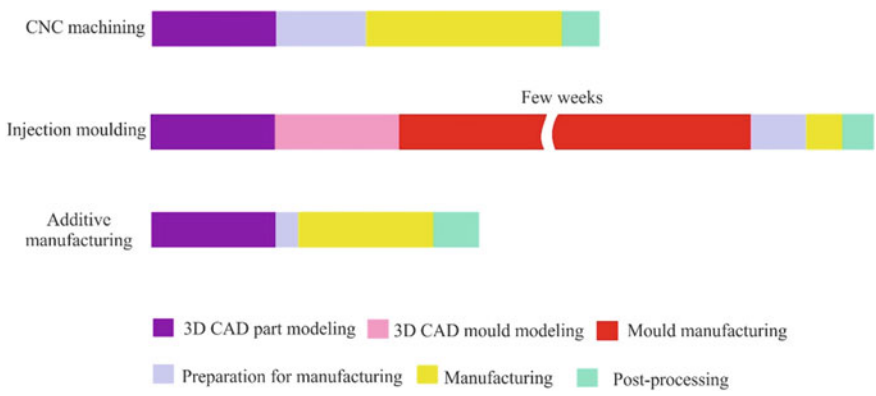

Fig. 1.1 Comparison of production time between classic processing (CNC milling) and AM (PolyJet process) (*Source* Ana Pilipović)

produce (prototypes) depends on the size of the product and on the thickness of the layers of which the product consists. Generally, the time can vary from a few mintus to a few days for production. This in itself is not fast, but when compared to conventional prototyping or conventional manufacturing, there is certainly a time reserve (Fig. 1.1).

The next step in the application of additive procedures is the rapid production of entire tools and moulds or their key elements (Rapid Tooling—RT). It is an application of additive manufacturing processes for the production of polymer, ceramic or metal tools and moulds which, due to the principle of layered building, make it possible to significantly reduce the production time of the most geometrically demanding parts of tools and moulds. When it comes to moulds for injection moulding of polymers, RT processes allow the creation of optimized tempering channels that ideally follow the shape of the mould cavity (Conformal Cooling), which can significantly shorten injection moulding cycle times and increase product quality.

Further development of materials used in additive manufacturing processes has led to the direct production of small batch or single finished products (Rapid Manufacturing—RM). These are procedures that allow manufacturing without the need for additional tools, so in the case of single production or small-scale production, they often present the only reasonable solution.

Additive processes can be divided by four main factors: the type of material, the energy source, the layer formation process, and the shape of the final product. These factors have an impact on the quality of surface finish, dimensional accuracy, mechanical properties, and time and cost of overall production.

After many years of vigorous development and extended application of RP/RT/RM processes, in 2009 an international commission ASTM International Committee F42 was established for additive manufacturing processes, and its first task was to terminologically define these procedures. As the term rapid in the use of additive processes has a relative meaning, the term additive manufacturing (AM) was defined as an umbrella term. The International Commission ASTM International Committee F42 defines additive manufacturing as the process of connecting materials when making objects directly from 3D computer models, usually layer by layer, which is in contrast to the subtractive mode of production.

1.2 Why Do We Need Additive Manufacturing

Additive manufacturing can shorten the time and cost it takes to make a new product from initial concept to production. Additive processes can help identify underlying errors on products that are expensive to correct in the later stages of their production. These processes enable the production of products of complex shapes directly from computer data in a very short time using the most automated processes. Assemblies can be made as one component or from two or more materials in one cycle. As a rule, these are the processes in which a product is built by stacking layers on top of one another, that is, an additive (generative) creation of a product.

Following categories can be strongly influenced by application of AM in product development and production processes:

1. Product Development
   - more iterations in product development are enabled and potential errors and difficulties are easier to spot
   - assemblies and connection points on the product can be checked in advance
   - the strength and durability of the product can be checked in advance
   - planning for product development and production is facilitated
   - product development time is shortened, and prototyping can be a powerful tool in concurrent engineering.
2. Product Quality
   - potential difficulties can be eliminated at the product, tool and mould development stage
   - it is easier to perceive a physical prototype than a blueprint or a computer model.
3. Production
   - it is possible to plan and eliminate potential errors on the elements of the production system
   - it is possible to anticipate possible mould problems in advance and optimize the design of tools and moulds
   - tool and mould elements can have improved thermal properties
   - tool and mould element manufacturing processes allow for uniform tempering (tempering channels can follow product contours).

4. Company's Position on the Market

   - the time from idea to product launch can be shorter and more reliable
   - market research using trusted product copies is much more credible
   - marketing materials for product promotion can be prepared in advance.

Another area for products made by additive manufacturing processes is during product development, primarily to improve the quality of communication between teams of professionals involved in development and to communicate with the market. Special prototypes can be used to analyze compliance with the prescribed standards (national and international) for products, product certification is possible, etc. The role of prototypes is also very important in the early detection of errors and omissions during product development.

Environmental requirements are becoming increasingly stringent today, so when developing a product, it is necessary to take into account the possibilities of its recycling and/or disposal. The use of models and prototypes also plays an important role in this segment. For example, using appropriate models, it is possible to analyze the disassembly of a complicated product or examine the ecological packaging of such a product, all at a very early stage in product development.

The existence of a large number of very rigid product design rules confirms the general opinion that in the classical process of product development and production, tool and mould production phases are the greatest limitation. Additive manufacturing processes, on the other hand, do not require the development and production of tools and moulds, and they provide almost limitless possibilities when it comes to the complexity of product geometry. By eliminating the need to make tools and moulds and the limitations imposed by design rules for classic processing operations, the only constraint in the development of new products becomes the designer's creativity.

Additive manufacturing processes can also be a solution to current trends of mass adaptation to market demands. Production batches are decreasing as new products appear on the market. Many customers want distinctive products that are intended only for them and no one else (product personalization). Additive manufacturing processes are precisely the ones which allow for a more cost-effective approach in cases of production of custom-made products. Since additive processes do not require the manufacture of tools and moulds, large-scale production is not required to depreciate the cost of making tools and moulds. On the other hand, the application of additive processes for direct production must satisfy production requirements such as quality control, traceability and repeatability of quality which is receiving increasing attention in order to bring the quality of products made by additive processes closer to those produced by conventional production processes.

While classic manufacturing processes result in components made from one type of material (with the exception of multi-component injection moulding), some additive processes allow the mixing and grading of materials in a large number of combinations. This leads to completely new opportunities and challenges for designers. The potential applications of Functionally Graded Materials (FGMs) begin with a simple example of a single material creation but with controlled porosity (for example, from

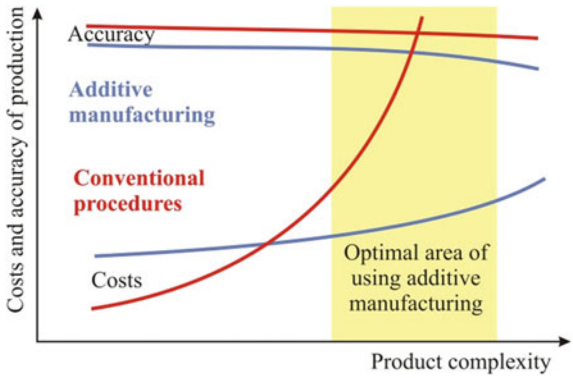

Fig. 1.2 Justification of the application of additive manufacturing (Courtesy of Pero Raos)

a hollow and softer core to a compact and hard surface), or products from two or more different materials. One of the current limitations in this area is the fact that modern CAD modelling programs do not support the development of products made of non-homogeneous materials.

However, products made by additive processes are not cheap. Their price is influenced by: the time of manufacture, the cost of the machine itself and subsequent maintenance, the work of the operator—during the manufacture, post-processing and cleaning, the price of materials and the price of materials for the supporting structure. Sometimes it is difficult to decide when to apply additive manufacturing and how many products to make to maximize their benefits (Fig. 1.2). Based on the cost of development and the accuracy of development and production as a benchmark, it can be concluded that there is an optimal area of application of additive manufacturing. Specifically, as the complexity (geometric and functional) of the future product increases, the costs of development and production with the conventional approach increase exponentially. The most demanding geometric shapes can be made by Additive manufacturing processes, without significantly increasing the cost of production. Therefore, it can be concluded that the justification for using additive manufacturing processes increases with the complexity of the product.

1.3 Additive Manufacturing Classification

Classification of additive manufacturing processes can be made upon several categories. There are a number of additive manufacturing processes which have some similarities in the process, material, machine type, surface finish, geometrical shape, required post-processing, etc. For many years, the additive manufacturing industry lacked categories for grouping AM technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings. These categories enable one to discuss a category of machines, rather than needing to explain an extensive list of commercial variations of a process methodology.

According to the *International Standardisation Organisation* (ISO) and *American Society for Testing and Materials* (ASTM) in ISO/ASTM 52,900, additive manufacturing can be divided in 7 categories (Fig. 1.3).

The processes are classified as follows:

1. Material extrusion (MEX)—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice
2. Vat photopolymerization (VPP)—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
3. Material jetting (MJT)—an additive manufacturing process in which droplets of build material are selectively deposited (example materials include photopolymer and wax)
4. Sheet lamination (SHL)—an additive manufacturing process in which sheets of material are bonded to form an object
5. Powder bed fusion (PBF)—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
6. Directed energy deposition (DED)—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. Focused thermal energy means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited
7. Binder jetting (BJT)—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

In these 7 categories, commonly comercial used additive manufacturing processes are:

1. Material extrusion (MEX): Fused Deposition Modeling/Fused Filament Fabrication (FDM/FFF)

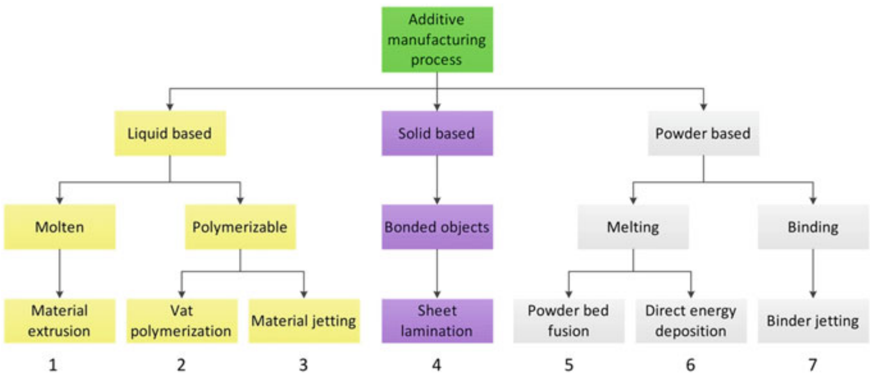

Fig. 1.3 Classification of additive manufacturing according to ISO/ASTM 52,900 (ISO/ASTM)

2. Vat photopolymerization (VPP): Stereolithography (VPP-UVL/P—SLA), Digital Light Processing (VPP-UVM/P—DLP), Continuous Liquid Interface Production (CLIP), Daylight Polymer Printing (DPP)
3. Material jetting (MJT): PolyJet, Drop On Demand (DOD), NanoParticle Jetting (NPJ)
4. Sheet lamination (SHL): Laminated Object Manufacturing (LOM), Selective Lamination Composite Object Manufacturing (SLCOM)
5. Powder bed fusion (PBF): Selective Laser Sintering (PBF-LB/P, SLS), Selective Laser Melting (PBF-LB/M, SLM), Electron Beam Melting (PBF-EB/M, EBM), Multi Jet Fusion (PBF-IrL/P, MJF), Selective Heat Sintering (SHS), High-Speed Sintering (HSS), Selective Mask Sintering (SMS), Selective Inhibition Sintering (SIS)
6. Direct energy deposition (DED): Laser Engineered Net Shaping (LENS), Aerosol Jet, Electron Beam Additive Manufacturing (EBAM), Laser Deposition Welding (LDW) and Hybrid Manufacturing
7. Binder jetting (BJT): 3D Printing (3DP)/ColourJet Printing (CPJ).

1.4 Vat Photopolymerization—VPP

Acrylate-based photopolymers are the first and most used resins developed for vat polymerization (VPP). Later were developed vinyl-ether and epoxy resins. All materials in vat polymerization are subjected to photopolymerization. The strategy behind the 3D photopolymerization is based on using monomers/oligomers in a liquid state that can be cured/photopolymerized upon exposure to light source of specific wavelength and form thermosets. A photoinitiator (with relatively high absorption coefficient) is required to convert photolytic energy into the reactive species (radical or cation) which can drive the chain growth via radical or cationic mechanism. The acrylates use a free-radical method, and epoxies and vinyl ethers use cationic method for polymerization. The polymerization can be shown schematically in 3 steps (Fig. 1.4).

Use of (meth)acrylate-based resins has proved effective in 3D photopolymerization, but they have certain disadvantages:

- These resins tend to undergo shrinkage during the polymerization. Pure (meth)acrylate resins tend to gel at low conversions depending on the functionality of the monomer used. This phenomenon would normally result in a very limited flow of the remaining uncured resin. Further photopolymerization above this conversion would lead to an increase in shrinkage stress with each newly formed bond. Depending on the molecular structure of the monomer/oligomer, the amount of shrinkage varies. Shrinkage and associated stress might result in curling and deformation during the layer-by-layer VPP
- Most of the (meth)acrylate-based photocurable resins contain multifunctional monomers which experience autoacceleration in the early phase of the chain growth (free radical) polymerization due to the fact that termination reactions are mobility restricted. The high kinetic chain length would result in the formation

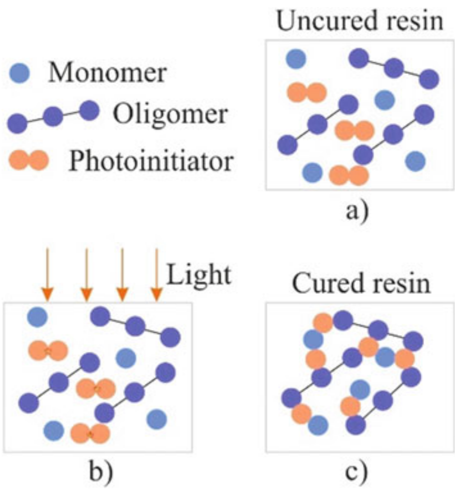

Fig. 1.4 Polymerization process (*Source* Ana Pilipović)

of networks with low uniformity and high brittleness, which is less efficient in dissipating stress, and therefore, cracks might propagate more readily.
– oxygen inhibition in the open vat.

Strategies to reduce the shrinkage are:

– the use of high molecular weight oligomeric acrylates (with less reactive group concentration) can reduce the shrinkage percentage; however, heating is required (during the 3D process) to reduce the high viscosity of these resins.
– the use of a radical step growth mechanism as an alternative to the chain growth polymerization.

To reduce brittleness:

– the use of chain transfer agents in regulating photocurable resins showed the ability to tune the cross-linking density, average kinetic chain length, and distribution of crosslinks alongside the backbone.

To lessen the oxygen inhibition:

– use of additives - but for resins containing both (meth)acrylate and epoxy might result in discolouration of the cured material.

The interest in using epoxide and vinyl ether monomers originates from their low volumetric shrinkage (~3%) that occurs during photopolymerization.

1.4.1 *Stereolithography—VPP-UVL/P (SLA)*

In the late 1970s and early 1980s, the concept of rapid prototype production began, based on the selective crosslinking of a photopolymer surface layer and the production of three-dimensional objects with consecutive layers. The process was called stereolithography, and in 1987 began the production of the first stereolithographic machines, i.e. the first machines in the field of additive manufacturing.

The principle of stereolithography is that the photopolymer solidifies when exposed to a light source. The build platform is located only one layer of thickness below the top of the liquid polymer surface. Helium cadmium (He-Cd) or argon (Ar) laser generates and focuses UV light and scans the polymer layer above the curing substrate. This step starts with the bottom section of the product. The build platform is then lowered down by the thickness of the next layer. The sweeper is used to avoid air bubbles in the product. As the product is being made in a liquid, it is necessary to secure its position by means of a support structure that is removed after the process is completed. The process is repeated until the final production of the whole product. The product is removed from the liquid polymer, and the excess polymer is washed in the solvent to obtain a so-called green phase. Subsequent curing takes place for a minimum of one hour. This step is necessary because some fluid can retain in layers.

Stereolithography process is shown in Fig. 1.5.

Recently, the production of multicolour products has become increasingly interesting to more users (e.g. in medicine). Therefore, a modified stereolithography procedure has been developed that enables the production of (for now) two-coloured products. The process consists of two steps. In the first step, a transparent photopolymer that forms the exterior of the product hardens, and in a second step a photopolymer mixed with pigments that forms the interior of the product. After the first step, the build platform on which the product is built is raised above the level

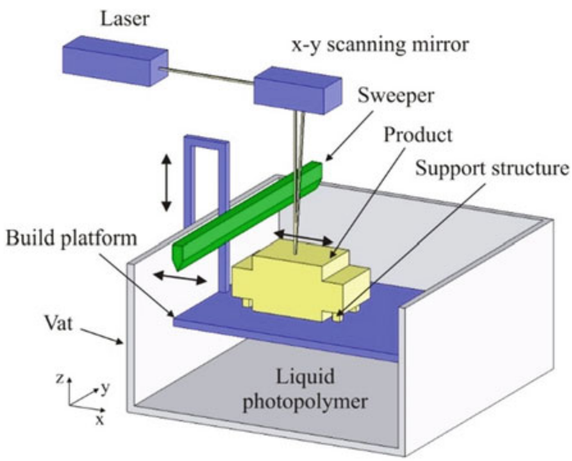

Fig. 1.5 Stereolithography (VPP-UVL/P) (*Source* Ana Pilipović)

of the photopolymer and the excess transparent photopolymer is removed. Subsequently, a coloured photopolymer is supplied to the production chamber using a special system. The laser outlines the required outlines on the coloured photopolymer and, after curing, the non-solidified photopolymer is removed and a transparent photopolymer is supplied. The substrate is lowered by one layer thickness compared to the position at the beginning of the previous step and the process is repeated.

The advantages of the VPP-UVL/P process are: combination of speed, precision (0.04 mm) and finish quality, very fine details (high resolution), machines produce very thin layers of 0.05 mm to 0.15 mm thickness, high productivity and production of transparent products.

The disadvantages of the VPP-UVL/P process are: high cost of materials, use of support structure, materials must be properly stored to prevent premature polymerization, possibility of using a narrow group of materials (photopolymers only), shrinkage of polymers after curing causes warpage and curling of the product, the product can be quite brittle, liquid material can be trapped in closed surfaces of the products, special space is required for the device because photopolymers develop harmful gases, post-processing like cross-linking of photopolymers and removal of the supporting structure is required, expensive laser maintenance.

Stereolithography products are used as prototypes, functional products, tooling models, injection moulding models, investment casting and sand casting models.

The following materials are used in stereolithography: poly(methyl methacrylate), epoxy resin, as well as materials having properties similar to polyethylene, polypropylene, polyamide 66, acrylonitrile/butadiene/styrene, polycarbonate and poly(butylene terephthalate). It is also possible to use a nanocomposites, as well as to use photopolymers (acrylic or epoxy resins) filled with metal or ceramic powder or particles. However, when using such composite materials of metal and ceramics, the removal of the polymeric binder at temperatures from 400 to 500 °C and final sintering of the filler particles at a temperature of about 1200 °C or higher is required after the stereolithography process. Figure 1.6a shows some products made using

Fig. 1.6 Products made by the VPP-UVL/P process: **a** transparent Accura Phoenix **b** the bridge (Photo by Ana Pilipović)

stereolithography. Figure 1.6b shows a large structure where it is particularly difficult to optimally remove the supporting structure.

1.4.2 *Vat Photopolymerisation Digital Light Processing—VPP-UVM/P (DLP)*

In the process of curing a photosensitive acrylic resin using a digitally processed light signal, the projected image from the VPP-UVM/P light source represents a cross-section of the product that cures in the polymer resin. Visible light is projected below the build surface. The device illuminates the entire layer at once, reducing the total cycle time (10 to 15 s depending on the polymer).

The projector is located under the build platform. The resin is contained in a glass-enclosed chamber that covers the projector. The first layer of the product is made on the bottom surface of the resin, which cures by the light projected from the projector. The build platform raises by the thickness of the new layer and the process starts from the beginning (Fig. 1.7).

During the process, millions of digital mirrors (1280 × 1024 pixels resolution) housed in a digital projector housing generate an image mask of each layer. Mirrors direct light through a mask that transmits some of the light at precisely defined locations, thereby achieving a controlled cure of the acrylic photopolymer. Thereby

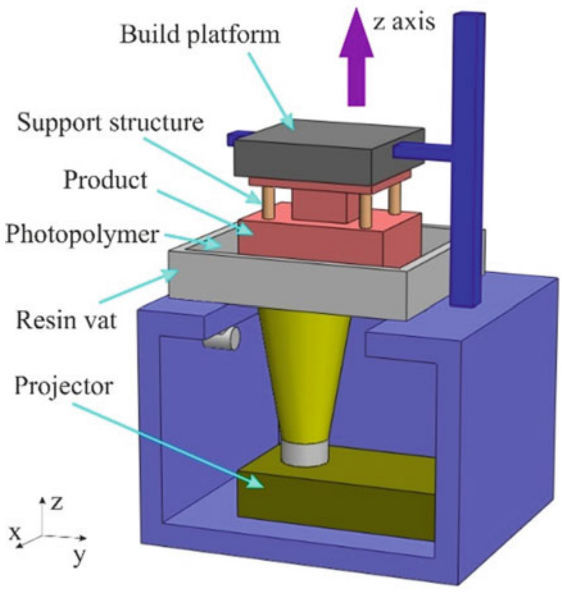

Fig. 1.7 Digital light processing (VPP-UVM/P) (*Source* Ana Pilipović)

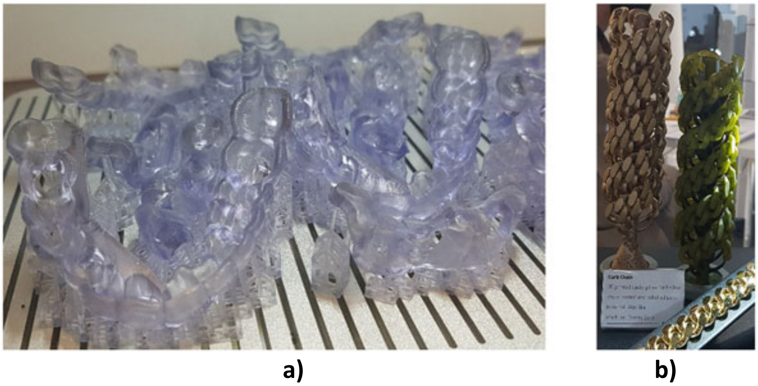

Fig. 1.8 Application of the VPP-UVM/P: **a** in dentistry, **b** for jewellery (Photo by Ana Pilipović)

the entire layer is simultaneously exposed to light and the curing is achieved in one step.

The advantages of the process are: quick and easy material change, the ability to apply a large amount of photosensitive materials (epoxy and acrylic resin, nano-composites, ceramic composites, photopolymer with wax content), as well as biocompatible materials.

The disadvantages of the process are: given the small size of the chamber, the process is only suitable for small-scale products and support structure is required.

The most common application of the procedure is in dentistry, medicine and jewellery (Fig. 1.8).

1.5 Material Jetting (MJT)

In material jetting (MJT) the liquid material is solidified through a process of photopolymerization. This is the same mechanism that is used in vat polymerization. Similarly to VPP-UVL/P, material jetted parts have homogeneous mechanical and thermal properties, but unlike VPP-UVL/P they do not require additional post-curing to achieve their optimal properties, due to the very small layer height used (16–32 μm). The materials used in MJT are thermoset photopolymers (acrylics) that come in a liquid form. Materials can be fully transparent and mimic ABS and rubber. Because material is sensitive to light, properties of the products can change over time.

1.5.1 PolyJet

PolyJet technology (Fig. 1.9) was developed in 2000, combining the good sides of stereolithography (VPP-UVL/P) and 3D printing.

The multi-nozzle printing head moves back and forth along y-axis and applies prints a layer of photosensitive polymeric material onto a 16 μm thick substrate, which is approximately 1/5 the thickness of the stereolithographic layer. Each layer of photosensitive polymer hardens under UV light, immediately after application, forming a fully cured product, without the need for subsequent curing. Liquid resin is heated to 30–70 °C to achieve optimal viscosity for printing. Two different materials are used: one for the model and the other for the support structure, i.e. half of the nozzles apply the material to the model and the other half to the support structure. After the first layer is completed, the build platform is lowered by the thickness of the next layer and the print head begins to create the next layer. After the product is made, the support structure (gel material) is easily removed with water at a pressure of 40 bar or manually, which depends on the shape, i.e. geometry of the product. Thin-walled and small products are cleaned at lower pressures and robust ones at high pressures, thus shortening the cleaning time.

The low layer thickness ensures the fabrication of a product with a very smooth surface, which requires no further processing. Finished products can be treated with particle jet, polished, sanded, painted, etc. Prototypes can be used as models for the production of silicone moulds for resin infusion process using a special combustion chamber.

The advantages of the process are: high quality (due to the very thin layer the products are very precise and have a very smooth finish), the ability to produce small details and thin walls, application in offices (there is no contact with the resin, the support structure is removed by water), the process is fast, no subsequent curing is required, it is possible to use different materials that provide different geometry, mechanical properties and colour. The great advantage of the PolyJet technology is, as with stereolithography, the production of transparent products.

The process is used in automotive, electronics, toy, footwear, consumer goods and jewellery industries.

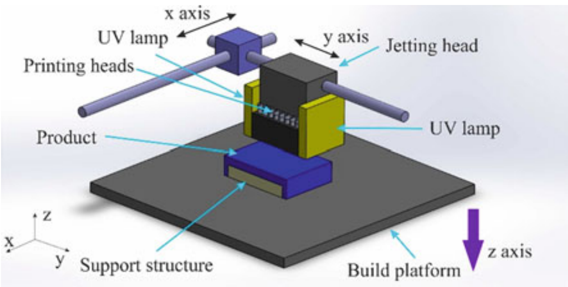

Fig. 1.9 PolyJet (*Source* Ana Pilipović)

Fig. 1.10 Product made with digital materials (Courtesy of Stratasys)

A newer version of the process, *PolyJet Matrix*, allows the mixing of materials and printing any two available materials (Digital Materials) simultaneously to achieve the target properties of the finished product (e.g. strength, elongation, hardness) (Fig. 1.10). Digital materials are designed in the computer, and it is possible to make products by combining different materials (e.g. rigid and flexible). The disadvantage of such a technology is the high cost of the printer. The building materials and support materials are separately supplied to synchronized printing heads. Each of the heads has 96 nozzles, through which the materials are injected into the workspace.

The advantages of the *PolyJet Matrix* technology over comparable technologies are: the possibility of making composite products with properties comparable to real products, a wide variety of black and white materials as well as coloured materials is possible, which enhances the visualization potential of the product. Also, there is no need for assembling of individual elements of the prototype set, and the technology is particularly suitable for developing injection moulded products and moulds for multi-component injection moulding.

The materials used in the PolyJet process are listed below.

FullCure photopolymer acrylic materials allow 3D models to be produced with high precision and fine detail. The variety of resins in the FullCure material palette offers the properties of transparency, colour, opacity, flexibility and rigidity. There are *FullCure 720, VeroBlue, VeroWhite, VeroGray, VeroBlack, VeroClear, Rigur, DurusWhite, TangoPlus, TangoBlackPlus, TangoGray*, and *TangoBlack* materials.

FullCure 720 is a transparent acrylic photopolymer suitable for rigid models. Advantages of the material include no post-treatment required, ultimate elongation of 20%, good flexural toughness, and the ability to machine, drill and chrome.

Vero materials are opaque coloured materials that allow fine detailing and reduce the need for colouring. They have excellent flexural strength and flexural modulus. VeroBlack is a material with a high flexural modulus and high moisture resistance, making it suitable for many applications. Opaque black allows for electronics use. *VeroGray* has excellent dimensional accuracy, low water absorption, high flexural strength (95 MPa) and flexural modulus. It is used in the automotive industry, for toy manufacturing, in medicine, electronics, etc.

DurusWhite is a material that has properties similar to polypropylene and possesses good flexibility, strength and toughness.

Tango materials have excellent ultimate elongation > 50%), flexibility and elasticity. There are *TangoBlack*, which provides maximum elasticity with a hardness of 61 Shore, *TangoGray*, which is a little stiffer (75 Shore), and *TangoPlus* with ultimate elongation of 218%.

Using the *PolyJet* technology, it is possible to make a product made of a material resistant to temperatures up to 80° C, which is called *ABS Like*, i.e. it has properties similar to ABS. It is often used to manufacture injection moulds (Fig. 1.11) that can withstand batches of up to 100 pieces.

More recently, coloured materials *VeroCyan*, *VeroMagenta* and *VeroYellow* have appeared on the market, which can also be combined with *Tango* materials to produce a flexible, coloured product (Fig. 1.12).

In PolyJet it is possible to make products with a glossy and matte finish. In the glossy setting, support material is added only when it is structurally required (i.e. for overhangs). Surfaces not in direct contact with support will have a glossy finish, while supported areas will be matte. The glossy should be used when a smooth shiny

Fig. 1.11 Injection mould made by PolyJet Matrix (Courtesy of Stratasys)

Fig. 1.12 Product made with digital materials: combination of Vero and Tango materials (Courtesy of Stratasys)

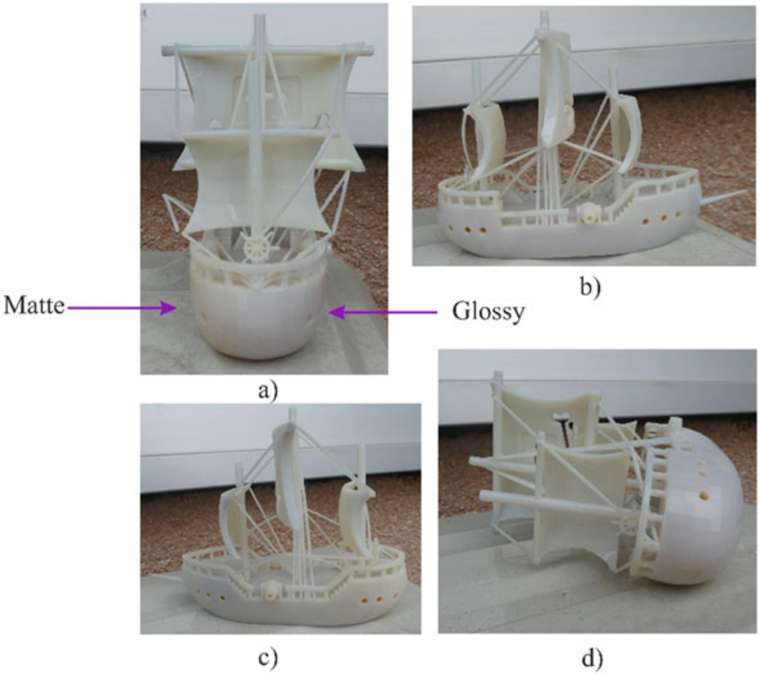

Fig. 1.13 A part printed in: **a** half glossy, half matte, showing the difference in surface finish, **b** glossy surface, **c** matte surface, **d** orientation during production (Photo by Ana Pilipović)

surface is desired. The cost of printing glossy is lower, as less material is used. The drawbacks of using this setting are the non-uniform finish of the printed parts and the slight rounding of the sharp edges and corners on the top, glossy surfaces. In the matte setting, a thin layer of support material is added around all the whole part, regardless of orientation or structural requirements. This way all surfaces have a matte finish. The matte should be used when accuracy and uniform surface finish are a requirement. The cost of the matte setting is slightly higher, as more materials are used and additional post-processing time is required. Notably, parts printed in the matte setting also have a relatively lower surface hardness (Fig. 1.13).

1.6 Binder Jetting (BJT)

Binder jetting (BJT) is process in which polymer, metal and sand products are commonly made. Metal-based binder jetting parts have relatively good mechanical properties thanks to the infiltration or sintering processes. They are also more cost-effective than PBF-LB/M (SLM) metal parts but have poorer mechanical properties because the grains of materials do not entirely fuse together. Compared to Laser

Beam Powder Bed Fusion (PBF-LB) in the BJT method parts are printed without heat so there is no differential cooling and therefore no warping and good dimensional accuracy. However, there are potential shrinkage issues during the infiltration or sintering processes. These are hard to predict and can cause parts to shrink by 0.8–2% of the part's total size.

Post-processing is often required to make the part stronger and give the binder-material better mechanical and structural properties. Some materials, like sand, require no additional processing. After printing, the parts are in a green, or unfinished, state and require additional post processing before they are ready to use. Often an infiltrate substance is added to improve the mechanical properties of the parts. The infiltrate substance is usually epoxy (in case of polymers), a cyanoacrylate adhesive (in case of ceramics) or bronze (in the case of metals). Another strategy is to put the product, in its green state, inside an oven to achieve a sintering of the grains of matter.

The build material is in powder form and binder is usually in liquid form. For build material it can be used metals (stainless steel, tool steel, steel/bronze, tungsten/bronze, cobalt chrome, copper, Inconel (nickel-chrome), titanium), sand, ceramics and polymers (PMMA). There are various types of binder materials, each suited for a specific application, like furan binder (for sand casting applications), phenolic binder (for sand moulds and cores), silicate binder (environmentally-friendly, for sand moulds and cores) and aqueous-based binder (for metals).

The binder, in the first place must be printable. An ideal binder would have low viscosity which allows the stream of individual droplet beads to form and then break off from the nozzles rapidly. Also, binder must have stability against the large shear stress induced by printing. Additional criteria include good powder interaction, clean burn out characteristics, long shelf life, and acceptable environmental risk.

1.6.1 3D Printing 3DP

3D printing got its name because of its similarity to ink-jet printing. In 3D printing (Fig. 1.14), binder or glue is ejected instead of ink. The build platform is positioned at a height necessary to place the powder layer on the substrate to the desired thickness. Typically, approximately 30% more powder per layer is applied to ensure good powder coverage on the build platform. The powder layer is selectively scanned by a 3D printer head that releases liquid binder and causes the powder particles/layers to adhere to each other. The nozzle head scans the powder to the desired cross-sectional shape. This starts with the lower cross section. The build platform is lowered for the thickness of the new layer. The new layer is scanned, adapting to the shape of the next upper section and adhering to the previous layer. The process is repeated until the top layer is made. Production time depends on the height of the product. After fabrication, the product is left in the powder chamber for some time to reach the required strength, then removed and the excess powder is removed with air. A subsequent tempering

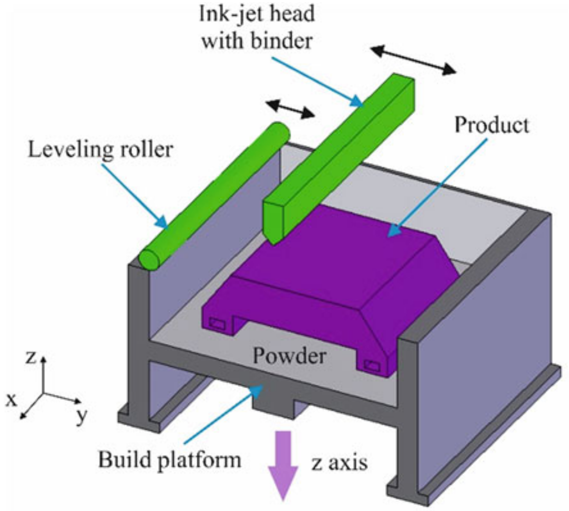

Fig. 1.14 3D printing process (*Source* Ana Pilipović)

process (10 min at 95 °C) and infiltration of wax, epoxy or cyanoacrylate is applied to harden the product.

An important advantage of 3D printing is the ability to create coloured products. Similar to 2D printing, the computer converts RGB colours (red, green, blue) to CMYK colours (cyan, magenta, yellow and black). Applying these four inks, the printer combines several dots into each printed pixel to produce a thousand colours. The same principle applies to 3D printing, that is, the binder can be ejected from a multi-nozzle head, with different materials, i.e. colours, in each nozzle (Fig. 1.15).

The result is almost complete density products that can be further processed or polished if necessary.

Fig. 1.15 Product with multiple colour combination (Photo by Ana Pilipović)

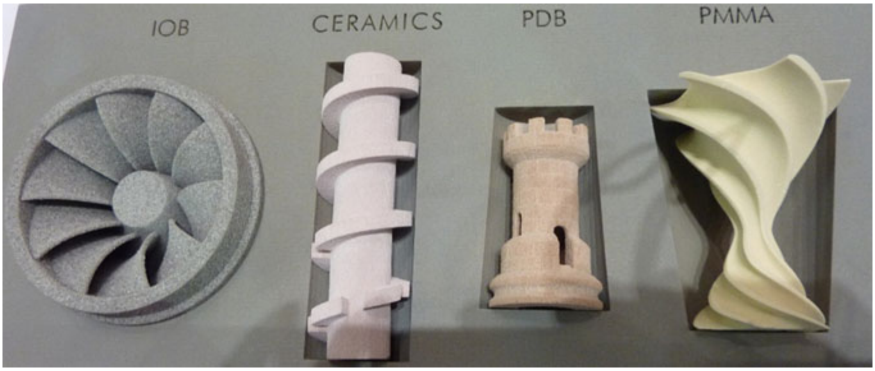

Fig. 1.16 Different materials for 3DP (Photo by Ana Pilipović)

Advantages of 3D printing process are: high speed of machine operation, possibility of usage of machines in offices (non-toxic materials), high precision of the printer, good dimensional tolerances of the products, possibility of printing of coloured materials, possibility of making very thin layers, low cost, no use of support structure is required, it does not require high energy for manufacturing, already used material can be reused.

The disadvantages of the process are: limited product dimensions, limited number of materials used and production speeds, poorer accuracy compared to other processes for large-sized products, high roughness, which requires additional machining, it takes some time to clean the product, products are after manufacturing fragile so they need to be further hardened with cyanoacrylate or epoxy adhesives.

Polymer materials used in 3D printing are: poly(methyl methacrylate) (Fig. 1.16), epoxy resin, and high strength and flexible polyurethane that is resistant to impact loads. Composite materials can also be used, especially for products with small details. The material consists of polymers with several additives that increase the surface finish quality, resolution, toughness and strength of the product. Such materials can be printed in different colours and is an ideal choice for delicate and thin-walled products, coloured products, accurate detailing and for the fabrication of products requiring high strength.

Fine casting materials are used to produce products that can be dipped in wax. The material consists of a mixture of cellulose, special fibres and other additives that allow the dimensions of the product to be accurate while increasing the absorption of wax and reducing the residue during the combustion process.

Direct casting material is used to make sand moulds (Fig. 1.17) for non-ferrous materials, as well as to make moulds into which metal can be directly casted, which is faster and less expensive compared to conventional metal casting processes. This material is a mixture of sand, gypsum and other additives that together result in high strength moulds with a good finish. The materials withstand the temperatures required for polymer casting.

Fig. 1.17 Sand moulds made with binder jetting (Photo by Ana Pilipović)

The elastomeric material allows the elastic parts of the product to be made. The material consists of a mixture of cellulose, special fibres and other additives that allow for the production of precision elastic parts.

Metal matrix composites are formed by infiltrating bronze into stainless steel. They have very good mechanical properties and are low in cost. They are used for construction products. Nickel has excellent chemical resistance and is used at elevated temperatures.

Loading new material into a 3D printer is a quick and easy process. All unused materials are recyclable, reducing the cost of the product.

3D printing can successfully produce prototypes, products, moulds and tools of very complex shapes. It was the first time that a mould of ceramic powders was made. When making moulds and tools made of metal powders, significant savings are achieved on production time and the cost of expensive post-processing.

1.7 Powder Bed Fusion Technologies (PBF)

1.7.1 Introduction to Powder Bed Fusion Technologies

Nowadays the additive manufacturing market offers a wide variety of AM technologies based on both metal and polymeric powders. These technologies evolve quite fast bringing new features and specs that make them more reliable, faster and more accurate. Hence, we can find more industrial applications of additive manufacturing, not only for rapid prototyping and design validation but also for final-use parts and industrial productions.

Powder based additive manufacturing is a technique of layer by layer manufacturing where an energy source is applied to melt or sinter metal, polymer and ceramic based materials.

Technologies reviewed in this book are the following:

- PBF-EB/M (Electron Beam Powder Bed Fusion of Metals) (or EBM—Electron Beam Melting)
- PBF-LB/M (Laser Beam Powder Bed Fusion of Metals) (or SLM—Selective Laser Melting)
- PBF-LP/P (Laser Beam Powder Bed Fusion of Polymers) (or SLS—Selective Laser Sintering)
- PBF-IrL/P (Powder Bed Fusion of Polymers with Infrared Light) (or MJF—Multi Jet Fusion).

Powder Bed Fusion Principles

Powder bed technologies use fine particles of different nature (metallic, ceramic or polymeric) as feedstock, we can find that depending on the am technique, they are provided with different power sources which aim is to consolidate the material creating 3D printed parts from fine powder layer by layer.

These AM technologies allows the production of very complex geometries using a heat source to fuse the powder particles layer by layer transforming the feedstock into solid parts.

Normally the PBF technologies work under a protected atmosphere so that the feedstock is processed in the right conditions avoiding oxidation during the process and therefore making possible that the powder can be used again after each build. Altough AM scenario is continuously evolving and different groundbreaking energy sources are being launched, PBF technologies use the following standard energy sources so as to selectively sinter the powders (Table 1.1).

Powder Bed technologies provide us with certain design freedom that varies depending on the technology and the materials to be processed, as general benefit of AM in comparison with traditional methods, we can create very complex geometries,

Table 1.1 Type of power source depending on PBF technology

	PBF-EB/M (EBM)	PBF-LB/M (SLM)	MBJT	PBF-IrL/P (MJF)	PBF-LB/P (SLS)
Power source	Electron beam gun	Laser beam (Fiber)	UV light source + furnace	UV light source	Laser beam (CO2)

inner channels and connections thanks to this design freedom that AM brings. Nevertheless, as in any process, AM technologies present also some kind of limitations that are gathered afterwards.

As a general overview of PBF technologies, they are all provided with powder tanks/deposits where the fine particles are picked up and delivered every layer by a raking system designed specifically for each process. Machines are also provided with a build platform that moves down as well as an energy source that sometimes is a punctual beam and sometimes heating lamps made up of UV bulbs. Although there are some "closed software" machines, we can normally adjust a wide variety of parameters within the process that enable us the development of new materials for AM.

In the PBF process the phenomenon called "melt pool" appears in a very small area where the laser source is describing the melting pattern. However nowadays we find very fast technologies based on heating bulbs as the Multi Jet Fusion Technology from HP where there is not a specific sintering/melting spot but the whole layer sintered at the same time.

Melt pool behaviour and energy deposition will vary depending on the process parameters and of course every material will require specific sets of processing parameters.

1.7.2 Electron Beam Technology (PBF-EB/M)

PBF-EB/M uses high-energy electron beam to fuse metal powders. The process takes part under a very high vacuum environment which allows reducing oxygen content during the heating-melting process. The production rates of the PBF-EB/M are much faster than the PBF-LB/M because of the high beam speed and the layer thickness parameter (higher than PBF-LB/M due to bigger particle size distribution in comparison with PBF-LB/M). Process is carried out while the powder and build platform is preheated so that parts manufactured by PBF-EB/M have neither internal stresses nor distortions. Process temperatures can vary depending on the material to be processed.

Since the particle size distribution (PSD) of PBF-EB/M is bigger, the feedstock used in this technology is cheaper than the one used in PBF-LB/M (sieving yields are more optimistic for bigger particles). As drawbacks, since the process is done while preheating, the "cake" obtained once the build ends is made up of parts surrounded by slightly sintered powder which makes difficult the part cleaning, especially when there is presence of small ducts and channels where powder remains trapped, for this reason a powder recovery systems (PRS) is required in the PBF-EB/M process, the aim of this so-called "PRS" is to blast powder from the same nature that the one processed in order to remove the sintered powder attached to the processed parts. Moreover, due to the increased size of particles in comparison with LPBF particles, surface roughness is especially accentuated in PBF-EB/M parts.

PBF-EB/M Components

In the PBF-EB/M production chain we will find the components pointed out in the following lines, all of them must be ATEX (Atmospheres EXplosible) approved:

– PBF-EB/M Machine: (3D Printer) core of the process where the parts are produced inside the high vacuum cabinet.
– Loading trolley: powder is stored in two hoppers that deliver a small amount of material to cover the build area each layer, the trolley is needed to handle the hoppers that can weigh between 40–80 kg.
– Powder Recovery System (PRS): (sandblasting equipment) the same powder used during the fabrication is also applied at high speed in this PRS in order to remove the sintered powder sticking to the parts. This powder is used again in further builds.
– Vacuum cleaner: after each build, the PBF-EB/M cabinet is opened and must be cleaned up from powder present all over the chamber. Powder recovered by the vacuum cleaner is sieved and used again in further builds.

PBF-EB/M machines are made up of three basic units: EB-Gun cabinet where the e-beam is generated, build chamber where the parts are built and control unit where the technicians manage the process parameters and mechanical adjustments. Giving a closer look at the PBF-EB/M Chamber, we can see two hoppers (tanks where the powder is stored before any build starts) and a heat shield placed just beneath the build area. The heat shield is a metal-plate structure necessary to keep the upper surface and the powder cake at a certain temperature during the whole build, this part prevents the damage of other componentes placed inside the chamber.

Regarding the build area, a rake is in charge of the powder delivery, it moves from one hopper to the oher picking a specific amount of powder that is deposited in the melting area where the parts are built. An overview of the PBF-EB/M technology is presented in Fig. 1.18.

On the other hand, the EB-Gun is made up of different kind of "lenses" present along the beam EB-Colum, focusing lens is aimed to increase or decrease the diameter

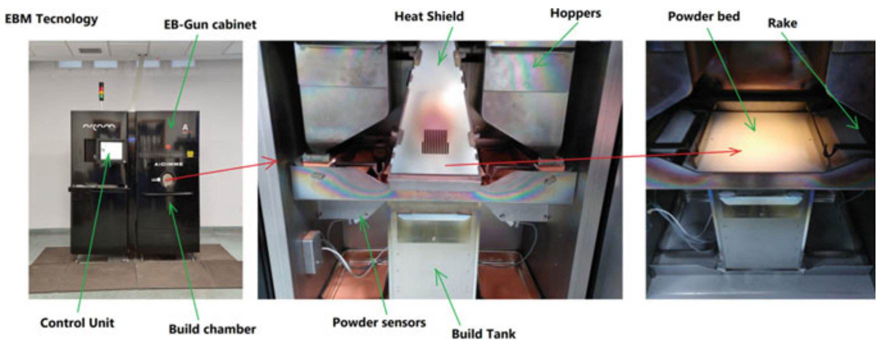

Fig. 1.18 PBF-EB/M overview (*Source* AIDIMME facilities)

of the spot. This parameter gives us the opportunity to modify the energy denisity deposited, whereas the deflection lens is aimed to describe the melting patterns stored in the layered file. These are not really lenses but magnets that distort the electron beam shape before it hits the powder bed.

Regarding the materials that PBF-EB/M is used to process, Arcam has the monopoly of EB technologies, and they are offering specific machines for specific materials as TiAl. But by large Ti based alloys and CoCr are the standard alloys.

It does not mean that the machines are not able to process other materials, as it has been demonstrated by AIDIMME several times, process (not only software but also hardware) can be adjusted so that the machine deals with nonstandard materials as pure Copper, Nickel based superalloys, and nanomodified Ti64 between others.

PBF-EB/M Workflow

Process starts from the very fist step of machine preparation where the technician cleans the build chamber from the previous build; it requires specific tools and liquids specially designed in order not to damage the components. During this fist step, powder that might have been spreaded within the chamber must be removed using an ATEX vacuum cleaner.

Once the machine has been cleaned up, there are certain short-term replaceable parts that must be doublechecked and changed if necessary, as the filament, the heat shield plates or rake plates and the thermo couple and ground wire. Technician must doublecheck the state of those parts as a preventive action in order to avoid possible issues. Provided that the machine is clean and the spare parts changed powder hoppers full of material are introduced into their clamping system, some powder is delivered by the rake so as to perform what in AM we call "bed levelling" in addition a beam calibration and powder measuring sensors calibration are mandatory as well.

Build preparation must be carried out by experienced technicians since a proper procedure will lead to a flawless build.

Once the machine is prepared and the powder loaded, air is pumped outside of the chamber until vacuum gauges reach a certain value. High vacuum is required in order not to damage the raw material and get good results in the consolidated parts.

Parallel to the tasks described below, the job file is prepared. The technician allocates the parts inside the build volume trying to face them in an optimal position, this is so important since many support structures can be replaced by positioning the part in a strategic place. Three different softwares are used to prepare a job file:

- Materialise Magics: is used to put the parts inside the build envelopment, support structures can be tailored in Magics for different materials and also for different technologies, during the allocating process the scale factors are applied to each model in order to compensate possible part distortions, these scale factors are controlled each build. Supports and scturtures are generated in Magics.
- Build assembler: is used to generate the project file (Arcam Build File). The model generated in the previous "Magics" step is loaded into this software in order to separate the different geometries (wafer, support, melt) so that specific process

parameters are usead for each kind of geometry, layer thickness is also set in this step.

– PBF-EB/M Control software simulator: prior to running a job, the build must be simulated so as to prevent possible issues as defects in the layering or supports. This step is carried out in order to verify the build file. In the PBF-EB/M simulator the technician is able to doublecheck every single layer of the build.

Once the 3D models are layered and loaded into the EB-Build software, a first step of start plate preheating takes part, this task is aimed to ramp up the temperature of the build platform that will be kept withing the entire build by several preheatings performed on the top surface of every single layer. Part construction phase is dividided into various steps as: powder preheating, contour melting, hatch melting, and wafer (supports and structures). During this phase a huge amount of variables and complex formulas modify the energy deposition depending on the trajectories to be described.

Once the process completes the last layer, a controlled cooling-down phase takes place. When the bottom temperature reaches a certain low temperature, machine can be opened and cake recovered. This cake full of semi-sintered powder is sandblasted and parts appear attached to the build platform by the support structures that are removed afterwards.

Many variables are controlled during the process and can be assessed in order to troubleshout possible issues that sometimes arise. A log file as well as a report is generated after the process in order to evaluate these variables.

Last but not least, when it comes to process parameter development for nonstandard materials, the user is able to modify plenty of variables such as scanning speed, focus offset, line offset, beam current, process temperature, number of contours, layer thickness and many other complex functions that affects the results obtained in the molten material.

1.7.3 Laser Melting (PBF-LB/M) Technology

Laser based powder bed technologies (PBF-LB/M) are the most common and extended metal additive manufacturing nowadays. These Additive Manufacturing machines offer different specifications such as as low temperature preheating, mutiple lasers, very small area for fine detailed parts and huge build envelopments for bigger parts.

PBF-LB/M uses similar principles as PBF-EB/M since both selectively melt the powder bed that is delivered layer by layer. However, there are some important diferences between these metal AM technologies.

Particle Size Distribution of PBF-LB/M powder is finer ((15–53 µm or 20–63 µm) therefore layer thickness parameter in this technology is slightly thinner than in PBF-EB/M. Foreseeably the parts obtained by laser-based technologies present better surface roughness but on the other hand the production rates are longer and the feedstock prices higher (sieving yields of finer particles are lower). PBF-LB/M technologies work under protected atmosphere, normally Ar or N, but in this case the chamber is at room temperature or low preheating temperatures up to 400 °C, which means that parts suffer from internal stresses and therefore post heat treatments are necessary to be applied as post processes. Nonetheless working at room temperature brings some benefits as non sintered powder nearby the processed parts, this eases the powder removal from the inner channels/geometries. Hence, we can manufacture very complex internal geometries because non melted powder is easy to remove afterwards.

PBF-LB/M Components

Laser based machines are made up of the build unit itself, a protective gas generator or deposit and the powder recovery system that gathers the non melted material and sieves possible contaminating particles.

- PBF-LB/M Machine (3D Printer): core of the process where the parts are produced. Latest laser based technologies lauched are equipped with a closed powder control loop in charge of the powder handling and storing.
- Powder Recovery System: powder recovered after each build is used again in further builds.
- Protective gas deposit/generator: provides the machine with inert gas so as to generate the protective atmosphere during the whole process.

Inside the build chamber, we can find the build tank where the build platform moves downwards and the powder deposits. Layer by layer the squeegee blade picks a cerain amount of powder that is delivered into the build envelopment.

An overview of the PBF-LB/M technology is presented in Fig. 1.19.

Most parts of the PBF-LB/M machines offered in the market are equipped with a fiber laser which works in a wavelength of 1064 nm (red spectrum laser). This is so because the absorption values of the standard materials present good values at this wavelength levels. Nevertheless, latest developments show that lasers of different wavelengths as the green laser (505 nm) can be usefull for specific materials which present low absorption.

Regarding the standard materials that Laser based technologies are used to process, we can find stainless steel 316, aluminium, titanium alloys, maraging stells, copper alloys, 17-4ph, chromium cobalt or inconels between others.

PBF-LB/M Workflow

As pointed out in the PBF-EB/M section, the first step in laser-based technologies is machine preparation and build job assembly, technicians must clean the machine up and make sure that the powder is properly stored in the deposits of the PBF-LB/M machine. Short-term spare parts must be changed as well, in this process the squeegee blade must be double-checked since it could have been damaged while delivering powder during the build.

Bed levelling process must be carried out in order to ensure good weldability in the very first layers and chamber inertization as well.

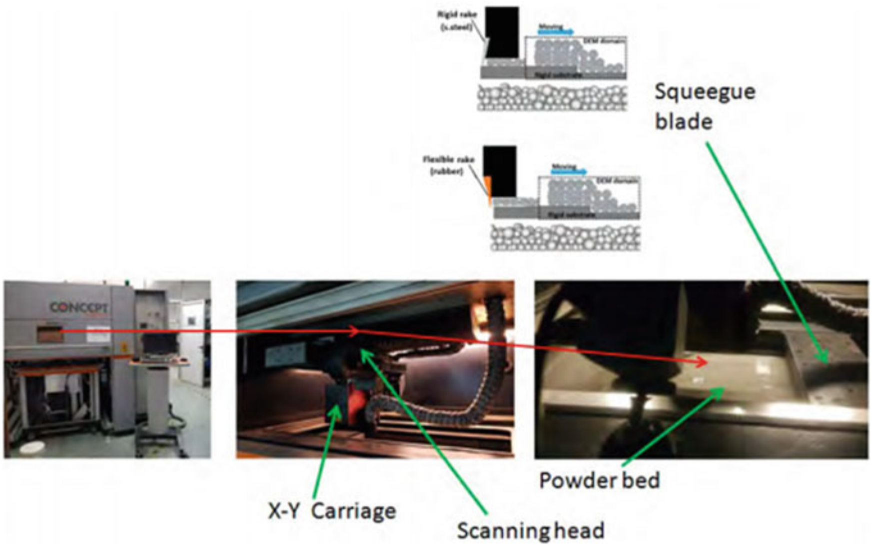

Fig. 1.19 PBF-LB/M overview (*Source* AIDIMME facilities)

PBF-LB/M build preparation is quite similar than PBF-EB/M but some considerations must be kept in mind as for instance the fact that we cannot nest parts in the Z axis but only if they are connected by support structures to parts attached to the build platform. Normally support structures required in PBF-LB/M technologies are denser than in PBF-EB/M technologies because of the room temperature conditions (non sintered powder) and the very fast cooling rates that take place during the process.

Regarding the melting process of laser based technologies, it varies depending on the strategy that each machine manufacturer follows, but normally the approach in laser based process is to perform controlled melting areas with equivalent energy. Concept laser M3 linear machine for instance follows the island pattern in which every layer is basically split into small squares of a certain dimension (5 $\times$ 5 mm) that are randomly melted afterwards in order not to accumulate the energy in specific areas of the layered geometries. These approaches are considered in order to reduce the swelling phenomenon.

Parameters that can be modified within the process are; current, laser speed or frecuency if the laser is pulsed, focus diameter (affects the shape of the laser), vector pattern (direction of the scanning vectors), overlap between scan tracks hatch-contour, number of contours between others.

Metal additive manufacturing processes are managed by very complex functions that vary the energy deposition. When it comes to a process parameter development for a new material, many variables can be modified in order to achieve good results in the consolidated material.

1.7.4 Selective Laser Sintering (PBF-LB/P) Technology

Selective laser sintering (PBF-LB/P) is an additive technology that uses a laser source (normally a CO_2 laser of 10,600 nm) to transform polymeric-based powder into solid parts based on 3D CAD models.

PBF-LB/P was one of the first additive manufacturing technologies developed in the mid 80-s, since then, the process has been adjusted to a wide variety of materials.

In the PBF-LB/P machines we can normally find two powder tanks where fine powder of a PSD 20–80 μm is stored and the build platform located in the middle. PBF-LB/P works under protected atmosphere (normally Nitrogen) and at a certain process temperature which is specific for each material. This temperature ramps up the temperature of the powder layer up to 12–16 °C below the melting point and the laser puts the remaining energy to melt the polymeric powder.

Some of the benefits of Selective Laser Sintering technologies are: (i) big parts can be manufactured, (ii) high strength polymers can be processed as polyamide, (iii) PBF-LB/P does not need support structures, thus design rules are much more flexible just trying to reduce the material as much as possible, and (iv) PBF-LB/P is able to reproduce very small geometries.

Nevertheless, powder not transformed into a part is affected by heat during the process; hence it must be refreshed with virgin powder in order to be reused again in the next build. Most part of the production costs of the PBF-LB/P technology comes from the feedstock; therefore, powder reusability is a key factor in order to cut down the part costs.

As a drawback, depending on the machine temperature stability is an important issue to deal with, because slight variations in the temperature whithin the process will lead to part distortions, curling and other typical issues of additive manufacturing.

PBF-LB/P Components

Among the components required within the PBF-LB/P process it can be found:

- PBF-LB/P cabinet where parts are built.
- Mixing station where already used powder is mixed and refreshed with virgin powder after each build.
- Powder recovery system where powder is sieved and possible comntamination or over sintered powder is removed.

Focusing on the production station and especially on the sintering unit, a low power CO2 laser is located on the top part of the machine. This laser is guided by two galvo mirrors that deflect the laser up to the powder bed. The roller picks a small amount of powder from the tanks and delivers it through the workpiece area creating a thin layer which is heated and melted.

In the PBF-LB/P machines we can also find several heaters allocated in diferent areas, some of them are aimed to preheat the workpiece area whereas others heat the powder tanks so that powder delivered is slightly heated before the deposition and therefore distortions are minimized.

In case of polyamide 12, which is the most common material processed by sintering technologies, process temperature is ramped up to 178–180 °C, it is rather important to keep a constant temperature along the entire build in order to reduce part distortions.

An overview of the PBF-LB/P technology is presented in Fig. 1.20.

PBF-LB/P Workflow

As described before machine and build preparation are crucial to achieve good results; the chamber must be cleaned up from powder of the previous build and bed levelled. Some preventive actions should be carried out in order to improve the results as for example cleaning the exit window of the CO2 laser since some very fine powder remains sticked to the face inside the chamber after each build.

Given the benefit of a support free technology means that parts can be placed anywhere within the build envelopment. Nowadays, it can be found nesting softwares as Materialse Magics which supports the technician in the parts allocation improving the build density as much as possible. The more parts fit in the build envelopment the cheaper the unitary costs will be.

Once the machine has been cleaned up and the powder stored in the tanks, the chamber is inertized and heaters are turned on.

Te build platform starts moving down while the powder is spreaded in a first phase called warm-up. This warmup stage aims to create a 10–12 mm height cake with no parts which pretends to create a heat barrier between the parts and the build platfor avoiding in this way phenomena like curling.

Once the warmup phase reaches 10–12 mm build starts; powder is dispersed by a roller in the shape of a fine layer. During the whole process a couple of heaters keep the temperature of the build platform at a certain point below the melting point of the material to be sintered. Once the layer has been deposited the laser source scans a cross-section of the 3D model (layered model) fusing the particles together

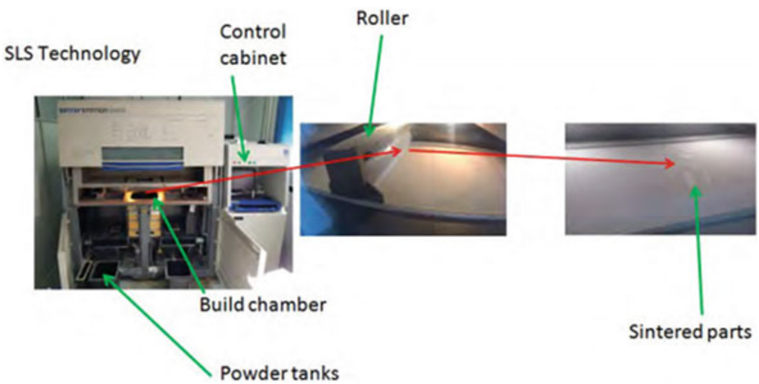

Fig. 1.20 PBF-LB/P chamber scheme (*Source* AIDIMME facilities)

in order to create a solid part. This process is repeated for each layer until parts are completed.

Once the build ends there is a cooling down phase where temperature is reduced in a controlled manner. A drastic cool down can lead to part deformation and distortions thus it is very important to naturally cool down the cake before removing the parts manufactured in each build. This phase takes between 12–24 h depending on how high the so-called cake is.

Powder reusability in PBF-LB/P is critical since most part of the production costs come from the feedstock itself, therefore a wrong powder reusability methodology can lead to a very affected powder batch that does not allow us to create high quality parts since phenomenon called "orange peel" appears (Fig. 1.21). For this reason, depending on the area where we recover the powder, we will treat the batch as more affected by heat or less affected by heat (Fig. 1.21).

It can be found in bibliography some methods like the Melt Flow Rate Test (MFRT) where we can quantify how affected the powder is. This method measures the time while a certain amount of powder is melted through an extruder at a specific temperature. Depending on this value already used feedstock must be refreshed in a controlled manner improving the reusability yields.

Looking deep into the selective laser sintering process, there are many variables that can be controlled (depending on the manufacturer) so that process can be adjusted to different materials. Some of them are: slicer fill scan spacing (distance between lines), laser power, and number of contours, layer thickness and temperature control variables.

Standard materials processed by PBF-LB/P are: Polyamide 11 & 12 & glass filled, TPU.

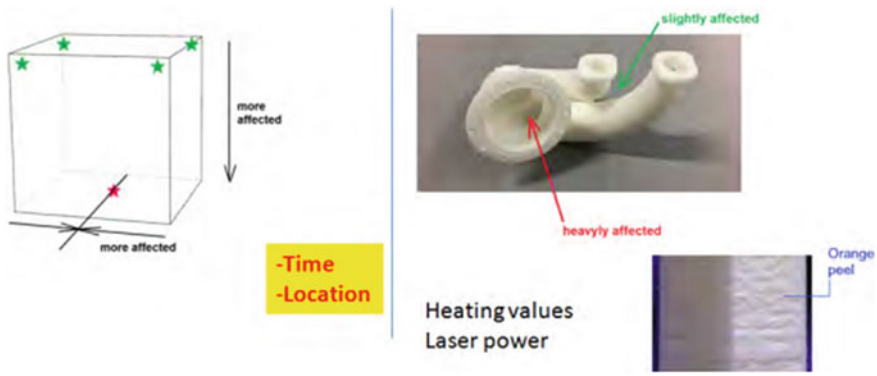

Fig. 1.21 Powder recovery from PBF-LB/P cake. Affected areas (*Source* AIDIMME)

1.7.5 *HP Multi Jet Fusion (PBF-IrL/P) Technology*

Multi Jet Fusion (PBF-IrL/P or MJF) is the named technology of the manufacturer Hewlett Packard (HP) developed in the last few years. Based on a similar concept like selective laser sintering but a complete new approach this technology allows creating end-use polymeric parts in high production rates and low cost per part.

The groundbreaking concept developed by HP has revolutionized the additive manufacturing scenario because parts conceived by this technology are completely isotropic and due to the high speed and production rates it can substitute injection molding at certain points for low production industrial parts for end-use and not for prototyping.

As benefits respect conventional PBF-LB/P, as pointed out, the build ratios and high strength materials isotropically consolidated by the technology, there is no need of support structures, PBF-IrL/P is able to reproduce very small and accurate details and most important; process stability and temperature stability are completely controlled by the HP software. This closed control loop leads to very good repeatibility and reliability in comparison with standard PBF-LB/P Systems.

As drawback, process parameters are locked thus development of new materials is not a possibility for these machines.

Standard materials offered are: polyamide 11 & 12 and gass filled PA, and TPU.

PBF-IrL/P Components

As an industrial scale 3D printer, the entire production chain is monitorized by the PBF-IrL/P software, on the one hand we can find the build unit where powder is processed and transformed into solid parts, on the other hand the PRS and part recovery station which manages the powder reusability ratios and mixes the powder from the last build in order to ensure good part quality.

Within the PRS we can also find the fast cooling unit that enables a slightly faster cool down phase and is normally used when parts are not so slim.

Part recovery requires minimal time and labor. After the print job is completed, finished parts are recovered from the cake and excess of powder is removed using auxiliary sandblasting equipments.

An overview of the PBF-IrL/P components in pointed out in Fig. 1.22.

PBF-IrL/P Workflow

Giving a closer look to the printing unit, it is equipped with high intensity High Voltage bulbs that heat the chamber, a powder dispenser and binding head.

As in any AM technology, machine preparation is similar; printing module is loaded with powder and machine cleaned up.

Warm up volume is also required in order to generate the heat barrier and after the warmup phase, parts are manufactured layer by layer. At this step the powder dispatcher moves back and forth and deposits a thin powder layer on the build area. Binding/UV head moves above the powder layer injecting two components called “fusing agent” and “detailing agent”. Fusing agent is aimed to reduce the melting

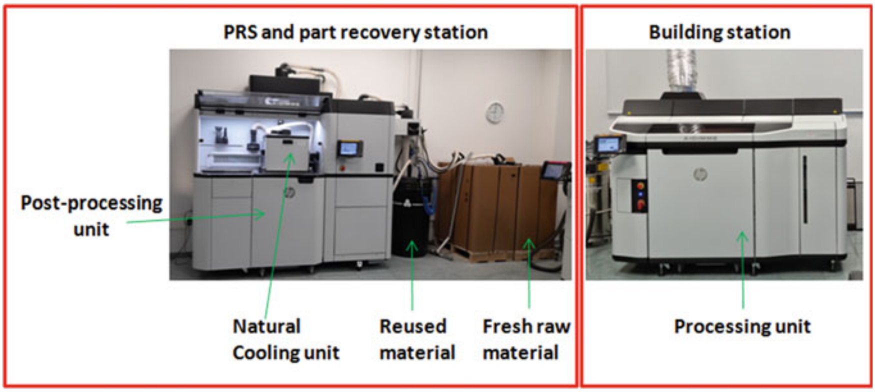

Fig. 1.22 PBF-IrL/P technology components (*Source* AIDIMME facilities)

point of the powder (black agent) powder that is injected with this material will be transformed into parts. Whereas detailing agent is aimed to increase the melting point, the detailing agent is applied in the border between the part and the non sintered powder in order to improve the surface quality and to stop the heat dissipation, it some way it creates a heat barrier that surrounds the part.

Once the build ends a natural cooling or a fast cooling can be carried out depending on different factors as the shapes included in the cake. Fast cooling is normally used when parts are small-size.

1.7.6 Metal Binder Jetting (MBJT) Technology

During the last few years, the additive manufacturing scenario has been evolving with a recent batch of innovative technologies where Metal Binder Jetting can be found.

MBJT follows the principles of Metal Injection Moulding (MIM) applied to a layer-by-layer technique (Binder jetting process).

Even tough the MBJT is not widespread yet, many important companies related to the additive manufacturing market are about to launch their own MJBT machines. Some of the benefits that this technology are very fast production ratios, very small features compared to the conventional Metal AM technologies like PBF-LB/M and PBF-EB/M, support free parts during the construction process (not during debinding and sintering) and a wide variety of materials (any material that can be sintered).

In addition, metal powders are not melted during the printing process thus many issues related to part distortions (residual stresses) dissapear.

As drawbacks, parts need to be debinded and sintered after the part construction. Debinding can lead to part distortions if not properly done and sintering leads to srinkage thus part size in this kind of process is cruzial.

MBJT Components

As basic components in the production chain of metal binder jetting, we observe that a debinding furnace and a high temperature furnace (sintering) will be required as well as a sandblasting equipment in addition to the 3D printer itself.

Metal binder jetting machines are made up of a powder dispatcher head or raking system that delivers fine powder layers and a binder jetting head with multiple inkjets that deposits very small droplets of binder in order to join the particles and a curing system to polymerize the binder agent.

Parts manufactured up to this step remain in a fragile green state infiltrated with a polymeric matrix and require being post processed in a sintering furnace that creates the full-metal part.

Binder jetting machines can work with a huge range of metal alloys, but they can also handle ceramic and sand-based materials.

1.8 Material Extrusion Additive Manufacturing (MEX) Technologies

Material extrusion additive manufacturing (MEX) consists of pushing soft material through an orifice and deposit such material in layers to build a 3D structure. Extrusion based additive manufacturing processes are among the most widely used AM processes, particularly when working with thermoplastics and thermoplastic composites. However not only thermoplastic materials can be extruded; some examples include low melting temperature metals, glass, ceramic slurries, suspensions containing graphene and other nanoparticles, silicones and concrete. Compared to other AM processes, the equipment used for MEX can be inexpensive and very easy to operate. Therefore, the main advantage of MEX is rapid and economical reproduction of standard components or prototypes with a variety of polymeric materials, low melting temperature metallic alloys and other materials.

Unlike other AM techniques, extrusion based additive manufacturing techniques are well suited for multi-material deposition and can be used with a wide range of thermoplastic materials. In general, most of the MEX machines are equipped with a single extrusion head, but there is the possibility of adding two or more extrusion units to allow for multi-material fabrication. Meanwhile new devices have been developed that allow mult-material printing with a single nozzle by fusing different filaments together before they are fed to the extrusion unit, for example the Palette 2S manufactured by Mosaic Manufacturing Ltd. (Toronto, ON, Canada) or the multi-material unit by Prusa Research (Praga, Czech Republic). The working principle of MEX suits itself for the fabrication of composite materials with continuous fibres; machines like the ones developed by Markforged Inc. (Watertown, MA, USA), and Anisoprint LLC (Moscow, Russia), allow the deposition of continuous fibres in a particular location where the reinforcement is needed, thus saving on the cost and weight of the manufactured components. Finally, the simple principle of operation of

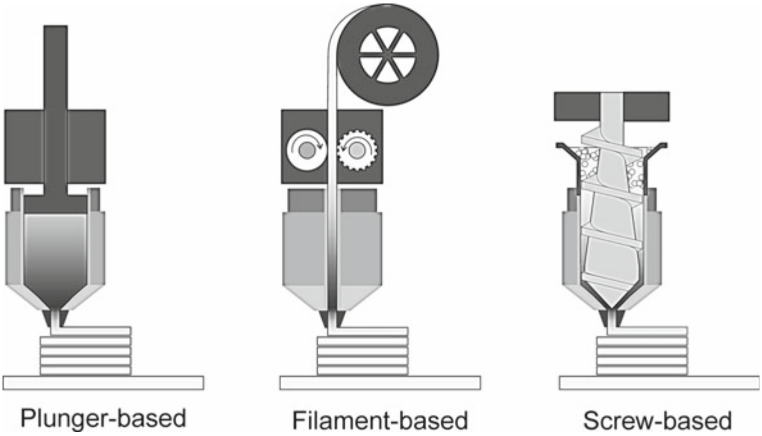

Fig. 1.23 Material extrusion additive manufacturing types (Gonzalez-Gutierrez, J.; Cano, S.; Schuschnigg, S.; Kukla, C.; Sapkota, J.; Holzer, C. Additive Manufacturing of Metallic and Ceramic Components by the Material Extrusion of Highly-Filled Polymers: A Review and Future Perspectives. Materials 2018, 11, 840, licensed under CC BY 4.0)

the extruder allows it to be mounted on machines with up to six-degrees of freedom, such as robotic arms, which further increase the functionality and versatility of MEX.

The basic principle of material extrusion additive technology involves loading and liquefaction of the material, moving the material through a nozzle or orifice by applying force or pressure, plotting liquefied material according to a pre-defined path in a controlled manner, and layer-by-layer bonding of the material to itself or secondary build material to form a coherent solid structure. After a layer is completed, the build platform moves down or the extrusion head moves up, and a new layer of material is deposited and adhered onto the previous layer. Whenever necessary, support structures are included in the process to enable fabrication of complex geometrical features. This basic principle enables the production of complex parts without a shaping tool other than a die with a simple geometry, generally round. Depending on the type of extruder used, one can classify Material Extrusion Additive Manufacturing (MEX) into different types, and they will be described in the following section and are schematically shown in Fig. 1.23.

1.8.1 Material Extrusion with Plungers

Extrusion with plungers occurs when a soft material is pushed through an orifice with a piston, or fluids like compressed air (pneumatic system). The material is loaded in cartriges and the piston squeezes out the material through a nozzle, similar to a syringe. This type of extrusion system is generally used with suspensions or slurries with a high fluidity and it is referred as robocasting, direct ink writing, direct-write assembly or microrobotic deposition. Examples of the materials used in extrusion with plungers, sometimes referred as inks, are highly concentrated (35 to 50 vol.%) colloidal suspensions designed to solidify via a drying induced pseudoplastic to dilatant transition; and colloidal gels consisting of a percolating network of attractive particles capable of transmitting a force above a critical powder loading. In order for the extrusion and the deposition of these materials to be more reliable their composition needs to be tailored in order to obtain the required rheological properties. The inks should have a relatively low viscosity under stress (shear thinning) and a high elastic modulus and high yield stress upon deposition, in this way the shape retention after deposition does not depend on the solidification or drying of the feedstock material. Therefore, there are no thermal gradients, and the extrusion pressures are smaller. Inks containing ferroelectric, metallic, bioactive, polymeric, graphene and numerous ceramics have all been successfully processed by plunger based-MEX.

Other relative low viscosity materials that can be extruded with a plunger system are silicone elastomers. Silicones can consist of a single component that cures with moisture, and multiple components including cross linker agents that can be cure thermally, or by UV hydrosilation. When the viscosity of the pre-elastomer silicones is sufficiently low a pneumatic system is used to push the contents of a barrel with a check valve to control the deposition of the material as the printing head or the platform moves to shape a three-dimensional object.

A piston can also be used to push thermoplastics and thermoplastic-based composites. One example of this technology is the process known as Thermoplastic 3D-Printing (T3DP) in which a particle-filled thermoplastic feedstock material is pushed through a nozzle in a drop-wise manner. The micro dispensing units have a nozzle with an orifice of 160 μm, and a piezo-driven hard metal piston moves up and down to produce droplets instead of strands. The thermoplastic used in this system is generally a mixture of paraffin and beeswax and using this technology different ceramics, metals and metal-ceramics components have been produced.

In general, plunger extrusion machines with plungers are meant to be used for shaping parts that eventually will be require post shaping steps in order to obtain the final product. For example, the silicones require a curing step, the inks used in robocasting, the thermoplastic suspensions used in T3DP, need to be sintered to obtain metal or ceramic specimens. The technologies that require sintering have feedstock materials containing a large amount of powder (35 to 55 vol%). The thermoplastic suspension uses similar materials as used in the well-established process of powder injection molding (PIM).

1.8.2 Material Extrusion with Filaments

Material extrusion of filaments was first patented by the company Stratasys and commercialized as Fused Deposition Modelling or FDM™. However, such name could be applied to other AM techniques that melt materials and deposit them onto a platform or onto previously deposited layers of material, such as pneumatic extrusion, micro injection of droplets (e.g. Freeformer), screw extrusion of pellets, and ram extrusion with rods. Also, FDM™ is a registered trademark of the company that first introduced the technology. Therefore, an alternative terminology was introduced as Fused Filament Fabrication or FFF. FFF is the most widely used MEX technique. The main reasons of its popularity are its safe and simple fabrication process, low cost of the equipment and the availability of a variety of filaments for printing. In the FFF process, the filament is extruded through a nozzle and deposited on a building platform one layer at a time where it solidifies. The printing chamber and bed are kept at temperatures below the material´s melting point, but higher than room temperature to promote adhesion to the printed bed and to reduce thermally induced stresses.

FFF machines are ram extruders, with the filament being the ram that pushes the softened material out of the printing head. In conventional FFF machines, the filament is first pulled by the driving wheels and then it is pushed by the same wheels into a liquefier and later on into a nozzle. Therefore, sufficient mechanical strength is required for the filament to retain its shape after being forced through the drive wheels. The filament has to transfer the force provided by the driving wheels forward into the liquefier. The force that is generated by the motors must be transferred to the filament via the wheels. This transfer of force can be altered by a number of factors. First, the motors must generate sufficient torque. Next, the wheels must have enough friction with the filament to transfer the force from the wheels to the filament. At the same time, the filament must be strong enough to avoid shearing due to the pinching from the wheels. Finally, the filament must not buckle between the drive wheels and the entrance to the liquefier. That is, the force transferred from the drive wheels to the filament should be efficiently transferred into the centre of the liquefier in the direction of the melt flow, with minimal loss due to filament buckling and compression. In addition to these requirements, the filament should also be flexible enough to be spooled, so that the filament can be easily stored in a compact place and fed in a continuous manner into the liquefier. As it can be expected not all materials can fulfil all of these conditions, yet numerous thermoplastics-based materials are available as filaments for FFF.

Examples of non-filled thermoplastics filaments commercially available include: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), acrylonitrile styrene acrylate (ASA), polyamide (PA), polypropylene (PP), polycarbonate (PC), polyphenylsulfone (PPSF, PPS or PPSU), polyetherimide (PEI), butenediol vinyl alcohol (BVOH), thermoplastic polyurethane (TPU), polyethylene terephthalate (PET), recycled PET (rPET), thermoplastic elastomer (TPE), high impact polystyrene (HIPS), thermoplastic copolyester elastomer (TPC), polyvinyl alcohol (PVA), polyether ether ketone (PEEK), polyvinlydene floride (PVDF), polyoxymethylene (POM), polyhydroxyalkanoate (PHA) blended with PLA and some other blends of the previously mentioned polymers. Examples of composite materials commercially available for FFF include: ABS reinforced with carbon fibers; PP reinforced with glass fibre, PLA with carbon fiber, graphite, stainless steel, bronze, brass, copper, bamboo fibers, wood fibers and iron particles; PA with carbon fibre, PET with carbon fibers; the filler content of these composites is between 5 and 40 vol.%. Examples of highly-filled (35 to 55 vol.%) polymeric materials for FFF plus sintering include fillers like 316 L steel, 17-4PH steel, Ti6Al4, NdFeB, copper, zirconia, alumina, silicon nitride, lead zirconate titanate, fused silica, tricalcium phosphate, hard metals, and cermets. Using these filaments and finding co-sintering conditions, it was possible to obtain multi-material parts combining ceramics and metals.

The process of extrusion of filaments was pioneered by Stratasys and in 1991 they introduced the first AM system of this kind. Their FFF system had two extrusion heads and used two spools of material, one material used to build the part and the second one for the support material. Based on the FFF system, a novel system for the manufacturing of multi-material parts was presented by the Rutgers research group, the Fused Deposition of Multiple Ceramics (FDC). Four extrusion nozzles were included in the system, i.e. four materials could be deposited at the same layer. Different demonstrators, such as piezoelectric components with layers of soft and hard piezoelectric ceramics were produced. Expiration of the Stratasys patents on FFF process and growing demand of customized products has driven other companies such as Beijing Tiertime Technology Co. Ltd as an emerging competitor in this market. In addition, personal fabrication markets are being encouraged with the open-source RepRap projects and several small and medium companies such as German RepRap GmbH, Apium Additive Technologies GmbH, Aleph Objects, Inc., MakerBot Industries, LLC., 3D system Inc., Delta Micro Factory Corp., Hage Sondermaschinenbau GmbH & Co KG, EVO-tech GmbH, BigRep GmbH, Printbot LLC, Indmatec GmbH, Rokit Inc., Ultimaker BV, Sharebot srl, MarkForged Inc., 3D Platform, Titan Robotics Ltd., Vixel8, Shenzhen Yuejiang Technology Co., Ltd., Wanhhao, Xery 3D Science and Technology Inc., Prusa Research a.s., CEL-UK Robox, Zortrax S.A., KUMOVIS GmbH, WASP c/o CSP S.r.l., Mass Portal SIA, Robert Bosch GmbH, XYZprinting, Inc., FlashForge Co., FELIXprinters, Modix Modular Technologies LTD, gCreate, Fusion3 Design, LLC, and Cosine Additive Inc., are producing FFF machines to mention a few.

1.8.3 Material Extrusion with Screws

Production of slurries, rods or filaments represents an additional task that requires special extrusion lines and know-how to obtain slurries with the right rheological behavior and filaments or rods with constant cross-sectional area and ovality, which are prerequisites to deposit the adequate amount of material and therefore have a reliable process in MEX machines. Also, not all materials can be made into filaments with the required mechanical properties to obtain a filament that can be spooled, but at the same time rigid enough that it can be pushed by the feeding mechanisms of FFF machines. Therefore, several research groups and companies are looking into screw-extrusion AM machines that can utilize thermoplastic pellets.

A screw extruder is divided into several zones. In the solid conveying zone pellets are transported to the melting zone where pellets are softened under heat and friction, and the metering zone in which the molten material is submitted to high pressure before its eviction through the nozzle. The rotating screw has a pumping effect and thus it moves the material from the feeding zone to the nozzle. Controlling the flow of the extruder for depositing the material in a precise manner can be a challenging task and requires other tools as compared to ram extrusion with filaments. Also, the size of the pellets should be controlled in order to obtain a uniform flow of extruded material. Nevertheless, solutions have been found and here some examples of screw extruder AM machines are described.

Bellini et al., developed a system called mini extruder deposition (MED), which consist of a mini screw-extruder mounted on three high precision linear motor tables. The three tables were connected to three digital servo drives to monitor the torque, velocity and rotational speed. The servo drives were also equipped with digital notch filters to eliminate mechanical resonance. The driver‘s position, speed and acceleration of the three axes could simultaneously be controlled. A separate controller was used to regulate the heaters and the motor of the extruding screw. Material temperature was checked at the entrance of the liquefier and closer to the nozzle. Even though the developed preliminary configuration shows opportunities for the use of wider range of materials, it can only be considered as a starting point for further development, due to the limited information provided by the researchers and the lack of follow up publications.

Cruz et al., developed their own screw-based extrusion system. The equipment consisted of a vertical single screw extruder with screw length of 90 mm, screw diameter of 15 mm and die with 2 mm diameter. Two band heaters were placed around the barrel to ensure a constant temperature (up to 250 °C) during the plastification process. The building platform was capable of moving in XYZ directions, controlled by step motors to control the trajectory and the material deposition. The printing process was controlled by a logical controller and a computer was used as an interface to enter the processing conditions (barrel temperature, screw rotational speed and material rate of deposition) and monitor the process. The designed extruder was capable of processing the feedstock with 59 vol.% of carbonyl iron; however no further details in terms of printability and printed parts were shown.

Tseng et al., constructed a screw extrusion-based additive manufacturing for processing PEEK. The extruder subsystem was firmly attached to a rigid frame fixed on a granite plate (600 mm × 600 mm × 50 mm). The thermal control subsystem included a thermal control panel, a heating plate installed in the build platform, and heaters installed within or around the barrel of the extruder. Three heaters were used to control the feeding, compression and metering zones. Usual temperatures to process PEEK were 180, 340, and 380 °C respectively. The build platform was installed on the X–Y-Z traversing subsystem, and quartz glass and stainless steel were the investigated build platform materials. It was found that a temperature of 280 °C at the build platform provided sufficient adhesion to build the parts. It was demonstrated that this printer is capable to print PEEK specimens with around 2% porosity that lead to an ultimate strength 95% of that of bulk material.

Yu et al., used a screw-based system to print pastes of yttria-stabilized zirconia ceramic pastes at room temperature. The feedstock used was a colloid fabricated by dispensing zirconia nanoparticles in an aqueous solution. The dispersant was ammonium polymethacrylate, and methyl cellulose as binder agent. The paste contained 60vol.% of solid particles and it was blended and homogenized using a vacuum mixer. The printer used was a delta robot with a pressurized cylindrical tank to store the paste and the paste was fed to a screw extruder at room temperature. The build-platform was also kept at room temperature during the printing process. Using this unique system and after debinding and sintering, zirconia parts with a relative density of 98.1% were achieved and the mechanical properties were better than parts fabricated by binder jetting and SLS.

One company that has developed and is commercializing a screw-based extrusion AM machine is AIM3D GmbH (Rostock, Germany). The AM machine from AIM3D is called ExAM 255 and it has two extruders that can take commercially available pellets from thermoplastics or metal injection molding (MIM) feedstock to build a tree-dimensional object. The building volume is a cube with 255 mm on all sides. Like many other systems the extrusion head moves in the x–y plane, while the building platform moves in the z-direction. As indicated in their website, the only material that is not in the beta phase of development is a MIM feedstock with stainless steel particles.

The company Pollen AM, Inc. (Paris, France) has also developed and is currently commercializing a screw based system capable of printing with up to four different materials. This machine is capable of mixing two materials during the printing process. Materials available include unfilled thermoplastics and filled thermoplastic pellets with natural fibers, carbon fibers, minerals and metal particles. The maximum printing temperature is 350 °C. The area available for printing is 300×300 mm^2 and the maximum printing speed is 400 mm/s.

Cincinnati Inc. (Cincinnati, OH, USA) and Oak Ridge National Laboratories (Oak Ridge, TN, USA) have developed a screw extrusion machine for large size additive manufacturing. The setup is called Big Area Additive Manufacturing or BAAM. It consists of a single screw extruder mounted vertically on a machine frame, similar to the frames used for laser-based AM machines. The extruder has a feed rate of 36 kg/h and a unique automatic taping mechanism, which is used to flat the deposited material to increase the contact between deposited layers. The setup is available in two sizes: $7.8 \times 3.7 \times 3.3$ m^3 and $10.8 \times 3.9 \times 4.4$ m^3. The motion system is driven by linear motors and the absolute position accuracy is $\pm$ 0.127 mm. Using BAAM the manufacturers have been able to print sections of car bodies and sections of buildings. The materials that have been tested include pellets of acrylonitrile–butadiene–styrene (ABS), polyphenylenesulfide (PPS), polyetherketoneketone (PEKK) and polyetherimide (PEI), as well as, composites materials containing carbon, glass fibers and NdFeB particles. Other companies selling screw-based MEX systems for large industrial applications are Cosine Additive Inc. (Houston, TX, USA), Modix Modular Technologies LTD (Ramat Gan, Israel), BLB Industries (Värnamo, Sweden), CNC Barcenas (Ciudad Real, Spain), and Titan Robotics LTD (Colorado Springs, CO, USA).

Using screw-based extruders and gantry systems new larger MEX machines are being developed and very large pieces are now being manufactured. For example, the

University of Maine Advanced Structures and Composites Centre manufactured a boat with a length of 7.6 m and weighing 2268 kg in October 2019. The machine used to build the boat has a building envelope with a length of 30.5 m, a width of 6.5 m and a height of 3 m. The extruder is capable of printing speeds of about 225 kg/h.

1.8.4 Disadvantages of Using MEX

The main disadvantages of using MEA include a rougher surface, which is limited by the nozzle radius; the accuracy and speed can be low compared to other AM technologies; there is anisotropy of the mechanical properties, with weaker properties in the Z-direction due to the lower cohesion of the deposited layers; and support structures are needed, since the building material is deposited only where it is needed.

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Chapter 2
General Process Workflow in Additive Manufacturing

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Abstract In this chapter, general workflow in Additive Manufacturing process is shown, from preprocessing activities that include preparing appropriate CAD model, selecting required STL file resolution, up to setting processing parameters for AM process.

General underlying principle of additive manufacturing can be seen on Fig. 2.1. Main goal is to slice the desired product in layers along desired axis and then to build the product by stacking of each layer along the slice axis.

With this type of product buildup "Stair step effect" is unavoidable, since each layer has a finite value of thickness. Most common axis layout is the one where layers are in *X*–*Y* plane and they are stacked along *Z* axis. It is important to remember that build accuracy and mechanical properties of finished products are not identical in all three axes. AM parts have a fixed value of accuracy in *X*–*Y* plane since this property is a limitation of AM machine hardware. Accuracy along *Z* axis can be altered by changing layer heights during slicing. By decreasing the layer height accuracy increases, but also the build time increases which is an important parameter to be considered. It is possible to slice a product in non-uniform layer heights which alleviates "Stair step effect" by decreasing layer height in areas where there is a substantial dimensional change between layers, and increasing layer heights in areas where layers are dimensionally similar, as shown on Fig. 2.2.

Generally, process workflow in AM can be divided in two main activity groups: pre-processing for AM and build and post-processing in AM.

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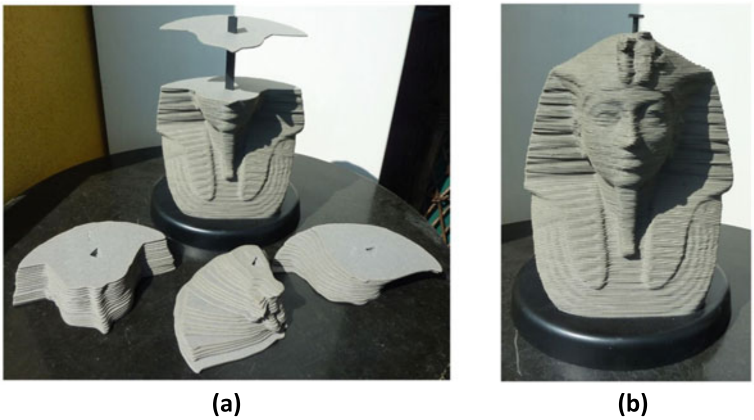

Fig. 2.1 General additive manufacturing principle: **a** layer buildup, **b** finished product (*Source* Ana Pilipović)

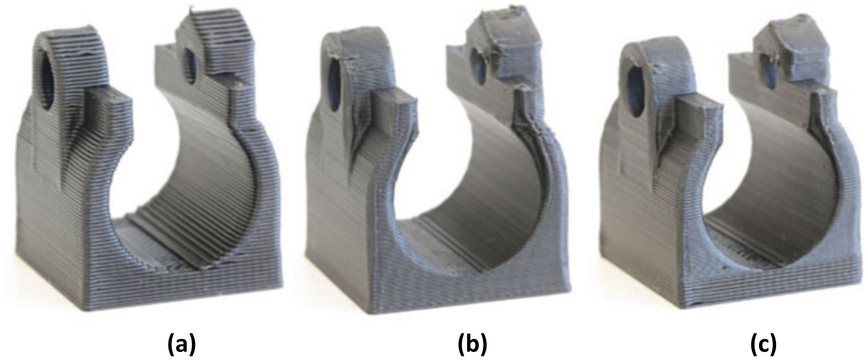

Fig. 2.2 Product created with **a** thick layers **b** thin layer and **c** variable layers (*Source* Tomislav Breški)

2.1 Pre-processing for Additive Manufacturing

All additive manufacturing processes begin with virtual representation of a desired product. Almost all commercially available 3D computer aided design (CAD) software can produce models which can be used for additive manufacturing. Models are supposed to be "watertight", which means that there should not be any gaps in enclosing surfaces of a solid model, as shown on Fig. 2.3.

In most feature-based CAD software models, which are represented as solid models in feature tree, generally do not have issues with gaps in enclosing surface. These issues can occur when models are created with 3D scanners or Computed tomography (CT) machines. Example of non-watertight model is shown on Fig. 2.4.

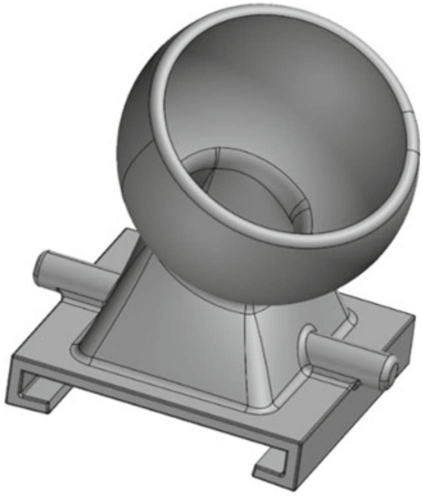

Fig. 2.3 CAD model (*Source* Tomislav Breški)

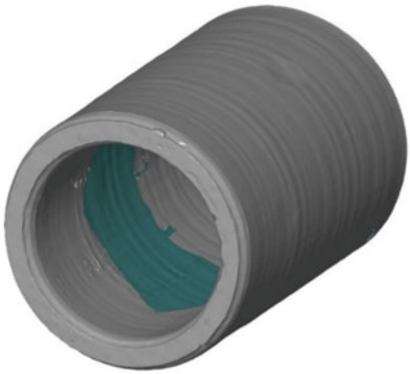

Fig. 2.4 Non-watertight model (*Source* Tomislav Breški)

Model of this cylinder was created with a 3D scanner which measuring volume was too big for this model and thus part of the inner cylinder was optically unreachable for both cameras of 3D scanner simultaneously, which is a requirement for a 3D scanner to adequately register a surface during 3D scanning.

There are many freeware software available (*Meshmixer*, *GOM Inspect*) which can do mesh alterations and closing of gaps in surfaces but it is important to keep in mind that by automatically closing large gaps in models, created geometry can substantially deviate from desired geometry.

2.1.1 File Formats Used in Additive Manufacturing

As already mentioned, first step in additive manufacturing is to design a product which will be produced. In most cases CAD models contain too much data, so they should be translated to a file format which contains only information about outer surface shell of a product. Most commonly used and oldest on the market file format of this type is *STL* (*Standard Tesselation Language*). STL files contain only data which describe surface geometry of a three-dimensional model (Fig. 2.5).

It is important to consider that not every STL file is manufacturable with additive manufacturing since STL files contain only data about the geometry. If a model is created only as a surface model but without thickness, STL conversion is achievable but additive manufacturing is not. Tesselation is a process of tiling an arbitrary surface with primitive geometric shapes (e.g. triangles, squares) without any gaps or overlaps. The model shown on Fig. 2.3 converted to STL file format is shown on Fig. 2.6.

By tessellating the model with planar triangles final representation is achieved which can be sliced in additive manufacturing software, in order to produce the desired part geometry. Planar surfaces of a model can be tessellated with large triangles, but non-planar surfaces of a model have to be tessellated with large number of small triangles which increases the number of triangles and thus increases the size of STL file. When manufacturing one item, file size is not an issue, but with emerging of powder bed fusion additive manufacturing technologies, which can produce large number of parts simultaneously, slicing can be substantiately shortened if parts are not tessellated with large numbers of triangles. Since non-planar surfaces are approximated with large number of small planar triangles dimensional difference between CAD and STL model is inevitable, but if deviations between models are smaller than

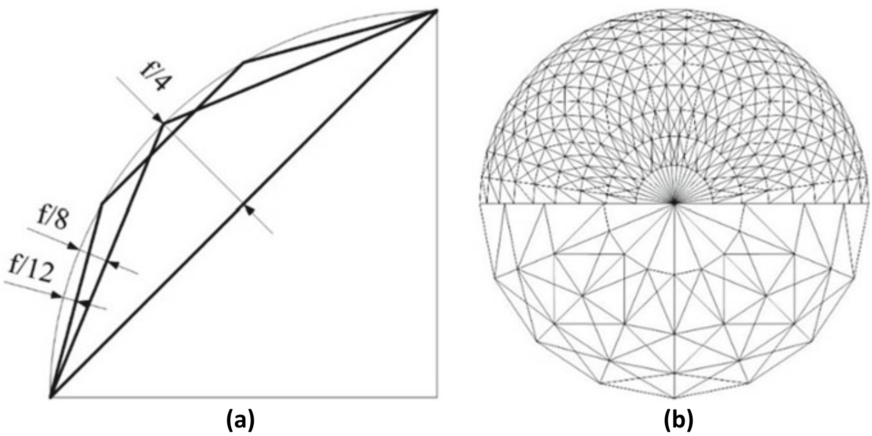

Fig. 2.5 Geometry approximation using STL model: **a** secant error of circular geometry with 4, 8 and 12 secants, **b** sphere approximation with varying number of elements (Courtesy of Andreas Gebhardt)

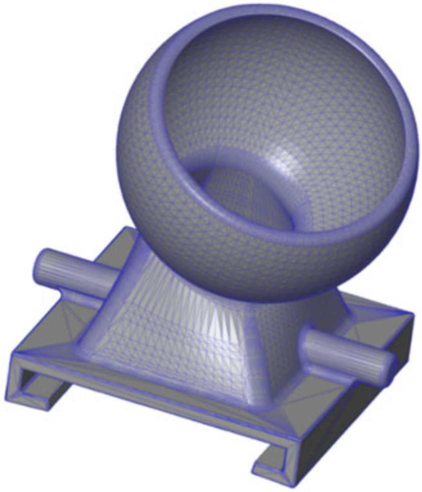

Fig. 2.6 STL model (*Source* Tomislav Breški)

additive manufacturing machine resolution and build accuracy these deviations are not translated to the final product.

Deviations between CAD model and STL model with 29,492 triangles are shown on Fig. 2.7. Largest deviations, as expected, are on non-planar surfaces, but there are also some unwanted artefacts on planar surfaces which were generated during conversion from CAD to STL file. As shown on histogram next to to the model representation, there is only a small percentage of geometry which deviates more than 50 µm from CAD file. Most deviations are in the range from −10 to 10 µm from CAD model, which can lead to the conclusion that conversion from CAD to STL file format is acceptable.

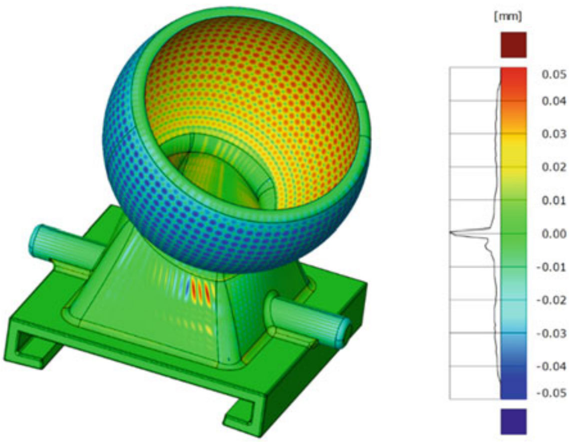

Fig. 2.7 Deviations between CAD and STL model (*Source* Tomislav Breški)

With emerging of additive manufacturing technologies which can produce parts with varying colours and textures STL file format is becoming lacklustre in the quantity of data which is needed to be transferred to slicing software. Information about color, material, internal lattice structures and constellations of multiple parts need to be linked with the geometry of part to be built. Furthermore, STL files do not provide information about the dimensional scale of the product, so if the user unintentionally imports a model in a different unit environment (milimeters vs. inches) there is big possibility that the final product would not be dimensionally correct. *Extensible Markup Language* (XML) has been recognized as the best way to structure all forementioned data to be transferred to slicing software. Currently there are two file formats which can store sufficient amount of needed data in a single file; AMF and 3MF. *Additive Manufacturing File Format* (AMF) is being developed by ISO/ASTM subcommittees and many of the problems regarding STL file formats are solved, but unfortunately this file format is not well accepted on the market of additive manufacturing. One of the biggest improvements of AMF file format regarding geometry is the possibility of tessellation of surfaces with curved triangles which improves part accuracy after conversion from CAD model. 3D Manufacturing Format (3MF) is a new file format being developed by the 3MF Consortium which inherited most of the properties from AMF file format. One of the biggest advantages of this file format is the fact that it is being developed through collaboration of the biggest stakeholders in additive manufacturing currently in the market. Main features of this file format are as follows:

- all the necessary model, material and property information in a single archive
- human readable by use of XML structuring of data
- short and clear specification for ease in further development and validation
- extensible by leveraging XML namespaces for both public and private extensions while maintaining compatibility
- unambiguity by using clear language and conformance tests which ensures that the file is always consistent from digital to physical
- access to and implementation of the 3MF specification is and always will be free.

Most of the features implemented in 3MF file format are shown on Fig. 2.8 which shows a product which could not be manufactured without all the information included with 3MF file.

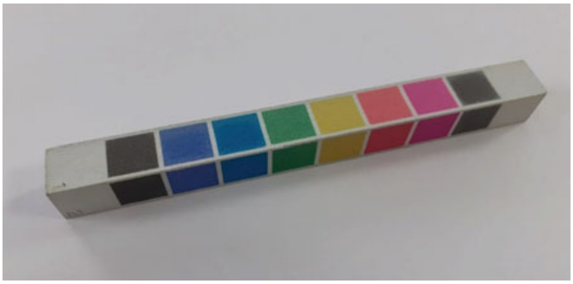

Fig. 2.8. 3D-printed part with variable colour (Photo by Tomislav Breški)

2.1.2 Part Placement in Machine Envelope, Slicing and Machine Setup

In order to generate machine commands for additive manufacturing, first step is to load of a given 3D model in appropriate file format. Most of the currently available AM machines have their own proprietary software for slicing and machine commands generation, but in this book, examples are given as screenshots from *Autodesk Netfabb* which has a large number of machine pre-sets (machine properties, build envelope, etc.) of commercially available AM machines. Part placement in build envelope is in most cases the defining factor for success in part manufacturing. Example of part placed in build envelope is shown on Fig. 2.9. Depending on the selected AM technology, with adequate part orientation, user can eliminate potential mechanical deficiencies due to mechanical properties anisotropy, increase production speed, optimize build material usage, etc.

Depending on the selected AM technology, part may or may not need support geometries for successful build. Furthermore, support geometries in polymeric AM technologies provide mechanical support for regions which are angled more than the specific value from vertical axis, while support geometries in metallic AM technologies in most cases are used for heat conduction and dissipation. Final part orientation with resulting support geometries for FFF technology is shown on Fig. 2.10.

With the emerging of powder-based AM technologies simultaneous production of multiple parts in one print job is getting more accessible. But in order to maximize production of those technologies, the user has to orient parts in such a way that there is minimum distance possible between each part. With such part orientation, build height is minimized, which is good for materials usage since unused powder in a

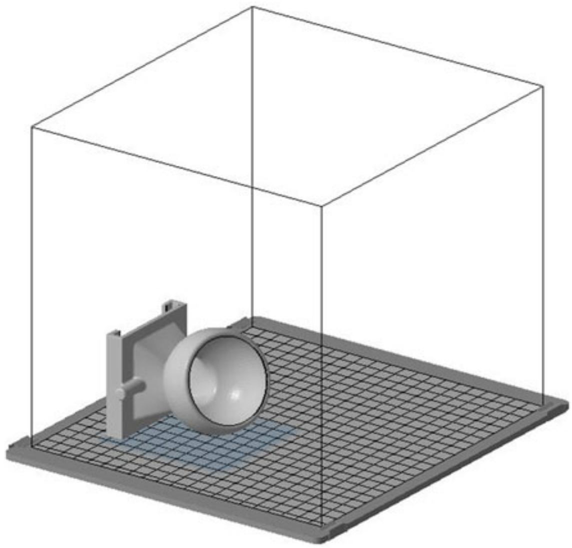

Fig. 2.9 Part placed in build envelope of FFF machine Ultimaker 2 (*Source* Tomislav Breški)

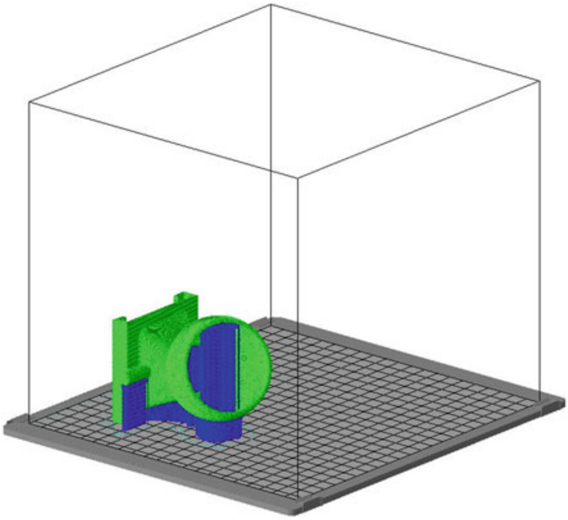

Fig. 2.10 Part (green) and support geometries (blue) (*Source* Tomislav Breški)

single layer must be recycled during post processing phase. Most parts produced with AM technologies generally have complex shapes, and such ideal part orientation is hard to achieve by manual orientation of single part in whole part group, so user has to use available optimization algorithms for optimal part orientation. Build envelope prepared for simultaneous production of 20 parts is shown on Fig. 2.11.

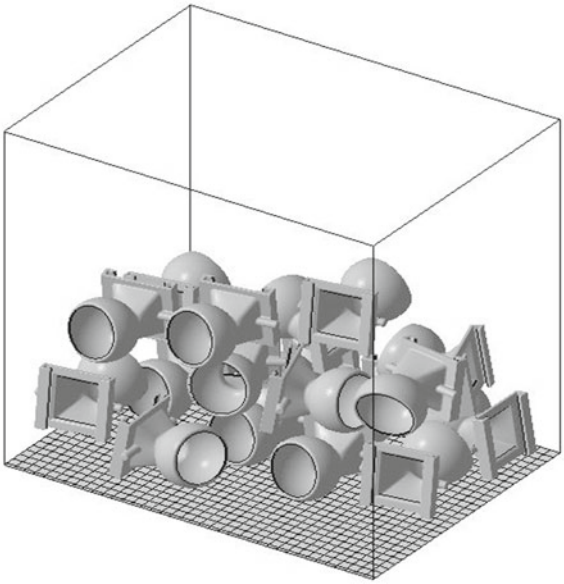

Fig. 2.11 Part nested in build envelope of HP Jet Fusion 580 machine using Monte Carlo algorithm (*Source* Tomislav Breški)

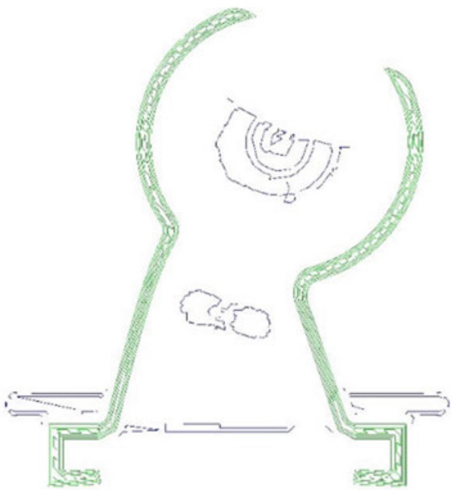

Fig. 2.12 Slice of build envelope for FFF machine (build material in green, support material in blue) (*Source* Tomislav Breški)

Slicing of build envelopes is in most cases done automatically and is specific for each AM technology. With the selection of layer height, computer algorithms do the slicing of whole build volume from initial build platform position to final build platform position in vertical steps defined by layer height. Specific AM technologies have various machine parameters which have to be adjusted for each individual build layer and after completion, packed in a single file which will be executed on the machine during production. Example of a single slice for FFF machine is shown on Fig. 2.12. Since modern FFF machines can use multiple materials in single production cycle, support geometries can be built with soluble materials which result in shorter part post processing time. Slices by themselves are a visual representation for users to visualize AM process, but AM machines need specific commands which they can process and use for production. In most cases G-code is used, and it is generated automatically with slicing software, and includes all the necessary commands for all machine components which are utilized during production. FFF machines are generally the simplest of AM technologies, and have the least amount of movable components which are moved by stepper motors.

Snippet of G code commands for build job is shown on Fig. 2.13.

2.2 Build and Post-processing

With diversification of AM technologies, one aspect of AM manufacturing mutual with all of them, is postprocessing of parts after being built on AM machine. To achieve desired mechanical and aesthetic properties or geometrical accuracy, most of the AM parts need to be post processed in varying amounts. Polymeric AM technologies can include operations such as manual support removal as shown on Fig. 2.14,

```
; Layer 0
M106 S0; turn off fan
; rapid-leaky
G1 X3.000 Y3.800 Z0.200; rapid
G1 E4.50000 F1500; engage filament
; bead-prime
G1 X222.000 E15.48537 F450
G1 E10.98537 F1500; retract filament
; rapid-dry
G1 X103.610 Y42.295 F9000; rapid
G1 E15.48537 F1500; engage filament
; bead-skirt/brim
G1 X103.569 Y42.349 E15.48621 F1800
G1 X103.626 Y42.423 E15.48738
G1 X103.359 Y42.628 E15.49161
G1 X97.025 Y51.050 E15.62375
G1 X92.988 Y51.840 E15.67534
G1 X84.664 Y51.858 E15.77972
```

Fig. 2.13 G-code snippet for initial layer build on FFF machine (*Source* Tomislav Breški)

Fig. 2.14 Manual support removal from FFF part (Photo by Tomislav Breški)

Fig. 2.15 Finished ABS part manufactured on an FFF machine (Photo by Tomislav Breški)

sanding, painting, etc. In extrusion-based AM technologies by utilizing of soluble support materials such as PVA, PVB, or HIPS mechanical support removal can be greatly alleviated and surface finish of supported surfaces has fewer geometrical artefacts which would need to be sanded.

Example of a finished part made from ABS polymer on an FFF machine is shown on Fig. 2.15. This part has gone through the process of support removal, sanding and painting.

Metallic AM technologies can include all of the forementioned operations, but in most cases they also include heat treatment operations such as stress relief, hot isostatic pressing or case hardening. Binder jetting AM technologies with metallic powders are becoming leaders in high scale additive manufacturing, but due to the nature of the process, parts are printed with internal porosities which must be eliminated with heat treatment (i.e. sintering or infiltration) at specific temperatures.

If all aspects of AM process are taken into consideration, from AM technology and material selection to adequate steps in post processing stage, AM parts can replace conventionally produced parts. Example of such project is shown on Fig. 2.16 where a part which was discontinued and thus unavailable for procurement, redesigned for AM and printed using FFF technology.

Fig. 2.16 Replacement part made with FFF AM technology (Photo by Tomislav Breški)

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Chapter 3
Standardisation in AM

Eujin Pei and Israt Kabir

3.1 Introduction to Standards

A standard is a published document that describes a technical specification or a list of guidelines in the form of rules, definitions, methods, vocabularies, or codes of practices. Standards provide a unified source of reference for specifying or representing products. Before the industrial revolution, manufacturers from different places used to compare and copy the dimensions and specifications of components to match those of a prototype. As mass-production led to parts being made at different factories, national standards became vital to provide unified information on materials, dimensions, and processes.

3.1.1 Significance of Standards

Standards formalise procedures, best practices and guidelines for every sector including several industries, academic institutions and the general society. It reflects good practice, builds trust with customers or users, improves productivity and efficiency, reduces cost and increases sustainability. Standards adoption and certification have a great impact on the quality of products and services. For example:

- Products that comply with established international standards will be more easily exportable and stay ahead of the game.
- Standards indirectly improve productivity, enhance the reliability of goods and services, and strengthen international competitiveness and enables access to overseas trade and markets.

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- Compliance with Standards enhances consumer confidence and trust in products, enabling shorter time to market and reduced cost from re-testing and re-certification.

The benefit of standards includes:

- Being precise with no room for misinterpretation
- Streamlining the process of a smooth transfer from design concept to manufacture
- Shortening the development time, increasing speed to market
- Improving the fit and function of parts
- Reducing production costs
- Achieving better quality and better product reliability
- Producing less waste and scrap
- Receiving fewer disputes over compliance.

3.1.2 *Standardisation Bodies*

Figure 3.1 presents the main actors at three levels of the system and their trajectories in Standards development. Standardisation bodies are the officially recognised organisations for the development and implementation of standards and certifications. These organisations principally act from three different levels in the form of national, regional, and international standardisation bodies as a joint system. National Standardisation Bodies (NSBs) and National Electrotechnical Committees (NCs) are the national points of access for standards development, usually one member per country, within the regional and international systems. They distribute and sell the implemented regional and international standards where applicable and withdraw conflicting national standards [1].

The regional level of the standardisation bodies works within a territory consisting of several member countries (e.g. European Union). These countries trade and run business sharing a single market. For example, European Standardisation Organisations (ESOs) develop and implement a common standardisation system within the European single market and free trade area. The ESOs consist of three officially recognised organisations named The European Committee for Standardisation

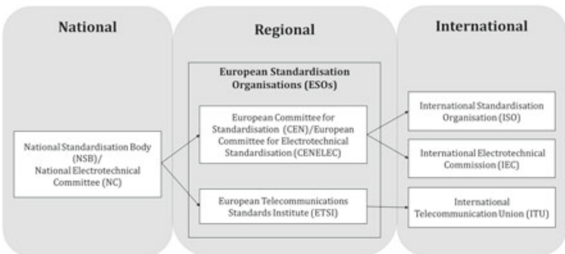

Fig. 3.1 The national, regional, and international standardisation bodies and their connections. (*Source* UBRUN)

Business Sectors of European Standardisation Organisations (ESOs)

CEN	CENELEC	ETSI
1. Chemicals 2. Construction 3. Consumer 4. Defence and Security 5. Digital Society 6. Energy and Utilities 7. Food and Agriculture 8. Occupational Health and Safety 9. Household Appliances and Heating, Ventilation and Air Conditioning (HVAC) 10. Mechanical and Machines 11. Mining and Metals 12. Services 13. Transport and Packaging 14. European Labels	1. Accumulators, Primary Cells and Primary Batteries 2. Electric Motors and Transformers 3. Electric Equipment and Apparatus 4. Electronic, Electromechanical and Electrotechnical Supplies 5. Electrotechnology General 6. Insulated Wire and Cable 7. Lighting Equipment and Electric Lamps 8. Low Voltage Electrical Equipment and Installations	1. Home and Office 2. Better Living with ICT 3. Content Delivery 4. Networks 5. Wireless Systems 6. Transportation 7. Connecting Things 8. Interoperability 9. Public Safety 10. Security

Fig. 3.2 Principal business sectors of ESOs (CEN, CENELEC and ETSI) (*Source* UBRUN)

(CEN), the European Committee for Electrotechnical Standardisation (CENELEC) and the European Telecommunications Standards Institute (ETSI).

To ensure the protection of consumers and interoperability of products, they facilitate cross-border trade and encourage innovation, technological development, environmental protection and business growth. ESOs work closely with the European Commission to ensure that the standards correspond with any relevant EU legislation. ESOs work within the following business sectors, shown in Fig. 3.2.

The international level of the standardisation bodies comprises three independent organisations, made up of the International Standardisation Organisation (ISO), International Electrotechnical Commission (IEC) and International Telecommunication Union (ITU), who develop voluntary, consensus-based, market-relevant International Standards that support innovation and provide solutions to global challenges. In 2001, ISO, IEC and ITU formed the World Standards Cooperation (WSC) to strengthen the standards systems of the three organisations. The WSC brings together experts from several NSBs worldwide to share knowledge and implement the international standards, wherever necessary.

Vienna Agreements

In 1991, ISO and ESOs signed the Vienna Agreement to avoid confusion, conflict and overlap across the organisations supporting the international trade. The agreement underlines the fact that international standardisation takes precedence over national standardisation as stipulated in the World Trade Organisation (WTO) Code of Conduct. This is because International Standards are designed to help harmonise national standards and technical regulations that reduce technical barriers to trade. The Vienna Agreement provides three main modes of cooperation between ISO and CEN, namely cooperation by (1) correspondence/exchange of information, (2) mutual representation at meetings and (3) parallel approval of standards at the international and European levels. Where an International Standard is simultaneously approved as a European Standard, it automatically becomes a National Standard for all CEN members. CEN members must recognise the status of all European Standards at a national level and withdraw any pre-existent and conflicting National Standards.

3.2 AM Standards

3.2.1 Structure of AM Standards

ASTM International and the International Organization for Standardization (ISO) signed a Partner Standards Developing Organization (PSDO) cooperative agreement to govern the ongoing collaborative efforts between ASTM International Committee F42 for Additive Manufacturing Technologies and ISO Technical Committee 261 for Additive Manufacturing. The agreement aims to fast-track the adoption process of an ASTM International standard as an ISO international standard; formally adopt a published ISO standard by ASTM International; maintain published standards, publications, copyright and other commercial arrangements.

This has resulted in a three-tier structure of AM standards presented in Fig. 3.3. The general AM standards are divided into ten categories including Test methods, Design guides, Data formats, Terminology, Test artefacts, Qualification guidance, Safety, System performance and reliability, Round robin test protocols and Inspection methods. This level is broken down into three classes specifying raw materials, process/equipment and finished parts. The other category of AM standards also focuses on the material, process qualifications and applications for AM.

The three key organisations at national, regional, and international levels working on standardisation and certification in AM are ASTM international, CEN and ISO. A brief account of the history and scope of the corresponding AM technical committees are further described.

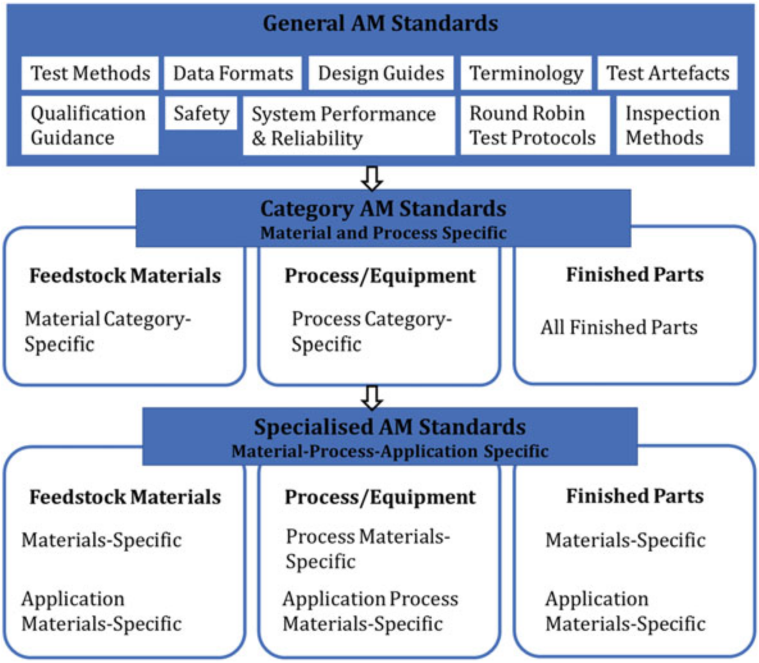

Fig. 3.3 Structure of AM standards. (*Source* UBRUN)

3.2.2 ASTM International/ASTM F42

History

ASTM International

ASTM International is a standardising and testing organisation with its headquarters in West Conshohocken, PA, USA. It was founded in 1898 in Pennsylvania by a group of railroad engineers and scientists, led by the chemist Charles Benjamin Dudley to address the frequent rail breaks in the fast-growing railroad industry. Originally called the "American Society for Testing and Materials", it changed its name to "ASTM International" in 2001. The association has more than 30,000 members, classified as users, producers, consumers, academics, and consultants. It has several offices in Belgium, Canada, China, Mexico and Washington, D.C.

ASTM F42

The first AM standard technical committee ASTM F42 was formed within ASTM international in 2009. The committee has over 725 members (154 outside the USA) and nine technical subcommittees. The subcommittees developed over 40 documents independently and collaborated with the International Standardisation Organisation

(ISO). The committee has strategic relationships with NASA, NIST, FAA, FDA, DOD, CMH-17, etc.

Scope of ASTM F42

The AM technical committee ASTM F42 focuses on the promotion of knowledge, stimulation of research and implementation of technology through the development of standards for Additive Manufacturing technologies. The work of this committee is to coordinate with other ASTM technical committees and other national and international organisations having mutual or related interests. It has nine subcommittees on different topics related to AM process chain and applications. Each main subcommittee in ASTM F42 is composed of several working groups that address specific segments within the general subject area covered by the technical committee, as shown in Table 3.1.

Table 3.1 List of nine technical subcommittees and their working groups of ASTM F42

F42.01 Test methods
F42.04 Design
F42.05 Materials and processes
F42.05.01 Metals F42.05.02 Polymers F42.05.05 Ceramics
F42.06 Environment, health, and safety
F42.07 Applications
F42.07.01 Aviation F42.07.02 Spaceflight F42.07.03 Medical/Biological F42.07.04 Transportation/Heavy machinery F42.07.05 Maritime F42.07.06 Electronics F42.07.07 Construction F42.07.08 Oil/Gas F42.07.09 Consumer F42.07.10 Energy
F42.08 Data
F42.90 Executive
F42.90.01 Strategic planning F42.90.02 Awards F42.90.05 Research and innovation
F42.91 Terminology
F42.95 US TAG to ISO TC 261

3.2.3 CEN/TC 438

History

CEN is a major provider of European Standards and technical specifications. It is the only recognised European organisation according to Directive 98/34/EC for the planning, drafting and adoption of European Standards in all areas of economic activity apart from electro-technology (**CENELEC**) and telecommunication (ETSI). There are 34 national members work together to develop voluntary European Standards (ENs). The member countries include 27 countries from the European Union (EU), 3 (Iceland, Norway, and Switzerland) from the European Free Trade Association (EFTA), former Yugoslav Republic of Macedonia (FYROM), Turkey and the United Kingdom. The Croatian standards institute (HZN) is also part of the CEN/CENELEC network.

CEN TC 438

CEN/TC 438 'Additive Manufacturing' committee was established in 2015 to standardise the process of AM, their process chains (hard and software), test procedures, environmental issues, quality parameters, supply agreements, fundamentals, and vocabularies. CEN/TC 438 cooperates with ISO/TC 261 and ASTM F42 to develop and implement AM standards in Europe. The committee also recommends new projects that relate to aeronautic, medical, 3D manufacturing and data protection. It has published 12 documents and developed 29 working programmes in AM sectors.

Scope of CEN TC 438

The main objective of CEN/TC 438 is to provide a complete set of European standards on processes, test procedures, quality parameters, supply agreements, fundamentals and vocabulary based, as far as possible on international standardisation work. The aim is to apply the Vienna Agreement with ISO/TC 261 Additive Manufacturing to ensure consistency and harmonisation. In addition, the committee aims to strengthen the link between European Research programs and standardisation in AM, and to ensure the visibility of European standardisation for AM.

3.2.4 ISO/TC 261

History

ISO

The International Organization for Standardization (ISO) consists of a network, representing NSBs from 164 countries and working in partnership with international organisations such as the United Nations and the World Trade Organisation. It was founded in 1946 by delegates from 25 countries and began operating in 1947.

ISO/TC 261

The ISO technical committee ISO/TC261 is dedicated to activities regarding Additive Manufacturing standardisation. The committee was established in 2011, after an initiative from the German Institute for Standardization (DIN) based on VDI Guidelines (Verein Deutscher Ingenieure/ Association of German Engineers). The committee consists of 26 participating and 9 observing NSBs (see Table 3.2) involved in developing AM standards.

Scope ISO/TC261

The scope of ISO/TC261 committee is to develop standards in the field of AM concerning their processes, terms and definitions, process chains (Hardware and Software), test procedures, quality parameters, supply agreements and all kind of fundamentals. Table 3.3 shows the figures of published and in-progress standard documents and the number of members involved in the process.

Table 3.2 The national standardization bodies (NSBs) of ISO TC 261

NSBs of ISO TC 261	Countries	NSBs of ISO TC 261	Countries
Participating members (26)			
SA	Australia	IPQ	Portugal
NBN	Belgium	GOST R	Russian Federation
ABNT	Brazil	SSC	Singapore
SCC	Canada	UNE	Spain
SAC	China	SIS	Sweden
DS	Denmark	SNV	Switzerland
SFS	Finland	BSI	United Kingdom
AFNOR	France	ANSI	United States
DIN	Germany	**Observing members (9)**	
NSAI	Ireland	ASI	Austria
SII	Israel	UNMZ	Czech Republic
UNI	Italy	ISIRI	Iran, Islamic Republic of
JISC	Japan	JSMO	Jordan
KATS	Korea, Republic of	ILNAS	Luxembourg
NEN	Netherlands	NZSO	New Zealand
SN	Norway	ASRO	Romania
BPS	Philippines	SABS	South Africa
PKN	Poland	TSE	Turkey

Table 3.3 Metric of ISO AM standards from TC261

Published ISO standards* under the direct responsibility of ISO/TC 261	14
ISO standards under development* under the direct responsibility of ISO/TC 261	30
Participating members	26
Observing members	7

Structure of TC261

The ISO/TC261 technical committee consists of eight working groups (WG). Among the working groups, five groups work independently, and three groups work jointly with another Technical Committee. Table 3.4 presents the working groups and their field of activities involved in the standards development.

WG 1 works on the terms and definition of each entity used in the AM process chain. WG 2 deals with process, systems and materials specifications. The standardisation of testing and quality control in AM is conducted by WG 3. WG 4 develops aspects of data and design standards for AM. WG 6 works on issues related to the environment, health and safety. There are two joint working groups JWG 10 and 11 working together with other with other ISO technical committees and subcommittees for AM in aerospace applications and plastics, respectively. There is another joint working group (Joint ISO/TC 150 - ISO/TC 261 WG) for AM in surgical implant applications, which is now merged in the technical committee TC 150. To date, ISO/TC 261 has published 19 AM standards and is developing 35 more projects as listed in Appendix A.

Table 3.4 Working groups of ISO 261

Working group	Name of WG
ISO/TC 261/WG 1	Terminology
ISO/TC 261/WG 2	Processes, systems and materials
ISO/TC 261/WG 3	Test methods and quality specifications
ISO/TC 261/WG 4	Data and design
ISO/TC 261/WG 6	Environment, health and safety
ISO/TC 261/JWG 10	Joint ISO/TC 261—ISO/TC 44/SC 14 WG: Additive manufacturing in aerospace applications
ISO/TC 261/JWG 11	Joint ISO/TC 261—ISO/TC 61/SC 9 WG: Additive manufacturing for plastics
ISO/TC 261/JWG 12	Joint ISO/TC 261—ISO/TC 150 WG: Additive manufacturing in surgical implant applications

3.3 Reading, Writing and Retrieving Standards

3.3.1 Reading Standards

The rules for developing Standards are documented in the ISO/IEC Directives. These documents are publicly available on the ISO website. The ISO/IEC directives provide the necessary procedures for developing international standards and other publications. Part 1 of the Directives contains the required rules to follow in standard development, and Part 2 explains the structure and writing of the draft standard documents.

Reading the Title

A maximum of three elements is used to form a *Title* in a standard document, which includes (a) Introductory, (b) Main, and (c) Complementary elements. The *Introductory* element gives a general subject area. The *Main* element mentions the main subject matter of the document relative to the subject area. The *Complementary* element indicates the specific category of the general subject area which distinguishes the document. The *Introductory* and *Complementary* elements can be optional for some document *Titles*. For example, the following *Title* belongs to an AM published standard showing the different fields or elements.

Additive manufacturing (General field or Introductory element)—General principles (Specific field or Main element)—Part 2: Overview of process categories and feedstock (Detail field or Complementary element).

Reading the Foreword

The *Foreword* is an informative and mandatory element of the standard document. The *Forward* provides the information on the organisation responsible for publishing the document, the committee that developed the document, procedures and rules under which the document was developed, the voting process, legal disclaimers, as well as other relationships between the present document and other documents. A typical *Foreword* of an ISO standard document is a single section with a few paragraphs. The content of the *Foreword* has two parts, general and specific. The general part is a fixed text which provides information relating to the organisation responsible, general and legal texts about the documents as well as the procedures and rules under which the content was developed. The specific part of *Foreword* supplied by the committee secretariat provides the designation of the technical committee and other internal organisation, relationship of the document with other documents, statements of amendments and indication using of additional language.

Reading the Structure

All documents must start with the following fixed structure, comprising of the *Scope*, *Normative References*, and *Terms and Definitions*. The *Scope* clearly defines the subject of the document and the aspects covered, thereby indicating the limits of

Table 3.5 The common terms and definitions of an ISO standard document

Terms	Definitions
2.1.2	Term number
additive manufacturing	Preferred term
AM	Abbreviated term
process of joining materials to make parts (2.6.1)* from 3D model data, usually layer (2.3.10)* upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies	Definition *Cross-reference
Note 1 to entry: Historical terms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication	Notes or examples
Note 2 to entry: The meaning of "additive-", "subtractive-" and "formative-" manufacturing methodologies are further discussed in Annex A	
[ISO/ASTM 52,900:2015(en) Additive manufacturing—General principles—Terminology]	Source

applicability of the document or parts of it. The *Scope* is succinct so that it can be used as a summary for bibliographic purposes, for example, as an abstract. The *Normative References* clause lists, for information, those documents which are cited in the text in such a way that some or all of their content constitutes requirements of the document. How a referenced document is cited in text determines whether it is listed in the *Normative References*, such as documents that are required uses the word *Shall*. For example, "The test shall be in accordance with ISO 12345". The use of *Shall* indicates that the requirement of the document is strictly followed and no deviation is permitted. *Terms and Definitions* provide information about certain terms used in the document. Table 3.5 shows how *Terms and Definitions* are included in the standard document.

Normative References, *Terms and Definitions* are mandatory elements. This section shall be introduced in each ISO standard document. If there is no requirement of these clauses, then it shall be left empty.

3.3.2 Writing Standards

The development of standards is based on achieving consensus. National standards are usually developed to meet purely national interests or to start a new work area. But this often leads to elevating them as International or European standards at some stage. Given the global nature of most industries and supply chains these days, multinational companies often prefer to refer to international standards so that they can use just one standard across all their subsidiaries and areas. In terms of European work, some of them are linked to European Directives, which is the

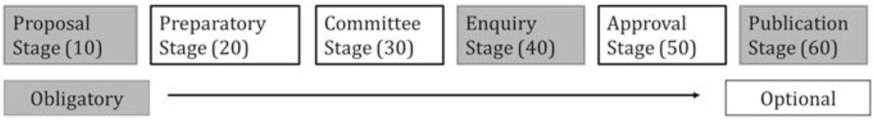

Fig. 3.4 Different stages of a standard development (*Source* UBRUN)

legislative framework developed in the EU. In some areas, European Standards might be more appropriate, depending on the nature of the industry, sector, or supply chain.

Standard Development Stages

The *Programme Management* for development of the standards comprises the *Proposal*, *Preparatory*, *Committee*, *Enquiry*, *Approval* and *Publication* stages shown in Fig. 3.4.

Proposal Stage (10) is the first step is to confirm that a new International Standard in the subject area is really needed. A new work item proposal (NWIP) is submitted to the committee for the vote using Form 4. The electronic balloting portal should be used for the vote. The person being nominated as project leader is named on the Form.

Preparatory Stage (20) commences when a working group is set up by the parent committee to prepare the working draft (WD). The working group is made up of experts and a Convenor (who is usually the project leader). During this stage, experts continue to look out for issues around copyright, patents and conformity assessment. The successive WD is circulated until the experts are satisfied that they have developed the best solution they can. The draft is then forwarded to the working group's parent committee who will decide which stage to go next.

Committee Stage (30) is an optional phase. During this stage, the draft from the working group is shared with the members of the parent committee. If the committee uses this stage, the committee draft (CD) is circulated to the members of the committee who then comment and vote using the electronic balloting portal. Successive CDs can be circulated until a consensus is reached on the technical content.

Enquiry Stage (40) is where the Draft International Standard (DIS) is submitted to the ISO Central Secretariat by the committee secretary. It is then circulated to all ISO members who get 3 months to vote and comment on it. The DIS is approved if two-thirds of the P-members of the committee are in favour and not more than one-quarter of the total number of votes cast are negative. If the DIS is approved, the project goes straight to publication. However, the committee leadership can decide to include the FDIS stage if needed.

Approval Stage (50) may be automatically skipped if the DIS has been approved. However, if the draft has been significantly revised following comments at the DIS stage (even if the DIS has been approved), committees can decide to carry out this stage. If this stage is used, the Final Draft International Standard (FDIS) is submitted to the ISO/Central Secretariat (ISO/CS) by the committee secretary. The FDIS is then circulated to all ISO members for a two-month vote. The standard is approved if a two-thirds majority of the P-members of the committee is in favour and not more than one-quarter of the total number of votes cast are negative.

Publication Stage (60) is where the secretary submits the final document for publication. Only editorial corrections are made to the final text. It is published by the ISO Central Secretariat as an International Standard. Committee secretaries and project leaders get a two-week sign off period before the standard is published.

3.4 Conclusion

In a manufacturing context, Standards are documents that comprise principles, rules and guidelines for the specifications of built parts. They are developed by a group of experts from a relevant field based on consensus building. From the industrial revolution to mass production to the evolution of information technology, Standards play an important role to enhance efficiency, consumer confidence and trust in products, enabling shorter time to market and reduced cost from re-testing or re-certification. This is even more important, especially in Additive Manufacturing, where new technologies, materials, processes and applications are continually evolving.

3.5 External Resources

The following links provide further detail about ISO standards and other resources:

1. ISO online: www.iso.org
2. List of committees on ISO online: https://www.iso.org/technical-committees.html
3. ISO/IEC Directives (including Parts 1 & 2, the Consolidated ISO Supplement and the JTC- 1 Supplement): www.iso.org/directives
4. Description of the different ISO deliverables: https://www.iso.org/deliverables-all.html
5. List of ISO members: www.iso.org/isomembers
6. Stages of development for ISO deliverables: https://www.iso.org/stages-and-resources-for-standards-development.html
7. How to Write Standards: www.iso.org/iso/how-to-write-standards.pdf
8. The ISO Code of Conduct: https://www.iso.org/publication/PUB100397.html
9. Guidance and tools for stakeholder engagement: https://www.iso.org/resources.html

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Chapter 4
Design for AM

Olaf Diegel

4.1 The General Thought Process of DfAM

Many industries approach AM as a direct replacement for conventional manufacturing technologies. This approach, however, does not fully utilize the unique possibilities that additive processes offer. For example, a production component designed for 3-axis computer numerically controlled (CNC) machining that is manufactured through additive processes will, generally, be more expensive to produce with AM. Additionally, parts generated through 3D printing may still require conventional machining-based post-processing in order to meet surface quality and engineering tolerance specifications. Thus, AM should be approached as a complimentary form of manufacturing through which novel products/forms of products can be generated. In general, it should only be considered as a viable production technology if the value it adds to the product is high enough to overcome the high costs of its relatively slow speed.

Much like the design requirements of established manufacturing technologies, the optimal fabrication capability of AM is dependent on the implemented design. It is through this design for additive manufacturing (DfAM) that parts of increasing geometrical complexity can be generated without the financial constraints found within conventional manufacturing. This enables the use of complex re-entrant geometries, lattice structures and otherwise difficult to produce geometries resulting from topology optimization.

AM also enables several design features that would otherwise be impossible or very expensive to achieve with conventional manufacturing. Through the layer-upon-layer process of AM, it is possible to produce internal voids without complex tooling or dividing the component into several parts. This enables, for example, internal conformal cooling channels to be added to molds to increase productivity and part

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quality. Additionally, AM has allowed for the generation of objects having multiple parts/components without the requirements of post-fabrication assembly.

Additive manufacturing, because of its layer-upon-layer process is, by nature, a slow manufacturing process. This relatively slow speed, especially when compared to conventional manufacturing technologies such as injection molding and casting, means it is also an expensive technology. For this reason, it is important to only use AM for production when it adds enough value to overcome the high cost of producing the part.

The overall thought process that can be useful in redesigning parts for AM includes:

1. **Reduce part to only those features that serve functionality.**

   With a conventional technology, such as CNC machining, we try to minimize the amount of cutting required for the part and, therefore, try to remove as little material as possible from the billet we start with. AM is precisely the opposite, because any material that does not serve a real engineering function is just material that has to be processed by the AM system and therefore costs time and money. Anything that breaks the 'even-thickness rule' is just unnecessary material that increases cost, causes more residual stress and therefore more supports and heat treatment.
2. If, after reducing the part to only those features that serve a real function, some of those features are disconnected, then decide how those features can be joined together.
3. Now **consider the most appropriate print orientation** depending on what is important to you. Print orientation will have an impact on part surface finish, mechanical performance, and the amount of post-processing that will be required. In the majority of cases, this decision will be a compromise in which some characteristics are improved, while others deteriorate.
4. Run it through support generation software to see results.

   - **Consider replacing temporary supports with permanent walls.** Support material can be thought of as a temporary wall that will be removed after the part is printed. So why not consider replacing the temporary wall with a permanent one that then becomes a feature of the part.
   - **Consider changing the angles of features requiring support.** If a feature is horizontal, it will require support material beneath it. But, if you can change its angle, chamfer or gusset the bottom horizontal face at 45 degrees then the need for support material can be avoided.

5. Reiterate.

As an example, let us look at the step-by-step design thought process that can be employed in the redesign of a 100 mm × 100 mm × 100 mm steel manifold.

Eliminate evrything that does not serve a purpose

The first step of the design process starts with eliminating everything in the manifold that does not serve a real function. In the case of a manifold, the only thing that performs a real function are the pipes, so the goal of the first step is to eliminate all the material that is not a direct part of the pipe network. The goal is the simplest possible representation of the 'block' manifold (Fig. 4.1) with just the actual channels for the transport of hydraulic fluid.

Once the block design has been simplified, the next step is to remove all the excess material of the cube to leave just the pipes that form the manifold channels. The majority of CAD software packages have some built-in functionality, often called a 'shell' function that makes this step relatively easy. In this example, we select all six outer faces of the cube to be removed, and apply the 'shell' function (Fig. 4.2), leaving only the internal channel structure with, in this case, a thickness of 2 mm.

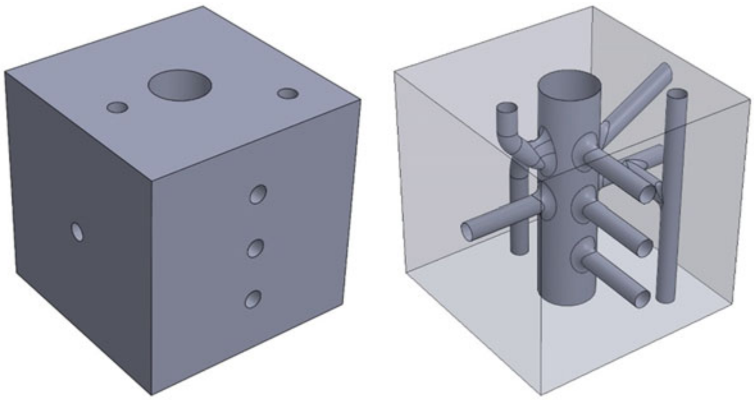


Fig. 4.1 Simplified 'block' design manifold with only the required in and out channels (Courtesy of Olaf Diegel [1])

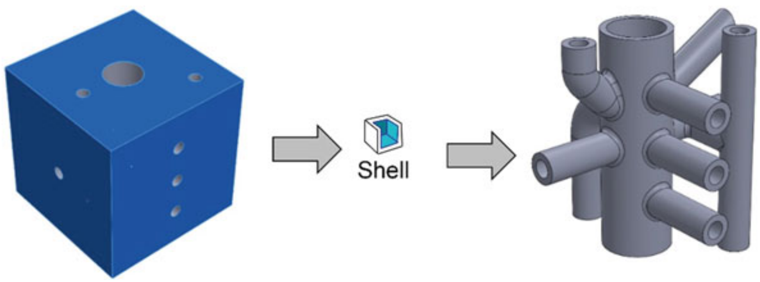


Fig. 4.2 Manifold design after shell operation on block design (Courtesy of Olaf Diegel [1])

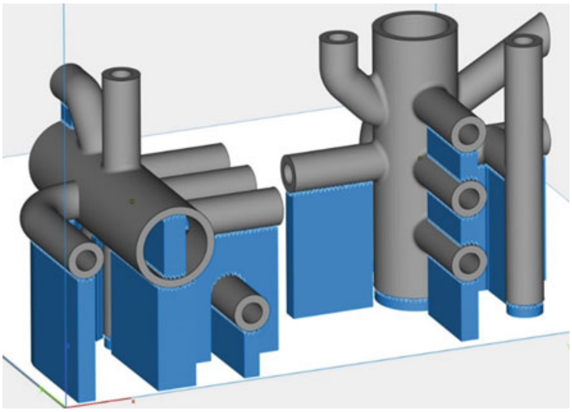


Fig. 4.3 Support material required by shelled-block design in 2 different print orientations (Courtesy of Olaf Diegel [1])

Decide on print orientation

One of the early decisions that needs to be made when designing for AM is the print orientation, as this will affect all other design decisions thereafter. This is because print orientation will have an impact on almost every aspect of the part. **When designing for additive manufacturing, one should always design around the specific orientation in which the part will be printed because part orientation will determine the direction of anisotropy, mechanical properties, surface finish, roundness of holes, support material, etc**.

When we run the manifold example through software used to generate support structures we see that support is generated between all the horizontal pipes (Fig. 4.3). In one of the orientations below, where the large diameter pipe is horizontal, we can see that support has also been generated inside the large diameter pipe.

It is important to remember that, in DfAM, there is no absolute that says one orientation is better, or worse, than the other. Instead, it must be a conscious exercise to examine what the effects of a particular print orientation are on a part. In our example, both print orientations will necessitate the removal of this support material after printing, as well as some surface treatment to improve the surface finish of the areas where the support material makes contact with the real part. This post-processing increases the amount of labour required to finish the part, extends the delivery time on the part, and increases cost.

One could possibly make the argument that, in the print orientation where the large diameter pipe is horizontal, it will be harder to remove the support from inside the pipe than from all the outside surfaces. So, unless there were some other advantage to having the large diameter pipe printed horizontally, the better print orientation might be the one where it is in the vertical position. However, without fully understanding the context in which the manifold will be used, one cannot guarantee that this is, in fact, the best orientation.

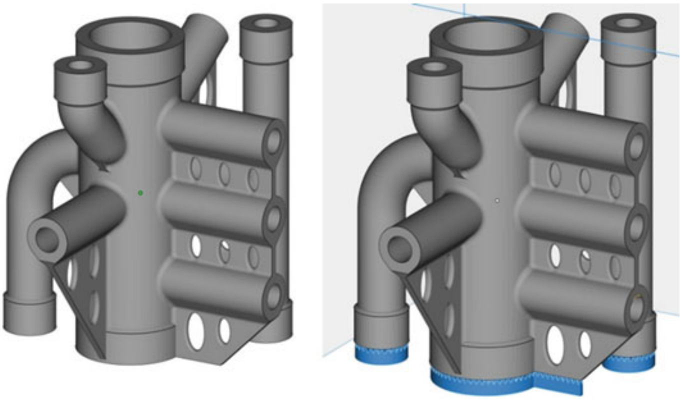


Fig. 4.4 Support material required by optimised for metal AM design (Courtesy of Olaf Diegel [1])

Eliminating support material

Support material is, essentially, a sacrificial temporary material, that serves a certain purpose during the print process, but is then removed after the print is finished. In many cases, a design option that is worth considering is to replace the support material beneath each of the horizontal channels with a permanent wall to eliminate the need for support material altogether. **The idea is that the added wall becomes the support material and becomes a permanent feature of the part**.

In the case of the manifold example, we can replace all of the support material with permanent walls, thus eliminating the need for support material entirely. The bottom walls are chamfered at 45°, as that is the angle we have set beyond which to use support material, and we can add elliptical, diamond, or teardrop-shaped holes in the walls to further reduce weight, yet without requiring support material in the holes. As can be seen below (Fig. 4.4), the only needed support material is a very small amount required to weld the part to the build platform.

In the case of the above manifold, the weight of the original 100 mm × 100 mm × 100 mm block design, in steel, would be 7.4 kg. In contrast, the optimised for metal AM design weighs only 600 g. That represents a greater than 94% weight saving, and a proportional reduction in print time and cost.

The above example demonstrates how some simple design decisions can greatly reduce the amount of support material required, and therefore, the post-processing, which means a better product at a lower cost. Remember, however, that in many cases of printing metal AM parts, some support material is unavoidable, but that the designers thought process should constantly be looking for ways to minimise it.

4.2 The Economics of DfAM

This section investigates economic arguments related to AM, namely how design-controllable factors of this manufacturing and the results of DfAM affected costs relate to operations, material, and processing.

Though the strategies implemented within this chapter apply equally to all AM technologies, a focus is made with respect to metal PBF AM because it is one of the technologies in which cost and time factors are the most significant. This section will evaluate the current economic relationships relative to operations within AM. An analysis regarding the current fabrication related costs is conducted to act as a better framework for discussions relating to design-based 3D printed part optimization. To further illustrate these ideologies, a case study is conducted through which the described DfAM techniques are demonstrated in the generation of previously discussed manifold part. The preferred design option for this example was fabricated with an EOS M290 selective laser melting system, in 316L stainless steel, to demonstrate that it could, indeed, be printed with minimal support material and post-processing.

4.2.1 Machine Costs

Printing parts in which DfAM has not been considered are susceptible to high costs. This is due to the expensive nature of industrial AM systems paired with comparatively slow part production rates. A metal production sized AM system, typically, costs between US$500,000 to over US$1,500,000.

A typical operational time (80%) for a metal AM machine results in approximately 7000 h of annual use. A desirable return on investment used by industry recoup the cost of a rapidly evolving technology infrastructure investment is, for example, 2 years. Whilst this may vary relative to individual companies, it will suffice as a benchmark for this work. Additional associated costs might include potential loan-based interest rates (e.g. 5%), installation labour and power consumption (both being relatively minor expenses in comparison to machine time). This simplified cost model is summarized in the Equation below and some examples for the hourly running costs of differently priced AM systems are shown below in Table 4.1.

Table 4.1 Machine hourly running costs for 2-year payback period and 80% utilization

Machine purchase cost	Hourly machine running cost
$500,000	$37.45/h
$650,000	$48.69/h
$1,000,000	$74.91/h
$1,200,000	$89.89/h

$$\text{Machine hourly running costs} = (\text{Machine purchase cost} + \text{interest})/ \\ (\text{payback period} * \% \text{ running time} * \text{yearly hours})$$

The above equation illustrates a simplified costing model from which hourly operational machine costs between US$500,000 to US$1,200,000 have been generated. From this range of potential costs (US$37–90/h) an average of US$65/h was used for the examples in this chapter. This is, in some cases, a potentially optimistic value as certain user specific expenses (e.g. overheads) have not been accounted for. Currently, metal AM technologies are associated with long operational times (e.g. dozens of hours to produce a part to, not uncommonly, greater than 100 h) demonstrating an operational cost vs. time vulnerability within the technology. These operational costs are, however, not dissimilar to other conventional high-end manufacturing technologies such as industrial CNC and injection molding machines. However, geometrically simple parts can be produced much faster with these conventional technologies than they can with AM.

4.2.2 *Material Costs*

Metal AM powders can range from US$70/kg (e.g. steel or aluminium) to US$300/kg (e.g. cobalt chrome or titanium) which is significantly more costly than the same material alloys used for traditional manufacturing. Costs for AM polymer materials are also substantially more expensive, between 10 times to up to well over 100 times, than their conventional manufacturing counterparts.

Powder-based metal AM also requires the use of additional support material for overhanging part geometries, to anchor the part to the build platform and to help with heat dissipation. This support material, together with losses from partially sintered powder, yields an estimated 8–10% loss/wastage of material. Thus, an argument can be made relating to the reduction in wasted material (relative to subtractive manufacturing) and therefore cost reduction in production. Currently these material costs are often negligible relative to the machine-time costs. However, the likely future increases in AM production speeds will result in an increased role of material costs in metal AM cost-based viability in the future.

4.2.3 *Post-processing Costs*

AM typically requires pre- and post-processing to yield a desirable part. This includes operations relating to the heat treatment of parts, support material removal and surface modification. The table below shows the estimated cost proportions of these tasks with values derived from a 2017 Wohlers Report service provider survey [2] (Table 4.2).

Table 4.2 Breakdown of pre and post-processing time versus print time

	Metal (%)	Polymer (%)	Both (%)
Pre-processing	13.2	10.9	10.2
Post-processing	31.4	20.2	27.0
Total pre/post	44.6	31.1	37.2
Printing	55.4	68.9	62.8

This data indicated that approximately 45% of metal AM expenditure is related to the pre- and post-processing required for part production. This value demonstrates the significant economic impact of parts which have not been designed to minimize these processes.

Time-consuming operations within AM are not solely limited to part geometry and post-processing. Such operations relate to the time taken to, for example, the spreading of material for a layer (recoater time) and the implementation of controlled environmental conditions. The requirements for purging (typically the removal of oxygen through inert gas addition) and the heating of the printing region are machine and material dependant. The recoater time is user dependant given the implemented part print orientation which will typically affect the required number of layers/recoating operations. However, if two parts, one well designed and one poorly designed, have the same overall height, then the recoater time will be the same for both, and is not affected by how good or poor the design is.

4.2.4 Time Factors That Are Affected by Design

Similar to the golden rule of injection moulding, where even wall thickness is always recommended, large masses of material, typically, offer little functional advantage. In fact, large material masses can be detrimental as those are the areas that are likely to contain residual stress which can cause distortion of the part. Moreover, in AM, large areas with solid material also greatly extend print times. There are many techniques for removing large masses of material, including the 'shell' technique described below. Others include filling solid parts with honey-comb, lattices, or even porous material. From a time-based perspective, it is best to print a part in the orientation in which it has the lowest vertical height as this will generally have the fewest layers, and therefore the fastest print time. However, because print orientation also plays a major role on part mechanical properties, geometric accuracy, surface finish, and support material, this decision can often be a compromise between print time and these other aspects.

Design factors that reduce laser operating time

Within most AM, printing time is directly related to the quantity of material which needs to be solidified. This is particularly true of powder-based techniques which employ a processing (sintering/melting) beam (laser or electron) to scan across

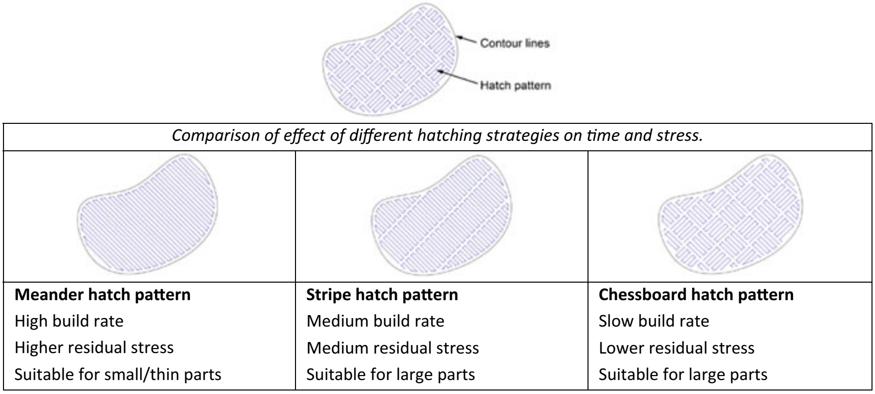


Fig. 4.5 Example form highlighting the typical implementation of laser scanning for *contourlines and hatch patterns* (Courtesy of Olaf Diegel [1])

a region of power to generate a fused layer/slice of a model/part. This scanning operation can be characterised as either a contour or hatching operation (Fig. 4.5).

The contour operation relates to the processing of the slice edge (which will become the part outer surface) and the hatching operation relates to the pattern employed to process the internal material of the part and can occur in various forms (e.g. meander, stripe or chess-board). A good analogue for the laser scanning process would be to draw a shape outline with a pencil (this being the contour operation) and then proceed to ‘colour in’ the internal area of the shape by running the pencil back and forth (hatching) many times.

As such it is desirable to implement techniques capable of reducing the quantity of material requiring laser scanning. Techniques of solid material substitution with shells, honeycombs or lattices result in faster manufacturing as they avoid unnecessary processing of material.

Design factors that affect print time and cost

The Table 4.3 further highlights the various stages within an AM process which are affected by part design and in which part design can, therefore, influence the cost of the part.

4.2.5 Economics Case Study: Metal AM Manufactured Hydraulic Manifold

Within AM, metal-based techniques yield the greatest opportunity to optimise the design for products otherwise designed for traditionally manufacturing. One example of which are manifold like objects, as per the example discussed in the previous section. These parts are typically generated by the drilling of channels within a large

Table 4.3 Factors within AM processes through which DfAM can yield economic improvements

AM process step	Affected by design
Pre-processing	
• Check quality of files, and fix if necessary	No
• Prepare print-job in software by arranging parts on build platform, generate support, slice, etc	No
Printing	
• Clean the AM system	No
• Purge the system of oxygen	No
• Preheat the AM system	No
• Print the parts	
Spread layer of powder (Recoater time)	No
Laser contour lines	Yes
Laser hatch pattern	Yes
• Remove build platform from machine	No
• Recycle powder	No
Post-processing	
• Thermal stress relief	Yes
• Remove parts from build plate	Yes
• Hot Isostatic Pressing (HIP)	Yes
• Removal of support structures	Yes
• Heat treatment	Yes
• Surface machining, shot-peening, abrasive flow machining, etc	No
• Inspection	No

metal block to form a network of interconnecting pipes. Of note is the requirement to drill separate holes through the block to act as internal connecting channels, some of which are then required to be appropriately blocked (plugged) post machining. The Fig. 4.6 below illustrates the previously discussed block manifold example for which a print layer is depicted to highlight the inferred AM material/material processing requirements.

The scanning hatch pattern for the example layer slice will require a relatively long beam scanning distance. For a manifold having dimensions 100 mm × 100 mm, and a hatch spacing set to 0.1 mm, **a scanning hatch distance of approximately 100 m is required per square layer**. For the purposes of this example, a beam travel speed of 330 mm/s and the previously derived machine operating cost of US$65/h will be utilized. This results in a layer hatching time of 100/0.33 = 303.03″ s = 5.05″ min. At $65/h this equates to US$5.47 in operational time.

The first fundamental step related to DfAM encourages a reduction in material requiring processing. The use of a hollowing (“shell”) based technique upon the generated model allows for the retention of the established surface morphology as

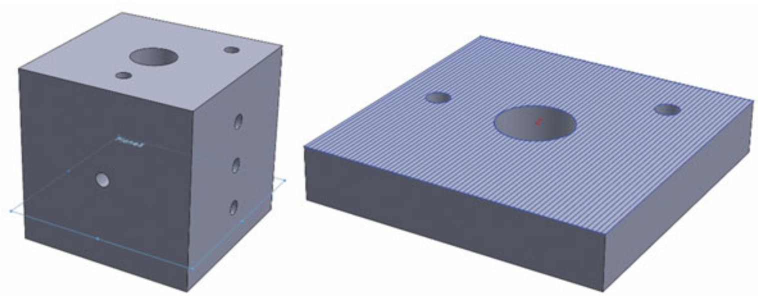


Fig. 4.6 A block manifold and an illustration of the laser scanning process to melt a single layer of the part (Courtesy of Olaf Diegel [1])

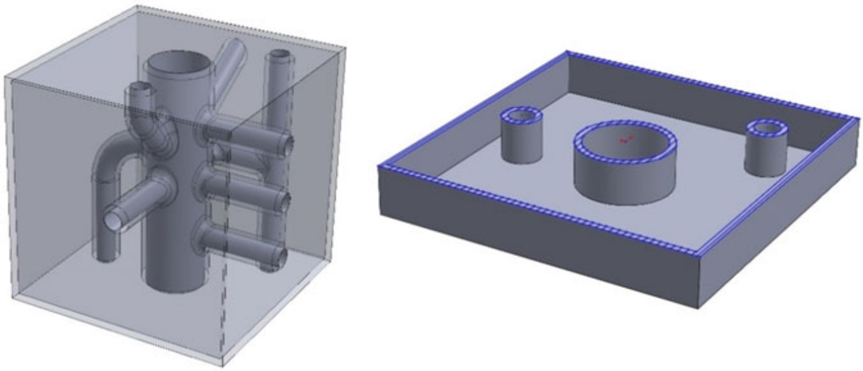


Fig. 4.7 A shelled block manifold and an illustration of the laser scanning process to melt a single layer of the part (Courtesy of Olaf Diegel [1])

well as the specification of a desirable uniform wall thickness. The results of this modification are depicted in the Fig. 4.7 below.

This simple alteration to the model results in a greatly reduced material processing (laser scanning) requirement, therefore reducing overall print time and cost. Utilising a ‘shell thickness’ of 2 mm and the previously described hatch settings **yields a total hatch distance of 4.5 m** (a > 95% reduction over the solid block). This will take approximately 13.6 s to hatch and result in a layer cost of US$0.24 (saving US$5.23 per layer). It is worth noting that within powder-based AM the generated cavity will be filled with un-melted powder. For applications in which this is not desirable, this powder can be removed via the inclusion of an opening/hole through which this excess material can be drained. It is worth noting, also, that support material is still likely to occur for the horizontal geometries within the shelled structure. The removal of these would be relatively complex or impossible.

Given the parts requirements, the outer surface (external box form) can be further removed yielding a part having solely the desirable functional form of the manifold thereby further reducing print time and the associated costs. Within this example, limited functional reduction in support material will be achieved via the variation of printing orientation for the manifold. Whilst the support material required for the part can be reduced by implementing an angular alteration (relative to the desired materials operational range) to the various extrusions of the manifold, this would not yield a functionally desirable result. Additionally, within metal AM support material is fundamental in anchoring the part to the build platform as well as aid in the controlled dissipation of thermal energy. As such it is required to minimise the potential thermally generated distortions which could occur to the part during fabrication. As such this example made use of designed permanent supporting structures which when added to the part both avoid automatically generated support as well as acted to reinforce the channels.

Great care must also be taken to ensure no/limited support material occurs within the manifold channels as this will result in flow distortion. The maximum diameter from which AM will no longer require support material will vary relative to the material and machine utilised. Within this example, the utilised material (Stainless Steel 316L) and EOS M290 Printer allowed for a minimum inner diameter of 8 mm for the manifold channels without requiring any additional support structures. The resultant manifold design including the implemented permanent support structures is demonstrated in the Fig. 4.8 alongside a version which depicts the limited automatically generated support material.

With regards to the aforementioned steps required in DfAM; step 1 related to the implemented hollowing/shell technique and removal of all the non-essential material, step 2 was not required as the design geometries were already connected, step 3 identified the potential regions and requirements for support material relative to printing orientation, and step 4 included the reduction in support material via inclusion of permanent support structures and software-based design validation. The resultant manifold developed through this process is shown below (Fig. 4.9). This required

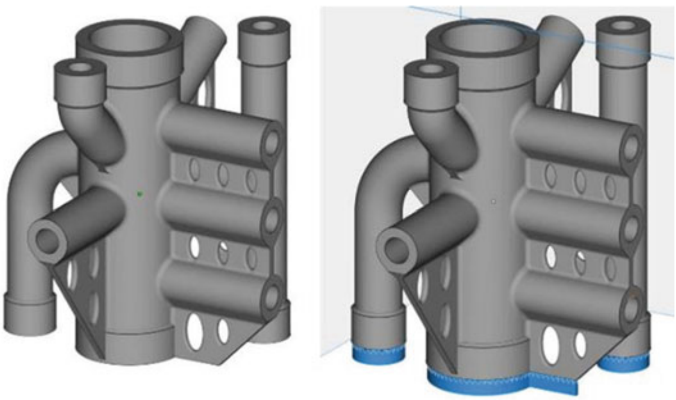


Fig. 4.8 Resultant manifold design having permanent support structures and model depicting software derived support material (blue) (Courtesy of Olaf Diegel [1])

Fig. 4.9 A designed for AM block manifold with reduced print time and support removal time (Courtesy of Olaf Diegel [1])

no further surface machining and the channels were manufactured free of support material, the part only needing removal from the printer build plate for use.

A costing comparison of the various stages of the part redesign (solid block, shelled block and optimized DfAM) was conducted through simulating these parts within Autodesk's Netfabb Ultimate 2018 software for an EOS M290 machine. The print material was set to 316L stainless steel and a layer thickness of 50 μm utilised. The simulations identified major reductions in time and cost namely; an approximate ~90% reduction in time, ~90% reduction in machine cost, ~92.5% reduction in weight and material cost. Additionally, external AM bureau quotes were requested and an 87% reduction in purchasing cost was identified. The results of these costing comparisons are shown below (Table 4.4). This case study acts as an example of how AM, and more specifically the DfAM can dramatically improve production cost and part size/weight.

This chapter demonstrates that machine cost and print time is one of the main factors that affects AM part production and the most significant controllable factor is the avoidance of large masses of material. These require extended hatching times, and the avoidance of support material aids in minimizing post-processing. It quantifiably demonstrates that a simple strategy of replacing large masses of material with even wall thickness shells can have a substantial impact on hatching times and therefore machine time and cost.

This chapter establishes the importance of DfAM from an economic point of view. The difference in cost between a part that has been designed for AM compared to that of a conventional part made with AM is so significant illustrating DfAM to be an essential part of successfully implementing AM. Moreover, if one includes the

Table 4.4 Manifold design print times and cost

	Solid block manifold	Shelled block manifold	Optimized DfAM manifold
Total print time from Autodesk Netfabb Ultimate 2018, for EOS M290 machine, 316L stainless, 50 micron layer thickness	191 h 1 m 33 s	36 h 31 m 21 s	19 h 40 m 39 s
Estimated machine cost @ $65/hour	$12,415.00	$2379.00	$1,261.00
Material weight	7.411 kg	1.232 kg	0.558 kg
Material cost @ $70/Kg + 10% waste	$570.64	$94.86	$42.96
Actual online AM bureau quotes for part in 316L stainless	$15,293.82	$3735.12	$1986.25

less quantifiable added value elements such as reduced weight, improved functionality, reduced time to market, reduced waste material etc., then the argument for the absolute necessity of DfAM is not hard to make.

4.3 Polymer Design Guidelines

A previous assessment of part geometry is recommended so as to evaluate whether additive manufacturing will bring benefits to our part or not, based on a first quick assessment we will be able to decide if AM, conventional manufacturing methods or both of them are required.

Some of the keypoints that must be analysed are:

- Part weight/volume assessment.
- Production costs (using traditional methods) AM technique that will be necessary.
- Part nestability (build density).
- Functional surfaces and part requirements (geometrical and dimensional tolerances to be achieved).

Although costs involved in the Additive manufacturing production chain vary depending on the technology, average values can be stablished as: (i) material (15%), (ii) human resources (30%), (iii) machine (55%), and (iv) post processes (if required).

Therefore, many variables take part in the process that will affect part production costs.

Part weight/volume

Given the material optimization that additive manufacturing processes permits due to the design freedom, this is not only an opportunity for the part to be optimized in terms of weight but also an opportunity to reduce the production costs in the AM processes. The more parts we manage to put inside the build envelopment the cheaper the production costs will be.

Hence the design for additive manufacturing is a key factor for the part and process optimization. Normally a part which is conceived for traditional methods will not be economically feasible for AM if the design is not adapted.

Production costs analysis

As in all the additive manufacturing technologies happens, there is a fix cost which comes from the machine preparation and build preparation, the cost will not vary if only one part is produced or plenty of parts are nested inside the build envelopment, therefore the unitary cost will vary depending on the amount of parts that are allocated in the build envelopment. Some calculations can be done so as to assess the feasibility of additively manufacture a certain geometry. A relationship between unitary costs and number of parts per build is found in Fig. 4.10.

As a summary, although there might be different approaches depending on the part complexity and each situation, there are a few questions that we must formulate so as to decide whether re-desing for additive manufacturing will be required or not:

- **Production**: number of parts that will be manufactured. Given a certain 3D model that it was conceived for standard methods as milling, CNC and so on, the re-design for additive manufacturing will require human resources. Hence if just one copy will be produced through AM, the entire re-design HR will be charged to this copy, whereas if the number of parts demanded is bigger, re-design costs will be distributed between them all.
- **Know the environment of the part and the working conditions**: prior to a redesign process, it is quite important to understand how the part works, the

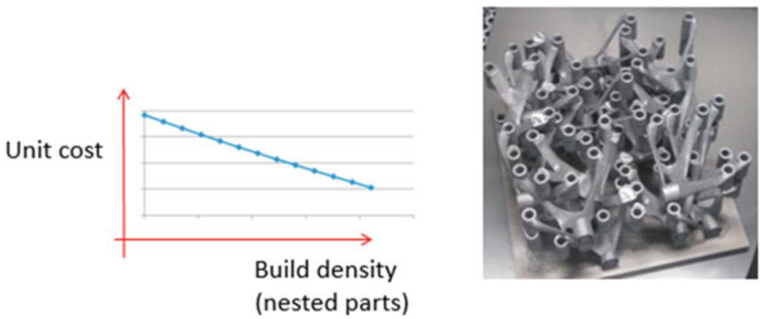


Fig. 4.10 Unitary costs versus number of parts in build envelopment (*Source* Skin Project—AIDIMME)

interaction with other parts in the assembly and the working conditions (loads and restrictions). Some of these restrictions might limit our design.

- **Know the dimensional and geometrical tolerances**: AM technologies are not as accurate as traditional methods, thus areas of the geometry where fine adjustments or very specific geometrical and dimensional tolerances are demanded, will require to be post processed. A good understanding of these limitations will allow us to focus our design thinking not only in the part construction, but also in the post processing steps, clamping areas, and so on.
- **Know the raw material**: we can find that in some occasions, parts are being manufactured in materials that are not necessary just because the production ratios make inefficient processes as injection moulding. (These methods require high productions in order to amortize the mould costs. Therefore, it is highly recommended to analyze the material to be used for the part construction, sometimes a part which was initially conceived in metal-based materials, can be produced in polymeric materials by additive manufacturing.
- **Know the surface finishes**: due to the layer by layer method of the AM processes, parts produced by these techniques present an important surface roughness that sometimes is detrimental in the final parts, just because the mechanical properties are slightly affected or because the part appearance is compromised. Thus, surface finish must be defined so as to determine which kind of postprocessing tasks will be applied and of course it will affect the DfAM.
- **Determine the AM process**: once the previous key factors have been analysed, AM technique must be defined. Design rules vary quite a lot from one technology to another, thus depending on the AM process that is selected, re-design approach will be different.

4.3.1 Designing for Material Extrusion (MEX)

Material extrusion is the AM process with the most anisotropy. The bond between the layers can substantially weaken parts in the vertical direction, so this is the process in which choosing the most appropriate print orientation can have the biggest impact.

Material extrusion accuracy and tolerances

There is a great difference in accuracy and tolerance between different material extrusion systems. This is particularly the case when comparing desktop systems to industrial systems. Accuracy and tolerance can also vary depending on geometric features and print orientation. The only sure way to know the accuracy and tolerance of any particular system is to print a test reference part and to measure it.

The numbers given in Table 4.5 are for industrial quality material extrusion systems. They represent a general tolerance and accuracy for material extrusion technologies.

Table 4.5 General tolerance and accuracy for material extrusion technologies

Layer thickness	0.1–0.3 mm (0.005–0.013 in.)
Accuracy	± 0.1 mm or ± 0.03 mm per 25 mm (±0.005 in. or ±0.0015 in./in.), whichever is greater
Tolerance	Reality rule of thumb for Material Extrusion: typically, 0.25 mm (0.01 in.)
Smallest feature size	around 1 mm (0.04 in.)

Layer thickness

Layer thickness is one of the first decisions that has to be made when using material extrusion. In general, the thinner the layer, the better the surface quality, particularly on rounded parts, as the stair-step effect will be much less visible. Remember, however, that the thinner the layer, the longer the part will take to print.

If a part is composed mainly of planar geometric features in the vertical direction, then printing it with thicker layers will not necessarily produce a substantially worse surface finishes that if it is printed with thin layers, but it will print much faster. If the part is made up of mainly curved surfaces, then thinner layers may be preferable in order to achieve the smoothest possible curved surfaces.

Support material

Some material extrusion systems print with soluble support material while others do not. If the supports need to be removed manually, rather than being dissolved away, then access should be allowed so the supports can be broken away. Also, with small and delicate features, care should be taken that they are not accidentally broken when the support is removed.

Another decision that has to be made is what type of support material structure options to use. Almost every different maker of material extrusion printer offers different options for this. But some of the common types of support strategies include supports shown in Fig. 4.11.

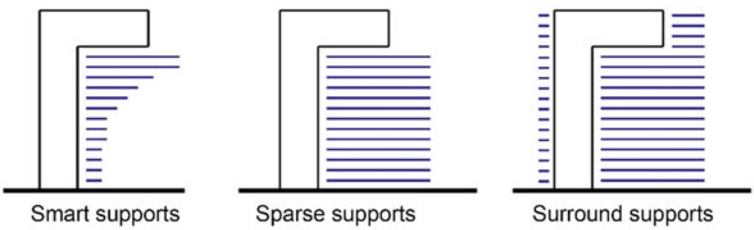


Fig. 4.11 Types of support strategies (Courtesy of Olaf Diegel [1])

Fig. 4.12 Examples of different interior infill percentage options (Courtesy of Olaf Diegel [1])

Fill style

Most material extrusion systems allow the user to choose if the part should be printed as a solid part, or as a 'sparse' part in which the interior void is filled with a scaffold structure. Some systems may also give the user the option to specify how thick the outer shell wall should be. Some systems also allow the user to select the infill percentage, or how dense the internal scaffold structure should be (Fig. 4.12).

Other considerations

A characteristic of the material extrusion process is a "stair-stepping" effect on gently inclined or curved surfaces of parts. This can be reduced by various post-processing techniques (such as acetone vapour smoothing for ABS parts), but this will have an impact on part accuracy, geometrical stability and sometimes material properties.

Material extrusion can, depending on the particular AM system being used, leave a small air gap between the laid down filament for certain wall thicknesses. This is because the software has to make a decision on whether to deposit an extra strand of material in the wall. For example, if the strand of polymer exiting the printer nozzle is 0.4 mm wide, but the wall thickness is 0.9 mm, the software must make a decision as to whether or not to add an extra strand of polymer between the two first tracks, or to leave a 0.1 mm gap. This very much depends on the machine brand and model,

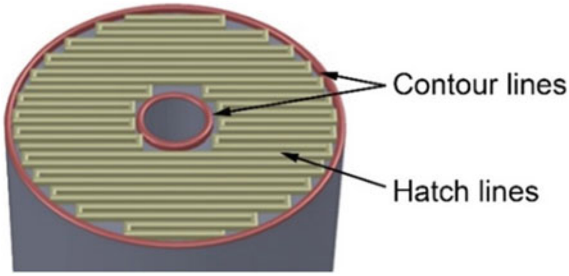


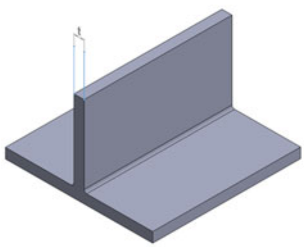
Fig. 4.13 Reinforcing the joint between contour and hatch lines (Courtesy of Olaf Diegel [1])

so it is best to do some tests and to find which wall thicknesses are not ideal for each brand of machine.

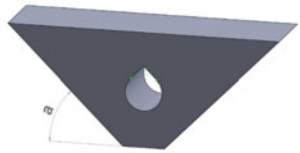
Holes in a Material Extrusion part are usually printed undersized. If tight tolerances are required, it is best to drill the holes to the required diameter.

Because of the sometimes weaker bond between contour lines and infill (or hatch) lines (Fig. 4.13), self-tapping screws can occasionally strip away the contour material in the screw bosses. A drop of cyanoacrylate (super glue), allowed to wick between the contour and fill material can improve this.

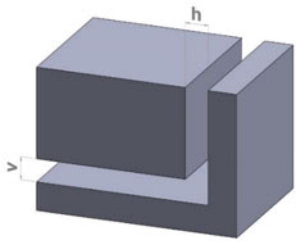
The following pages contain general design guidelines for the material extrusion process.

Vertical wall thickness			
Process variable	Wall thickness (t)		
Layer thickness	Minimum	Recommended minimum	
0.18 mm (0.0071 in.)	0.36 mm (0.014 in.)	0.72 mm (0.028 in.)	
0.25 mm (0.0098 in.)	0.50 mm (0.02 in.)	1.00 mm (0.039 in.)	
0.33 mm (0.013 in.)	0.66 mm (0.026 in.)	1.32 mm (0.052 in.)	
Comments Avoid unsupported large flat surface areas. Warping may occur with extended lengths of unsupported walls (i.e., no ribs or intersecting walls). In this case, avoid using the minimum wall thickness Avoid sharp transitions. Fillets at the points where walls join are recommended In general, an even wall thickness is recommended on all walls, both vertical and horizontal			
Horizontal walls			
With material extrusion technologies, horizontal walls can, theoretically be as thin as a single layer of material. In practice, however, to produce a horizontal wall with some strength and consistency, at least 4 layers of material are recommended Again, it is best practice to keep all walls of your product at the same thickness			

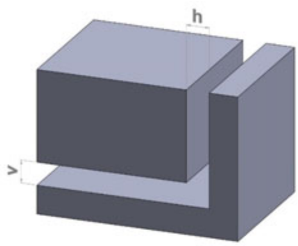
Support material overhang angles
Maximum overhang angle (a)
45° This is a safe default number. But the angle can vary greatly from printer brand to printer brand, and depends on the material used and desired surface quality
Comments Overhang angles less than 45° (measured from horizontal) require support material, which is normally added automatically by the system software. Be aware that some systems measure the support angle from the horizontal, while others measure from the vertical Excessive supports that need to be broken away manually will increase post-processing time. Soluble support structures require much less manual labour, but they still waste material and time Horizontal holes (e.g., cooling channel profiles) can often be modified into teardrop or ovals shapes to minimize the need for internal supports that are hard to remove



Clearances between moving parts with soluble supports		
Process variable	Minimum clearance	
Layer thickness	horizontal (h)	vertical (v)
0.18 mm (0.0071 in.)	0.36 mm (0.014 in.)	0.18 mm (0.0071 in.)
0.25 mm (0.0098 in.)	0.50 mm (0.02 in.)	0.25 mm (0.0098 in.)
0.33 mm (0.013 in.)	0.66 mm (0.026 in.)	0.33 mm (0.013 in.)
Comments Large areas of close proximity will slow down the removal of support material. Clearance between parts built separately and assembled later must be at least equal to the general build tolerance of the system		



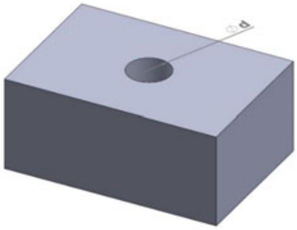
Clearance between moving parts with break-away support material		
Process Variable:	Minimum clearance:	
Layer thickness	horizontal (h)	vertical (v)
0.18 mm (0.0071 in.)	0.36 mm (0.014 in.)	Adequate access to facilitate supports removal
0.25 mm (0.0098 in.)	0.50 mm (0.02 in.)	
0.33 mm (0.013 in.)	0.66 mm (0.026 in.)	

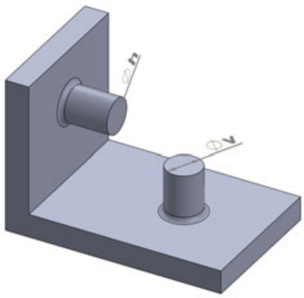


(continued)

(continued)

Comments The main challenge with printing moving parts on a printer without soluble support is in the difficulty of removing the support material from between the moving parts Large areas of close proximity will slow down the removal of support material. Clearance between parts built separately and assembled later must be at least equal to the general build tolerance of the system

Vertical circular holes		
Required diameter (d)	CAD model diameter	
5.0 mm (0.197 in.)	5.2 mm (0.205 in.)	
10.0 mm (0.394 in.)	10.2 mm (0.402 in.)	
15.0 mm (0.591 in.)	15.2 mm (0.598 in.)	
20.0 mm (0.787 in.)	20.2 mm (0.795 in.)	
Comments Holes are generally built undersized, typically by around 0.2 mm (0.0079 in.) across the diameter (*Note* this value needs to be verified for each machine/material combination being used). This can be remedied approximately by adjusting the CAD model using the values above, or more precisely by drilling out the hole after the part has been built If using self-tapping screws, the column of contour material that surrounds the hole can sometimes be stripped out by the screw. A drop of super-glue, allowed to wick in between the contour and fill material, can alleviate this problem		

Circular pins		
Minimum diameter for vertical pins (v)	Minimum diameter for horizontal pins (h)	
2.0 mm (0.079 in.)	2.0 mm (0.079 in.)	
Comments Pins with small diameters, vertical ones in particular, are prone to breaking off if only supported at one end Always fillet the pin where it joins the wall. Even 0.5 mm is enough to substantially strengthen the pin		

4.3.2 Designing for Polymer Powder Bed Fusion (PBF-LB/P)

What differentiates polymer powder bed fusion processes, be they laser-based or multijet fusion-based, from the majority of other AM processes is that they do not require support material. The part being constructed does not require supports because the unfused powder surrounding the part provides sufficient support. It can therefore be argued that this gives the designer greater freedom than most other AM system.

Parts created using polymer powder bed fusion usually have some degree of vertical anisotropy, particularly for small features that are less than about 25 mm^2 in surface area in the vertical direction. Engineers must design around this by, for example, ensuring that highly stressed features are built horizontally rather than vertically.

Powder bed fusion accuracy and tolerances

There is a difference in the accuracy and tolerance between different manufacturers systems. They also vary depending on geometric features and print orientation. The only sure way to determine the accuracy and tolerance of any particular system is to print a test reference part and measure it. The numbers given in Table 4.6 are for industrial quality powder bed fusion systems.

Layer thickness

A common layer thickness for powder bed fusion is 0.1 mm, but some systems allow for thinner layer thicknesses. Compared to other AM technologies, however, the stair-stepping effect is less visible on polymer powder bed fusion technologies. It is only on very gently curving surfaces of a relatively large surface area that it is visible.

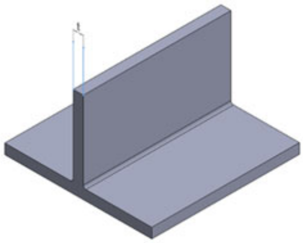
Avoiding large masses of material

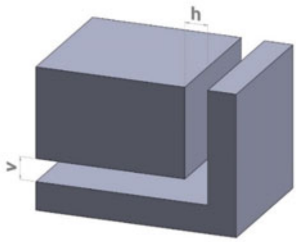
Designers need to be careful in trying to avoid uneven thicknesses of plastic in their parts and to avoid large masses of material. These can cause distortion in the part and will add substantially to the time and cost it takes to make the part. The same applies with multijet fusion because, for large masses of material, much more fusing agent needs to be deposited by the print head, which can substantially increase the cost of the part.

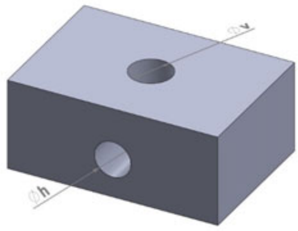
The following pages contain guidelines on how to design features to be built using polymer powder bed fusion.

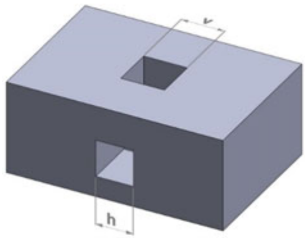
Table 4.6 Tolerance and accuracy for powder bed fusion

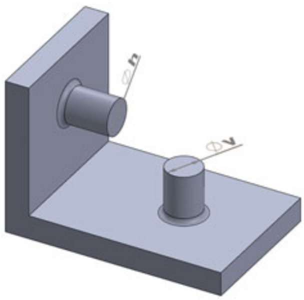
Layer thickness	0.1 mm (0.005 in.)
Accuracy	± 0.3% (lower limit of ± 0.3 mm (0.010 in.)
Tolerance	± 0.25 mm (0.010 in.) or ± 0.0015 mm/mm (0.0015 in./in.)—whichever is greater
Smallest feature size	around 0.5 mm (0.04 in.)

Wall thickness		
Minimum wall thickness (t)	Recommended minimum wall thickness (t)	
0.6~0.8 mm (0.031 in.)	1.0 mm (0.039 in.)	
Comments Though it is, on occasion, possible to print walls thinner than 0.6 mm, their success is highly dependent on the rest of the part geometry, print orientation, etc Thin walls with a large surface area are likely to warp during the cooling process. If large surface area thin walls are required, consider adding ribs to stiffen the walls Thicker walls and any large volumes of material will result in excess heat retention in the part and hence shrinkage, resulting in geometric deformation. Therefore, a maximum wall thickness of 1.5~3 mm is also recommended. If walls must be thicker than this, consider shelling them. This will both help to reduce distortion and greatly speed up print times In general, an even wall thickness is recommended on all walls, both vertical and horizontal		

Clearance between moving parts		
Minimum horizontal clearance (h)	Minimum vertical clearance (v)	
0.5 mm (0.02 in.)	0.5 mm (0.02 in.)	
Comments The required gap between moving parts is highly dependent on the surface area of the faces that are in close proximity. If faces in close proximity have surface areas of only a few mm^2, then gaps as small as 0.2 mm between the faces are possible. The 0.5 mm gap stated above is one that will work in most situations and on most different manufacturers systems Large areas of close proximity will slow down the removal of excess powder. Clearance between parts built separately and assembled later should be at least equal to the general build tolerance of the system		

Circular profile through holes			
Process variable	Minimum diameter		
Wall thickness	vertical hole (v)	horizontal hole (h)	
1 mm (0.039 in.)	0.5 mm (0.019 in.)	1.3 mm (0.051 in.)	
4 mm (0.157 in.)	0.8 mm (0.031 in.)	1.75 mm (0.069 in.)	
8 mm (0.314 in.)	1.5 mm (0.059 in.)	2.0 mm (0.079 in.)	
Comments Small round holes, typically below 1.5 mm are related closely to wall thickness. As the wall thickness increases, powder becomes increasingly difficult to clear from small holes. As the wall thickness decreases, smaller through holes become feasible			

Square profile through holes			
Process variable	Minimum diameter		
Wall thickness	vertical hole (v)	horizontal hole (h)	
1 mm (0.039 in.)	0.5 mm (0.019 in.)	0.8 mm (0.031 in.)	
4 mm (0.157 in.)	0.8 mm (0.031 in.)	1.2 mm (0.047 in.)	
8 mm (0.314 in.)	1.5 mm (0.059 in.)	1.3 mm (0.051 in.)	
Comments Small square holes typically below 1.5 mm are related closely to wall thickness. As the wall thickness increases, powder becomes increasingly difficult to clear from small holes. As the wall thickness decreases, smaller through holes become feasible			

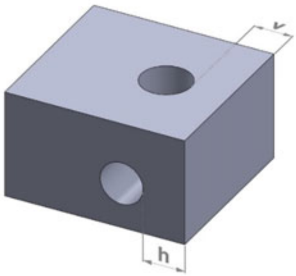
Circular pins		
Minimum diameter for vertical pins (v)	Minimum diameter for horizontal pins (h)	
0.8 mm (0.031 in.)	0.8 mm (0.031 in.)	

(continued)

(continued)

Comments
Pins with small diameters are prone to breaking off if only supported at one end Always fillet the edge where a pin joins a face

Hole proximity to wall edge		
Design variable	Minimum distance to edge	
Hole diameter	vertical hole (v)	horizontal hole (h)
2.5 mm (0.098 in.)	0.8 mm (0.031 in.)	0.8 mm (0.031 in.)
5.0 mm (0.197 in.)	0.9 mm (0.035 in.)	0.95 mm (0.037 in.)
10.0 mm (0.394 in.)	1.05 mm (0.041 in.)	1.0 mm (0.039 in.)



Comments
Larger holes require slightly greater distances to the edges of walls

4.3.3 Designing for Vat Photopolymerisation (VPP)

Although many of the previously covered polymer design rules apply equally to vat photopolymerisation, there are certain guidelines that are specific to resin-based processes.

Resolution

Vat photopolymerisation resolution in the XY-direction is dependent on the laser spot size and can range from 50 to 200 µm. The smallest feature size can therefore not be smaller than the laser spot size.

Resolution in the Z-direction varies from 10 to 200 µm depending on the choices of layer thickness allowed by the machine. As with other AM technologies, choosing a very fine vertical resolution is a trade-off between speed and quality. For a part that has few curves or fine details, there will be little visual difference between a print at 25 µm and one at 100 µm.

Print orientation

When orienting a part for vat photopolymerisation, particularly on a bottom-up SLA machine that cures the part from the bottom and pulls it out of the vat of resin, the biggest concern is vertical cross-sectional area. The forces involved with a print sticking to the bottom of the tank are directly proportional to the 2D cross-sectional area of the print. Because of this, a part with large cross-sectional areas, is often best printed at an angle to the plate. Minimizing the cross-sectional area along the Z-axis is the best way to orient parts for vat photopolymerisation prints. Reducing the number of horizontal areas relative to the print orientation, hollowing out components and reducing the cross-sectional area are all steps that can be taken to optimize a design for vat photopolymerisation.

Support material

Vat photopolymerisation does require support material for overhanging features. This is because the uncured resin is not viscous enough to support features on its own. This support material must be removed in post-processing. On most vat photopolymerisation systems the process of adding support material to the part is largely automated but, with experience, the user can manually edit the supports to avoid having supports in areas where surface finish is critical.

Overhangs

Overhangs generally pose very little issue with vat photopolymerisation, unless the model is being printed without adequate support structures. Printing without supports can lead to warping of the print, but if printing without supports is necessary, any unsupported overhangs should be kept to less than 1.0 mm in length and at least 20° from horizontal.

Isotropy

Vat photopolymerisation is one of the AM processes where the parts are relatively low isotropic. This is because the layers chemically bond to one another as they print, resulting in near identical physical properties in the X, Y, and Z-direction.

Hollowing parts and resin removal

Vat photopolymerisation machines can print solid, dense models but, if the print is not intended to be a functional part, shelling the model to be hollow can significantly reduce the amount of material needed as well as reduce the print time. It is recommended that the walls of the hollowed part be at least 2 mm thick to reduce the risk of failure during printing. If printing a hollow part, drainage holes must be added to allow the uncured resin to be removed from the part. Drain holes should be at least 3.5 mm in diameter, and at least one hole must be included per hollow section, although two holes can make the resin much easier to remove.

Details

Embossed details (including text) include any features on the model that are raised slightly above the surfaces around them. These must be at least 0.1 mm in height above the surface of the print to ensure the details will be visible.

Engraved details (including text) include any features which are recessed into the model. These details are at risk of fusing with the rest of the model while printing if they are too small, so these details must be at least 0.4 mm wide and at least 0.4 mm deep.

Horizontal bridges

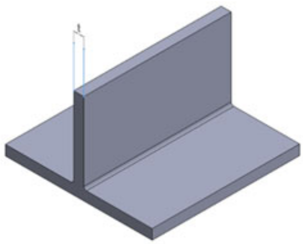
Bridges between two points on a model can be successfully printed, but one must keep in mind that wider bridges must be kept shorter (usually under 20 mm) than thin bridges. Wider bridges have a greater cross-sectional area of contact which increases the chance of print failure during delamination from the bottom window.

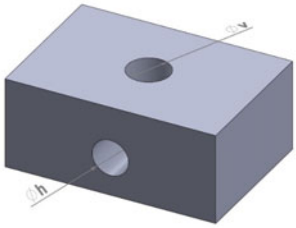
Clearances for connecting parts

If parts are being made that need to connect together, it is always best have a certain tolerance between the parts that fit together. For vat photopolymerisation, these tolerances are typically:

- 0.2 mm clearance for assembly connections.
- 0.1 mm clearance will give a good push or snug fit.

If interlocked moving parts are being printed, then the tolerance should be 0.5 mm between the moving parts. The following pages contain guidelines on how to design features to be built using vat photopolymerization.

Wall thickness		
Minimum wall thickness for supported walls (t)	Minimum wall thickness for unsupported walls (t)	
0.4 mm (0.016 in.)	0.6 mm (0.023 in.)	
Comments Supported walls are walls that are connected to other structures on at least two sides, so they have very little chance of warping. These should be designed at a minimum of 0.4 mm thick. Note that if the supported wall has a large surface area, a larger thickness may be required Unsupported walls are walls that are connected to the rest of the print on less than two sides, and are at a very high chance for warping or detaching from the print. These walls must be at least 0.6 mm thick Always fillet the corners where one wall meets another wall to reduce stress concentrations along the joint In general, an even wall thickness is recommended on all walls, both vertical and horizontal		

Circular holes	
Minimum diameter h & v	
0.5 mm (0.019 in.)	
Comments Holes with a diameter less than 0.5 mm in the X, Y, and Z axes may close off during printing	

4.4 Metal Design Guidelines

4.4.1 General Design for Metal PBF

Metal AM technologies can be broken down into the technology categories in the Fig. 4.14 below.

In this chapter we will give recommendation for powder bed fusion technologies based on lasers and electron beams, which are the most widely spread technologies for producing metal parts.

Metal powder bed fusion is an AM process in which thermal energy selectively fuses regions of a powder bed. Materials used include stainless steel, tool steel, aluminium, titanium alloys, nickel-based alloys, cobalt chrome, and precious metals

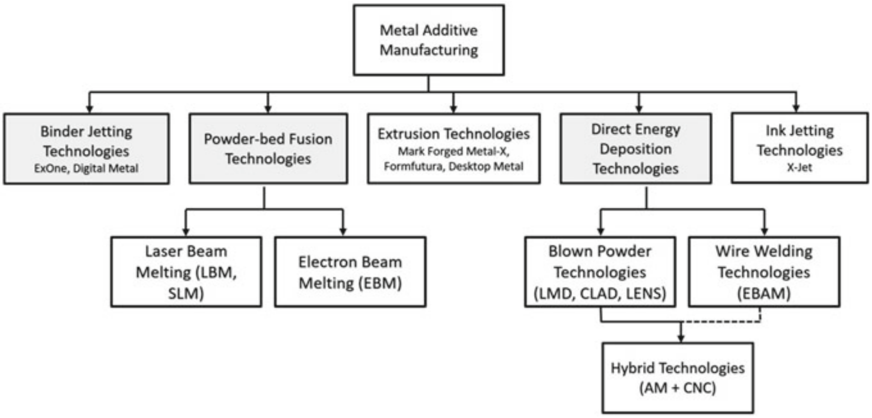


Fig. 4.14 Hierarchy of metal AM technologies (Courtesy of Olaf Diegel [1])

such as gold. The part being constructed normally requires supports (sometimes called anchors) to be added, built from the same material as the part. These supports are removed manually after the build process.

If we compare metal PBF AM parts to conventionally produced metal parts, AM parts, with no post-processing other than support material removal and shot-peening, would perform as follows (Table 4.7):

With suitable post-processing, however, AM parts can, in some cases, approach the mechanical properties of forged or wrought parts.

The PBF-LB/M AM process

The powder bed fusion process begins by spreading a thin layer of powder onto the build plate, and an energy source is then used to scan the powder and fuse it together where required. The process is then repeated for subsequent layers (Fig. 4.15).

As metal AM is an expensive process (see the chapter on the economics of AM for details), and parts can require substantial post-processing, you need to have a good reason to make a metal AM part. In general, parts that are not specifically designed for metal AM are not worth doing with AM. There are exceptions to this, like spare

Table 4.7 Performance of AM parts compared to conventionionally produced parts

	Mechanical properties	Surface finish
Sand cast	AM Superior	AM Superior
Investment cast	AM Superior	AM inferior
Wrought or forged	AM inferior	AM inferior

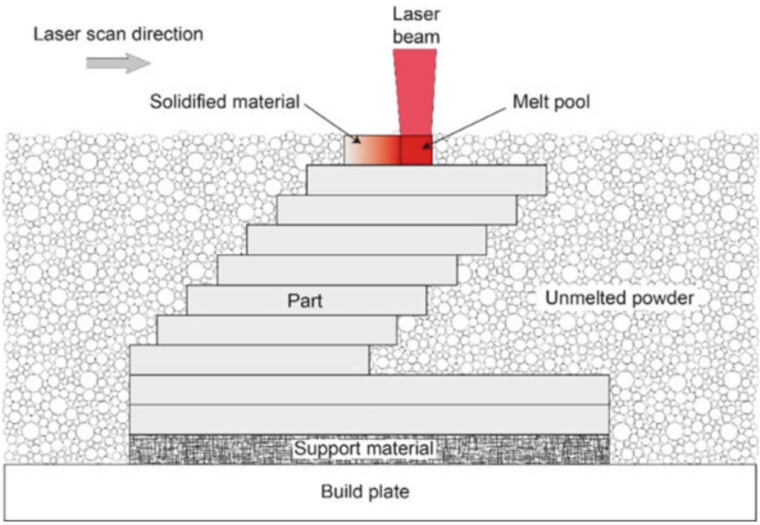


Fig. 4.15 The overall metal AM build process (Courtesy of Olaf Diegel [1])

parts for example, but, in general, the geometry of the part should be complex enough that it cannot easily be made through traditional manufacturing.

Topology optimisation

Because of the high costs associated with metal AM, topology optimisation is an excellent technique to apply to metal parts. Because one of the benefits of AM is its ability to make very complex geometries, topology optimisation, which can often create cell-like biologically inspired structures, offers the ability to make much lighter components than with conventional manufacturing. Please refer to the chapter on topology optimisation for further information on how to apply this technique to additive manufacturing.

Lattice structures

Lattices are another excellent way of producing light-weight parts, but extremely strong, parts that can also reduce the time and cost it takes to make metal AM parts. A lattice is a cellular structure made of repeated unit cells to form a larger volume. There are many options for the shape and size of such lattice cells, and for the pattern in which they are is repeated. Lattices can be uniform, where the same cell size is repeated in all directions of the part, or variable, where the size and spacing of the cells is different in different directions. There are four main techniques for applying lattice structures to additively manufactured parts:

Convert the entire part into a lattice

This technique transforms the entire volume of the part into a lattice structure (Fig. 4.16). It is commonly done for medical implants, and parts where the exterior surface of the part is not critical.

Fill the inner body of the part with a lattice structure, leaving an outer shell of a specified thickness:

In general, this method requires salt-shaker holes so that the unsintered powder can be removed from inside the part. If designed correctly, the internal lattice structure (Fig. 4.17) also acts as the support material for heat transfer within the part.

The part is subdivided into solid and lattice areas

Here a conscious decision is made as to which features of the part remain solid, and which get converted to lattices. The easiest way to achieve this is usually to split the part up into its different regions in the native CAD software the part was created in, and to then import the separate parts into the lattice conversion software to convert the required parts into a lattices while leaving those that must remain solid untouched (Fig. 4.18). Once this is done, a Boolean operation can be performed to join the lattice parts and solid parts to form a single part ready for AM.

Variable lattice structure based on FEA results

This uses any of the above techniques but, instead of a constant cell-sized lattice, uses a lattice structure where the cell size and spacing varies based on a finite element

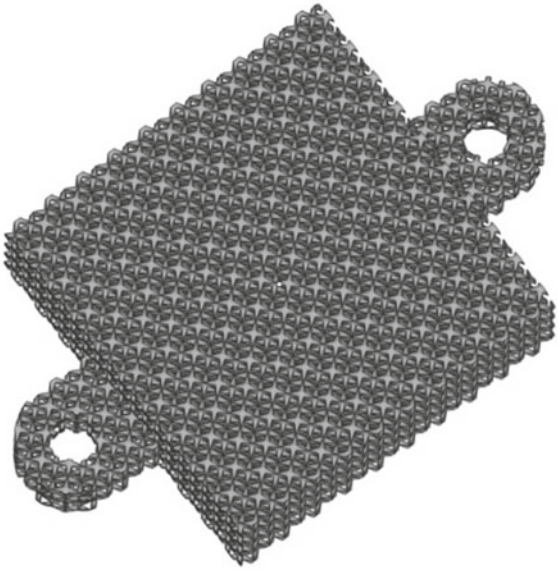


Fig. 4.16 Complete lattice structure (Courtesy of Olaf Diegel [1])

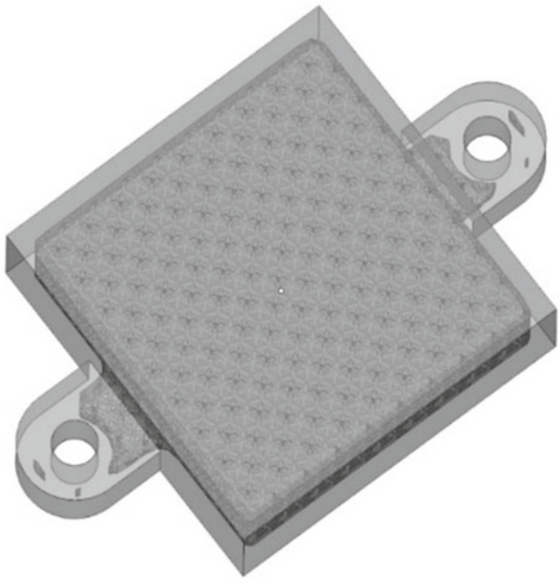


Fig. 4.17 Interior lattice structure (Courtesy of Olaf Diegel [1])

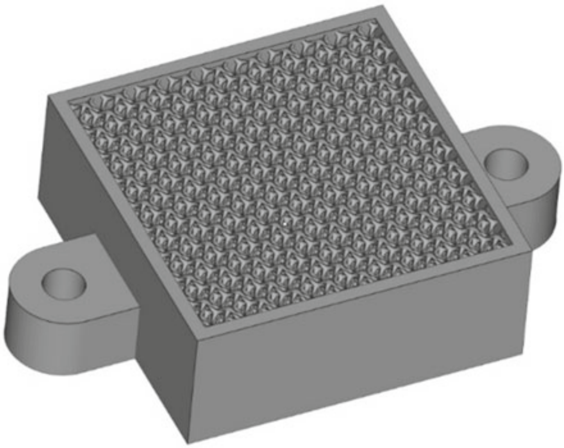


Fig. 4.18 Hybrid lattice structure (Courtesy of Olaf Diegel [1])

analysis to produce a dynamically-sized lattice structure. The more highly stressed areas of the part wither use thicker lattice members, or a denser spacing of the lattices.

The strut diameters used in lattice structures must be of a diameter such that they can both be manufactured as well as provide the required mechanical properties to the part. Theoretical minimum strut diameter for metal AM is around 0.15 mm. Common sense, however, tells us that a 0.15 mm strut will have relatively little mechanical strength or resistance to fatigue. A more sensible minimum strut diameter to use is, therefore, between 0.5 mm to 1 mm.

When designing lattices, it is important to use lattices that are self-supporting and can be printed without requiring support material. It is possible to have horizontal struts, but they must be short enough to have a surface area below that which requires support material. In the lattice cell shown below (Fig. 4.19), if forces are applied in the directions shown, then design B will resist the force better than design A, but

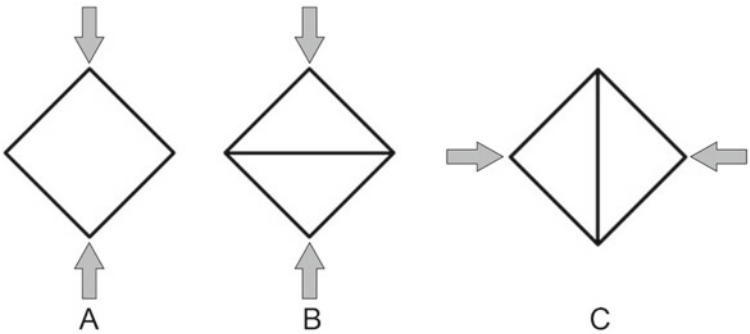


Fig. 4.19 Lattice cell A is weak against the forces, Lattice B is stronger but hard to print because of the horizontal strut. Lattice C both resists the forces and is easier to print (Courtesy of Olaf Diegel [1])

may not be printable because of the horizontal strut. If, however, the cell is printed after being rotated by 90 degrees as shown in C, it will resist the forces and it will print better.

Overhangs and support material

Though it may sound like repetition, it is important to emphasize that supports are absolutely critical in the production of metal AM parts. Supports should not only be considered during part design but can become one of the factors that influence AM part design. The angle and surface area of any overhanging feature of the part determine whether the part will require supports. It is almost always a trade-off to orient the part for minimum build time, easy to remove supports (particularly from inside the part), surface quality, and part warpage. Some aspects will improve, while others deteriorate, depending on the support material being used.

In metal AM, support structures have several functions:

- Support the part in case of overhangs.
- Strengthen and fix the part to the building platform.
- Conduct excess heat away.
- Prevent warping or complete build failure.
- Prevent the melt-pool from sinking down into lose powder.
- Resist the mechanical force of the powder spreading mechanism on the part.

Most metal AM pre-processing software allows the selection of a number of different support types, each of which has different heat transfer and mechanical strength characteristics. Some of the support types offered by most AM preparation software include solid, walls, trees, cones, lattices, blocks, points, lines, webs, and gussets (Fig. 4.20). Which type of support to use very much depends on the part geometry, and how much residual stress it will contain, and how hard the support material will be to remove. The best advice to understand the effect of different types of support offered by your system is to design a part made up of a series of bridges, under which each bridge is printed with a different type of support. The effect of each type of support can then be observed, both in its impact on surface finish and on removal difficulty.

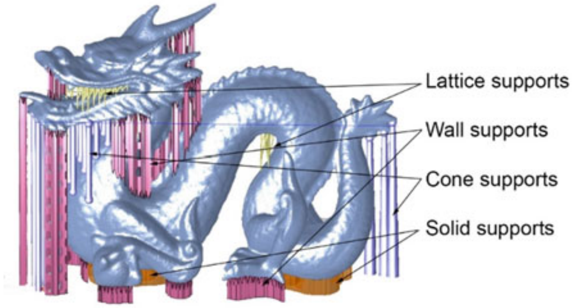


Fig. 4.20 Examples of different support types. Note that these are just used to show examples of different types of support material, and may not be ideal for this particular part (Courtesy of Olaf Diegel [1])

Printing parts with large horizontal surfaces

Parts with large horizontal areas of material will require much stronger supports than the rest of the part. This is because the sudden change in cross section to a large molten sheet of material will cause substantial stress and will, in all likelihood, cause cracks in the part if the support is not very strong and dense. In such situations, one must sometimes use 'solid' supports. If at all possible, parts should be oriented so as to avoid large horizontal flat areas, or sudden changes in surface area.

Angle for support material

A general guideline for angles that do not require support material are angles greater than 45° from horizontal. This does, however, vary from material to material and machine to machine. Specific angles relevant to particular materials are given in the table on "Feature type: overhang angle" later in this chapter. Some manufacturers specify angles from horizontal, while others specify them from the vertical. Remember also, that these angles represent the minimum angle at which the part can be produced without supports. In general, using angles that are steeper than those minimum, will yield parts with better surface qualities.

Unsupported angles, overhangs, and bridges

The area melted at the focal point of the energy beam cools very quickly and the stress generated tries to curl the material upwards. Supports act as an anchor to the build plate to avoid such upward curl.

Angles

Poor surface roughness is the result of building directly on loose powder instead of using the support structure as a building scaffold. It occurs because the laser penetrates the powder bed and agglomerates loose powder around the focal point instead of dissipating the heat through the support structure. At a certain point, the unsupported angle becomes such that the part either has an unacceptable surface quality or crashes the recoater mechanism.

Overhangs

Overhangs differ from self-supporting angles in that they are abrupt changes in a part's geometry, such as a small feature that protrudes horizontally at 90 degrees. Powder bed fusion is fairly limited in its support of overhangs when compared to other 3D printing technologies. In general, any design with an overhang greater than 0.5 mm (0.020 in.) will require additional support to prevent damage to the part. As an overhang extends past about 0.5 mm, the surface quality either becomes unacceptable, or the upwards curl can become such that it causes the recoater mechanism to crash.

Bridges

A bridge is any flat down-facing surface that is supported by 2 or more features. The minimum allowable unsupported distance for the powder bed fusion process is around 2 mm (0.080 in.). Parts that exceed this recommended limit will have poor quality on the downward facing surfaces and may not be structurally sound. They can also cause the recoater mechanism to crash.

Residual stress

One of the most challenging aspects of producing good metal AM parts is residual stress. Like any welding process, metal AM induces a substantial amount of stress on the parts. This is one of the reasons why support material is often needed on metal parts. This residual stress and stress concentrations must be relieved through heat-treatment before the parts are removed from the build plate. Residual stress can, in some cases, be so large that it causes the entire build plate to bend, or the part to detach from the build plate, or crack the part itself. Residual stresses are stresses that remain in a solid material after whatever caused of the stresses has been removed.

Residual stress can occur from a variety of mechanisms including:

- temperature gradients existing from the surface to the centre of AM part during cooling (particularly in large masses of material) where the inside of the part cools slower than the outside of the part.
- inelastic (plastic) deformations.
- structural changes (phase transformation).
- Heat from the laser may cause localized expansion which, in AM, is taken up by either the molten metal or sections of the part that have already solidified. When the finished part cools, some areas cool and contract more than others, leaving residual stresses.

The very best solution to combatting residual stress is to try and eliminate as much of the residual stress out of the part as possible through its design

Designing to reduce residual stress

There are a number of relatively simple design techniques that can be employed to minimize residual stress. These include:

- Get rid of areas of uneven thickness. Large masses of material are the single biggest, but easily avoidable, source of residual stress.
- Try to avoid large changes in cross-section. This may, sometimes, mean having to print your component at an orientation other than horizontal.
- Pre-heat the build plate.
- Heat the build chamber.

In addition, many of the design rules for conventional casting apply equally to metal AM.

If large masses of material are completely unavoidable (which is rare), use different laser hatch parameter settings to minimize the build-up of residual stress.

- Smaller chess-board hatch patterns will, for example, create less residual stress than bigger ones, or than large scan areas. But they will slow down the build process a bit.

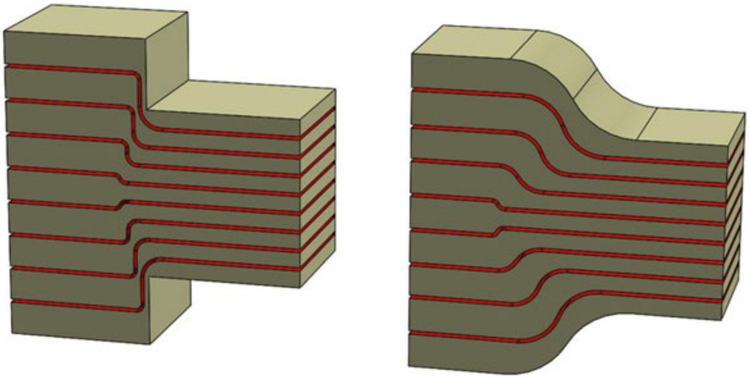


Fig. 4.21 Stress concentrations are the areas where cracks will most naturally form. Eliminating such stress concentrations can be critical to part quality (Courtesy of Olaf Diegel [1])

- Rotate each hatch scan, usually by 67°, for each layer.

Ultimately, some residual stress is unavoidable. The real question, however, is whether it will affect the function of the part. A well designed for AM part, however, can often require minimal, or no, heat treatment compared to a part that has not been designed for AM.

Stress concentrations

A stress concentration is a location in a part where stress is concentrated. These stresses occur both within the AM fabrication process, and in the heat treatment of AM parts. With metal AM, this is a design opportunity where a well-designed part can minimize the areas of stress concentration. Fatigue cracks almost always start at areas of stress concentration, so removing the areas in which such defects can occur can minimize such defects and greatly increases the fatigue strength of the part (Fig. 4.21).

The best way of minimizing the amount of heat treatment required is to design your parts to have as little stress induced or concentrated in them as possible. Simple strategies, like filleting all sharp corners (reduces stress concentrations), even wall thicknesses, and avoiding large masses of material (reduces residual stress), can help a lot. In the simple part below (Fig. 4.22), for example, the sharp internal corner has a good chance of causing a stress crack. In addition, the sharp corner has a larger mass of material than the horizontal and vertical walls and will, therefore, contain some residual stress which could cause the wall to distort. In contrast the filleted corner has eliminated the possibility of a stress crack, and it is even wall thickness has minimised the potential of residual stress.

Horizontal holes

In metal AM, horizontal holes (or holes angled below the minimum support angle) over a certain diameter will require support material inside the hole. For pipes that

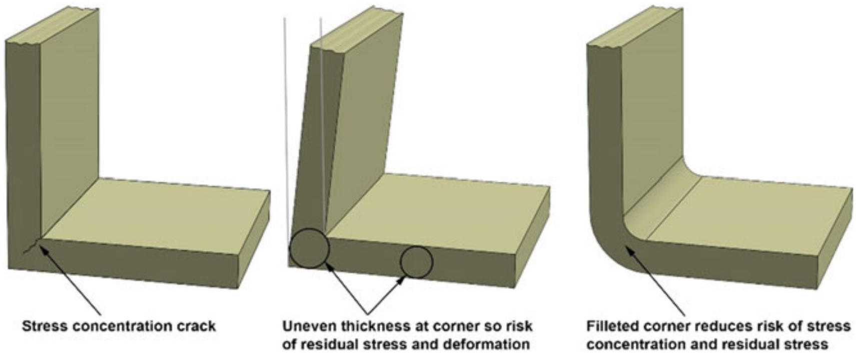
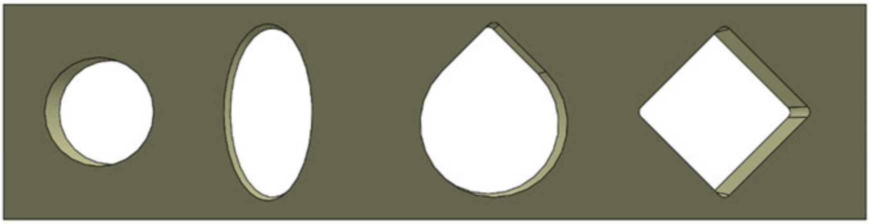


Fig. 4.22 Example of simple filleting to eliminate both stress concentrations and residual stress (Courtesy of Olaf Diegel [1])

are not straight, in particular, the support can be hard to remove from inside the pipe. As a general guideline, holes below a diameter of 8 mm (0.314 in.) can be printed without supports. If larger diameter holes are required, the most common technique is to change the hole from circular to a shape that can be printed without the need for support material. These shapes commonly include ellipses, teardrops, and diamonds (Fig. 4.23).

4.4.2 Design for Laser Powder Bed Fusion (PBF-LB/M)

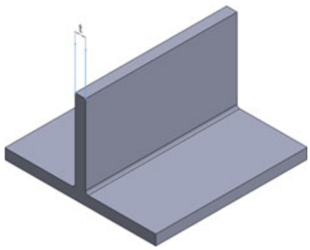
The design guidelines below apply to laser powder bed fusion metal processes. The guidelines will vary from machine manufacturer and model to machine manufacturer and model so, if in doubt, it is recommended to print a test piece to verify each set of design parameters.



Round holes can, generally, be built without support up to a diameter of around 8mm. Holes larger than this will require supports. Note that this diameter varies based on the machine and material used.	Elliptical holes, when the height of the ellipse is twice the width, can be printed to about 25mm tall, depending on the system being used.	Teardrop shaped holes can be printed to almost any diameter providing the top angle is no less than the minimum support angle. It is good practice to fillet the top of the teardrop to avoid a stress concentration.	Diamond shaped holes can be printed to almost any size. It is good practice to fillet the corners of the hole to avoid stress concentrations in the corners.

Fig. 4.23 Hole shapes that can be printed without the need for support material (Courtesy of Olaf Diegel [1])

The following pages contain guidelines on how to design features to be built using laser powder bed fusion.

Wall thickness		
Minimum wall thickness (t)	Recommended minimum wall thickness (t)	
0.3 mm (0.016 in.)	1 mm (0.039 in.)	

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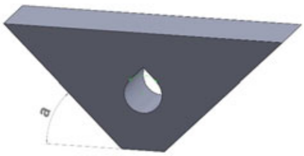
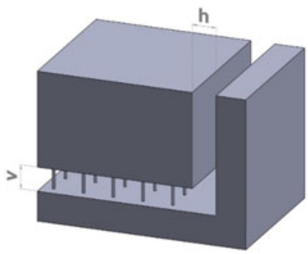
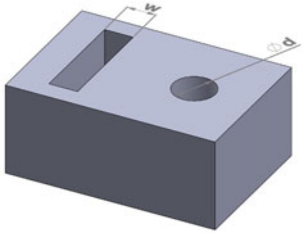
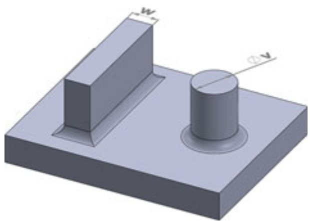
Comments
Problems may occur with extended lengths of unsupported walls (i.e., no ribs or intersecting walls). Without adequate reinforcement, large surface area thin walls are likely to distort. In this case, avoid using the minimum wall thickness, or reinforce the wall with ribs, gussets, or use extra support material to prevent it from distorting Always fillet the corners where the walls meet another surface. A good rule of thumb is to make the fillet ¼ of the thickness of the walls

Overhang angle		
Maximum overhang angle (a)		
DMLS stainless steel	60°	
DMLS inconel	45°	
DMLS titanium	60°	
DMLS aluminium	45°	
DMLS cobalt chrome	60°	
Comments Overhang angles less than the numbers shown above (measured from horizontal) will require support material, which may be added automatically by the system software. Excessive supports that need to be removed manually will increase post-processing time Beware that some manufacturers measure support angles from the horizontal, while others measure it from the vertical Feature shapes (e.g., cooling channel profiles) can often be modified to minimize support requirements, and horizontal holes less than 8 mm (0.236 in.) can be built without supports. Se the chapter of this book on the design guidelines for horizontal holes		

Clearance between moving parts		
Minimum clearance		
horizontal (h)	vertical (v)	
0.2 mm (0.079 in.)	Adequate access to facilitate the removal of support material	
Comments In general, with metal AM, all moving parts will need to be welded to the build platform, or connected to each other, so that they are now swept away by the recoater system. They only become moving parts once they have been cut off of the platform or the joining links have been cut Large areas of close proximity will make the removal of supports more difficult. Clearance between parts built separately and assembled later must be at least equal to the general build tolerance of the system		

Vertical slots and circular holes		
Minimum width for slot (w)	Minimum diameter for circular hole (d)	
0.5 mm (0.02 in.)	0.5 mm (0.02 in.)	
Comments As the thickness of the part increases powder inside the slots or holes may become hard, or impossible, to get out Values for horizontal features are not available as they are too dependent on each specific machine If possible, fillet all sharp internal corners to avoid stress concentrations		

Vertical bosses and circular pins		
Minimum width for boss (w)	Minimum diameter for circular pin (d)	
0.5 mm (0.02 in.)	0.5 mm (0.02 in.)	
Comments It is good practice to fillet the bottom of all pins and bosses. A general guideline is that the radius is ¼ of the thickness Values for horizontal features are not available as they are too dependent on each specific machine		

Built-in external screw threads

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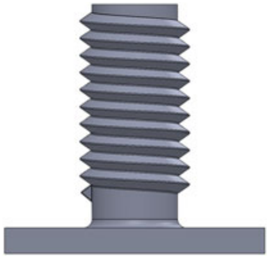
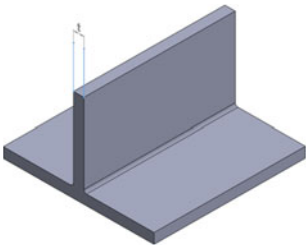
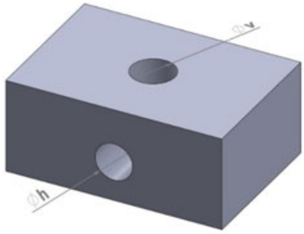
Threads should always be built vertically, if at all possible	
Comments Though threads down to about M4 can, theoretically be printed, their surface roughness means they will need to have a tapping die run over them to clean up the thread Tapping is recommended for all threads and sufficient space must be left around the post to allow access for the tapping die Fillet the bottom of the boss where it meets the wall to avoid stress concentrations. A good rule of thumb is to make the fillet ¼ of the thickness of the walls	

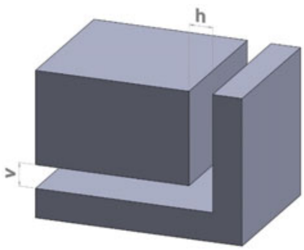
4.4.3 Design for PBF-EB/M Guidelines

Electron beam melting is a powder bed fusion process that uses an electron beam as the energy source to melt each layer of powder. The electron beam is controlled by electromagnets that move it over the powder in a controlled manner to draw the slices of the part to be produced (more in Sect. 1.7.2).

Wall thickness		
Minimum wall thickness (t)	Recommended minimum wall thickness (t)	
0.6 mm (0.032 in.)	1 mm (0.039 in.)	
Comments It is possible to build vertical walls with a thickness of 0.6 mm in solid material, but this can be difficult to achieve in all orientations and with walls of large surface area. A safe recommended wall thickness is 1 mm. For short lengths, such as in lattice structures, different melt strategies can be used so the part can be as thin as 0.3 mm. However, this is not suitable for structural walls as they can suffer from delamination or layer shift Always fillet the corners where walls meet each other		

Vertical slots and circular holes		
Minimum diameter for circular horizontal hole (h)	Minimum diameter for circular vertical hole (v)	
0.5 mm (0.02 in.)	1 mm (0.04 in.)	

Comments
Holes, slots or tubes built into EBM parts at any angle will be filled with partially sintered powder. This block of powder allows different diameters to be built without the need for supports but can be hard to remove unless access to the hole is easily done with blasting media or with hand tools, so this must be considered during the design stage
A minimum diameter of 1 mm vertically or 0.5 mm horizontally is recommended to ensure that rough surfaces do not cause the holes to close up
In walls thicker than about 2 mm, vertical holes will generally need to be no smaller than 2 mm and, for horizontal holes, no smaller than 1 mm

Clearances to remove powder		
Minimum clearance		
horizontal (h)	vertical (v)	
1 mm (0.04 in.)	1 mm (0.04 in.)	

Comments
As there is a partially sintered cake of powder surrounding the parts that are built, access must be given to allow trapped partially sintered powder to be blasted away from small gaps, holes and mechanisms. Larger spaces may have to be included around complex parts to ensure the cake can be removed. In general, 1 mm clearance is usually sufficient to thermally isolate each part on the build platform

Screw and threads

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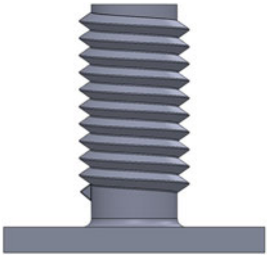
Threads should always be built vertically, if at all is possible	
Comments Because of the relatively rough surface finish of EBM, all threads will need to be tapped/machined Fillet the bottom of the boss where it meets the wall to avoid stress concentrations. A good rule of thumb is to make the fillet ¼ of the thickness of the walls	

References

1. Diegel, O., Nordin, A., Motte, D.: A Practical Guide to Design for Additive Manufacturing. Singapore: Springer Singapore (2019)
2. Wohlers Associates, Inc.: Wohlers Report 2018. 3D Printing and Additive Manufcaturing State of the Industry. Fort Collins, CO, USA: Wohlers Associates, Inc (2018). Available online at https://wohlersassociates.com/2018report.htm. Checked on 25 May 2020

Chapter 5
General Process Simulations

Axel Nordin, Per Kristav, Julia Ureña Alcázar, José Ramón Blasco, Olga Jordá Ferrando, Mario Martínez, and Luis Portolés

Simulation of AM products can capture a number of aspects. Apart from the traditional types of simulation of the end product, such as mechanical, thermal and fluid analyses, it is possible to simulate the AM build process. While simulating products intended for AM can sometimes be performed in exactly the same way as with products intended for traditional manufacturing, there are several aspects that may require a specialized workflow. In particular, the great benefit of AM in offering "complexity for free" is also a major challenge in simulating the part performance. In this section, a review of the various tools and methods for simulating AM products will be made.

This chapter will be structured according to the basic workflow of setting up a simulation, that is, a geometry needs to be defined and most often discretized, material properties need to be defined, boundary conditions need to be applied, analysis settings need to be defined and results need to be interpreted, as illustrated in Fig. 5.1.

5.1 Simulation

5.1.1 Geometry Definition

The task of defining the geometry for analysis is obviously a part of the design process, which is dealt with in other chapters of this book, but some aspects are worth noting regarding simulation.

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D. Godec et al. (eds.), *A Guide to Additive Manufacturing*, Springer Tracts in Additive Manufacturing, https://doi.org/10.1007/978-3-031-05863-9_5

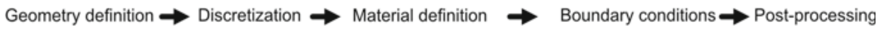

Fig. 5.1 Simulation workflow (Courtesy of Axel Nordin)

Fig. 5.2 Left: Original part intended for manufacture. Right: Simplified model intended for optimization (Courtesy of Axel Nordin, original model by Olaf Diegel)

Simplification

A geometry intended for production is often not ideal for simulation. More often than not, simplification steps need to be taken to make it feasible to analyse the geometry. However, since many use cases of AM relies on exploiting "complexity for free" it is not always straightforward to exclude complex features from the analysis. Traditionally, features such as non-structural rounds, lettering, screw threads, small holes etc. are eliminated from the geometry before analysis (as seen in Fig. 5.2). This can either be done through the original modelling software, or through specialized pre-processing defeaturing software. This process is largely manual and often requires considerable effort if the model is complex. Moreover, it is important to not oversimplify the model by removing features that may initially look irrelevant to the performance of the product.

When dealing with models intended for AM, it may not even be possible to simplify away features such as lattice structures or organic shapes with many rounds. Although computing power is ever increasing, many simulations of highly complex lattice structures may not be currently feasible to run, at least not if several iterations of the design are expected. There are approaches, such as homogenization, where complex small-scale structures are replaced by a solid material that replicates the properties of the structure. These approaches, however, require additional work to characterize the material response and are not easily applicable when the small scale-structure varies in, for instance, lattice member diameter.

Facet-Based and Parametric Models

Traditionally, the geometry intended for simulation is represented in a parametric CAD format, such as STEP. Parametric formats represent curved surfaces as, for instance NURBS (Non-uniform rational basis spline), which can in turn be discretized into finite elements or volumes with varying density. As parametric models are represented by surfaces, it is straightforward to determine aspects such as curvature, which simplifies discretization and application of boundary conditions. Moreover, parametric models enable non-geometric data to be linked to the model, such as surface-ids and material data, which can help reduce some of the modelling effort when analysing several variants of the same basic concept.

However, within AM, it is common to have geometry represented as facetted polygon meshes in, for instance, the STL-format. As the facetted representation is already discretized and does not easily allow for the identification of surfaces such as planes and cylinders, facet-based models pose several challenges for simulation pre-processing. While there are some tools that simplify the selection of connected areas of triangles, these selections will typically only be valid for that particular mesh. If a slightly modified version of the model is to be analysed, all selections will have to be updated again manually.

There are several tools for transforming a facet-based representation into a parametric model, sometimes called reverse engineering tools. These tools analyse the facetted mesh to identify areas that can be represented as, for instance, cylindrical or planar surfaces and can fit NURBS geometry to the underlying facets. This makes discretizing and applying boundary conditions easier, but the process is computationally expensive, often requires manual adjustment and will need to be redone if the mesh is altered.

5.1.2 Discretization

For discretizing a facetted model without first translating it into a NURBS-representation, the main approach is to voxelise it. This process generates a number of volumetric elements, or voxels, approximating the facet-based model. The voxels are usually aligned with the coordinate system and may also be aligned to the face of the mesh, to better approximate the shape of the mesh, as shown in Fig. 5.3.

This is a robust method for making a facet -based model compatible with simulation and is less computationally expensive than re-interpreting the mesh as surfaces. Table 5.1 gives a summary of the advantages and disadvantages of the different methods.

Table 5.1 Summary of the advantages and disadvantages of the different methods

Method	Advantages	Disadvantages
NURBS translation	• Easier selection of faces • Better discretization options • Potentially more information about the geometry	• Computationally expensive to create • Often requires manual input • Needs to be redone with new facet-based model

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Method	Advantages	Disadvantages
Voxel-based	• Less computationally expensive than re-interpreting • More automated and stable	• Selection of faces requires more manual work • Fewer discretization options • Potentially more computationally expensive analysis

If you are doing the analysis for validation and will not be analysing several iterations, re-interpreting the geometry is probably a good option. If you are analysing several concepts or will be iterating on the design, voxel-based meshing is probably a good option.

5.1.3 Material Properties

While many research teams are very actively characterizing the material properties of AM parts, it is still hard to know beforehand what material properties the finished part will have. This is in principle due to the large number of parameters that affect the part properties, such as type of energy source (e.g. electron or laser beam), energy density, scanning strategy, powder properties, heat treatment, part geometry, part orientation, etc. While build process simulation tools can take many of these factors into account on a small scale, it is not currently feasible to simulate an entire product in such detail. Instead, most simulations are based on estimated properties calibrated from printed samples. Moreover, factors such as yield and ultimate strength, fatigue life, surface roughness, and thermal and electrical conductivity can only be estimated and need to be tested to ensure reliable results. As AM is inherently anisotropic, the material properties also vary in the different directions and need to be tested individually. Moreover, many AM methods produce parts with considerable residual stresses, which may need to be accounted for through, for instance, build process simulation. The produced geometry will also differ from the CAD-model, not only due to the tolerances of the machine, but more importantly due to the residual stresses and deformations. This effect will be more or less pronounced depending on the production method, part geometry, support strategy and heat treatment. Part warpage can be compensated for by build process simulation.

5.1.4 Boundary Conditions

Applying boundary conditions to AM parts is, in principle, no different from parts intended for traditional manufacturing. The only new challenge is if the model is facet-based, and thus lacks information about underlying surfaces and volumes, as shown in Fig. 5.4. Depending on the type of analysis, it may be beneficial to convert

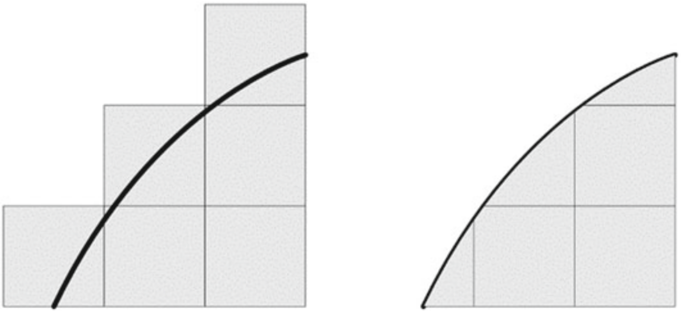

Fig. 5.3 Left: Orthogonal voxel meshing. Right: Face-aligned voxel meshing (Courtesy of Axel Nordin)

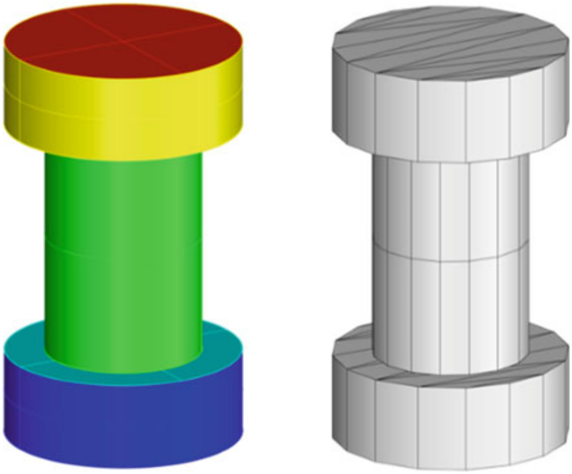

Fig. 5.4 Left: Parametric model with each individual surface represented by a different colour. Right: Facetted model with a single manifold surface (Courtesy of Axel Nordin)

the facet-based model into a parametric model using reverse-engineering tools such as SpaceClaim. Otherwise, the boundary conditions will have to be applied to individual elements after discretization. As this type of selection does not typically automatically update if the facet-based model is modified, applying boundary conditions for repeated analysis of similar designs can be time-consuming and is not easily automated.

5.1.5 Post-processing Results

Results need, as always, to be analysed with care. In AM products, that are often complex with many small-scale structures such as lattices, this is particularly true. Stress concentrations are not always immediately obvious and mesh independence should, as always, be checked for. However, due to the limitations of facet-based models in terms of resolving small features, it may not always be possible in practice to simulate the model as precisely as needed. Therefore, predictions about maximum stresses and fatigue life are not always accurate and should be validated through physical testing if the design is intended for critical applications. However, for concept design evaluation and comparison, the results should yield usable numbers.

5.2 AM Build Process Simulation

There are now several commercial vendors of build process simulation software. While they differ in several respects in terms of capabilities and material libraries, the basic principles and main features are similar. A build process simulation can take into account the layer-by-layer build process of a part including the machine-specific parameters, support material, heat treatment and the removal of support material (Fig. 5.5).

Fig. 5.5 Build process simulation workflow (Courtesy of Axel Nordin)

5.2.1 Geometry Definition

As geometry is commonly available in facetted formats, the simulation software supports both parametric and facet-based formats. To fully capture the effects of parameters such as build-plate heat conduction and the effects of surrounding loose powder, the part needs to be positioned in the same position and orientation as it will be built in. Apart from the product geometry, the geometry for the support material also needs to be defined or imported. Some software can automatically create support material based on the part geometry, but it is often more convenient to generate the support material geometry in a dedicated build preparation software.

5.2.2 Discretization

As models are often facet-based, voxel-based meshing methods are common for build-process simulation. This is a robust and convenient way of discretizing complex non-parametric models, but the amount of detailed control over the discretization is limited. Separate discretization settings for support and part geometries is usually

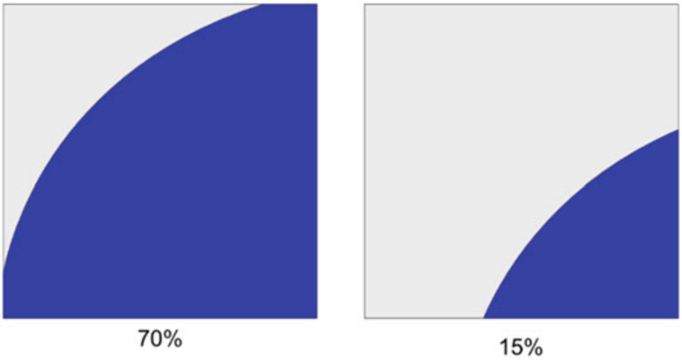

Fig. 5.6 Left: A voxel filled to 70% by the model geometry. Right: A voxel filled 15% by the model geometry (Courtesy of Axel Nordin)

possible to reduce the computation time. As voxel-based discretization often has the same voxel-size throughout the model, it may not be possible in practice to fully resolve small features such as lattice structures. Instead, a sort of homogenization of the small-scale features is possible in some software. Homogenization in this case means that the properties of each voxel is based on how much of its volume is filled by the actual geometry, as illustrated in Fig. 5.6. It is, however, important to make sure that the voxel-size is chosen with respect to wall-thicknesses and minimum feature sizes in the model.

5.2.3 Material Definition

The material properties are typically provided by the software vendor.

5.2.4 Build-Process Parameters

To fully represent the build-process, the intended AM machine needs to be described. This is typically done by inputting information such as energy densities, scan speeds, layer heights, scan strategies. However, unless a full thermo-mechanical simulation of the beam-path is done, other approaches for approximating the material behaviour during printing is needed. Typically, this is achieved by printing and measuring a set of calibration specimens, designed to capture information about the residual strains in the material in different directions, as shown in Fig. 5.7. This type of calibration data, however, is only valid for a particular set of build-process parameters, and thus needs to be done again if, for instance, the laser power or scan strategy is altered.

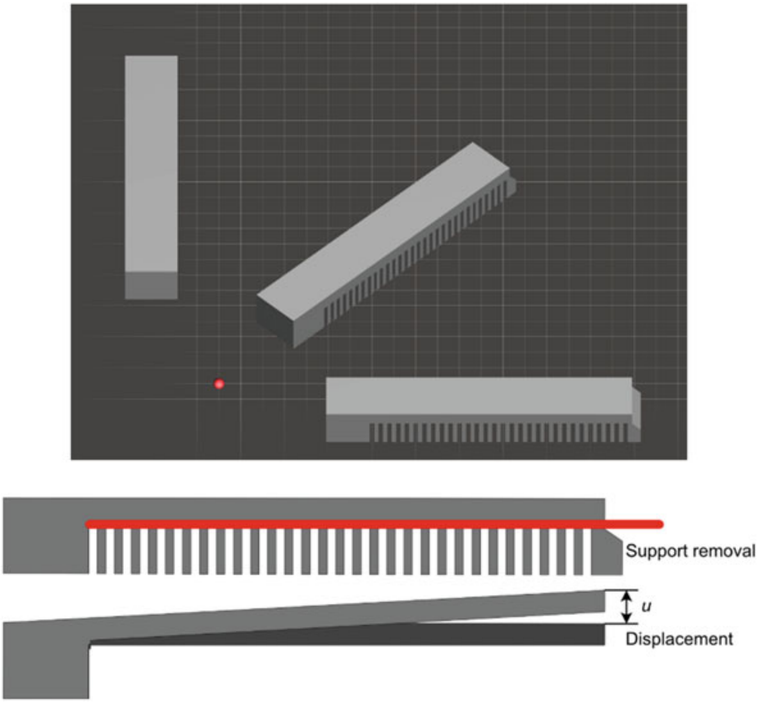

Fig. 5.7 Top: Calibration specimens printed in different orientations. Bottom: Measurement of part warpage as support is removed (Courtesy of Axel Nordin)

Using calibrated data like this allows for several layers to be simulated in bulk, greatly reducing the computation time.

5.2.5 Post-processing

Commonly available results include stresses, strains and deformations, but most software can also display plots of likelihood of part failure, likelihood of recoater impact, missing layers due to deformation of the part during print. Additionally, it is common to be able to export a deformation-compensated version of the original model, where the predicted deformations of the part due to the build process are used to compensate the geometry in the opposite direction. As there is no direct relationship between the deformations and the correct compensation, several iterations of simulation, compensation and re-simulation may be needed to reach a geometry that is sufficiently close to the original model to meet the dimensional specifications.

5.2.6 Limitations

While build-process simulation is becoming more common and the accuracy and computational efficiency is increasing, it is still best used for a rough estimate of problems that may arise during printing and to rule out completely unfeasible build-orientations or designs.

5.3 Optimization

As with any design, optimizing the part performance is crucial. Design optimization can be done in a number of ways, such as size optimization and topology optimization. Size optimization is often done on parametric models to fine-tune dimensions and is a relatively well-established field with many commercial software options. While size optimization is a very general method that can be applied to almost any optimization problem where constraints and objectives can be quantified, it quickly becomes unfeasible as more parameters are added. On the other hand, topology optimization can quickly indicate where material should be added or removed from a design to optimize its performance. However, topology optimization is limited in the types of constraints and objectives that can be handled and is thus not as general as size optimization.

5.3.1 Topology Optimization

Methods for topology optimization (TO) started being developed around the same time as additive manufacturing. Due to the organic and often quite complex shapes produced through topology optimization, the usefulness of the approach for products intended for traditional manufacturing methods has been limited, but with AM the number of feasible applications has grown. The number of commercial software intended for TO has grown quickly over the last years, as has the number of applications. At its core, topology optimization is used to minimize or redistribute material within a design space according to certain constraints and objectives, such as minimizing the compliance or deflection of the part. While TO has mainly been used for structural applications where light weight is of importance, other types of physics are possible (e.g. thermal, fluid flow, eigenfrequencies). Topology optimization for AM is not limited to applications where the end product needs to be as light as possible, for instance within the aerospace industry, but is also beneficial for reducing the print cost and production time.

TO can largely be divided into 8 steps.

1. Define design space
2. Define non-design space

3. Define boundary conditions
4. Define constraints and objectives
5. Define optimization settings
6. Solve
7. Interpret the results
8. Validate.

5.3.2 Define Design Space

The design space is the volume within which the TO algorithm can redistribute material. In order to give the optimization algorithm, the best possible starting point, the design space should be as large as possible. An overly constrained design space will not allow the algorithm to find the optimal load paths, as illustrated in Fig. 5.8. A good starting point can be to look at the interfaces to other components that need to be respected. It is also beneficial to reduce the complexity of the design space as much as possible, that is, to remove unnecessary details like small rounds, threads, decorative elements or holes. Another factor in determining the design space is build size limitations of the intended machine. As with any optimization decision, iteration may be necessary to find the optimal design space if the results indicate that the optimal load carrying path exists outside of the design space.

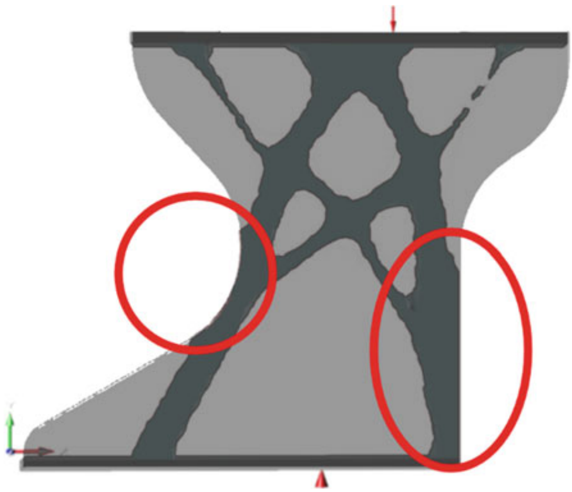

Fig. 5.8 Areas where the design suggested by the topology optimization coincide with the design space boundary typically indicate that the design could be improved if the design space is expanded (Courtesy of Axel Nordin)

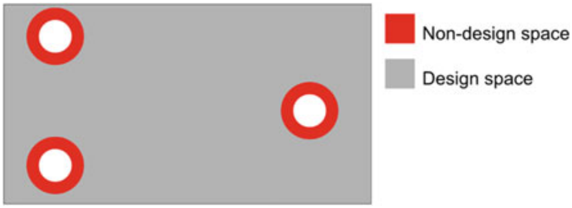

Fig. 5.9 Non-design space regions around areas with boundary conditions (Courtesy of Axel Nordin)

5.3.3 Define Non-design Space

As surfaces where the product interfaces with other parts, such as fasteners or bearings, should remain unaltered by the optimization, these should be marked as non-design space. While it sometimes is possible to simply exclude them entirely from the design space, it is often convenient to be able to apply boundary conditions on the non-design spaces, as shown in Fig. 5.9.

5.3.4 Define Boundary Conditions

As with any analysis, the boundary conditions need to be chosen with care. They should as closely as possible represent the real loading of the part. It is easy to, for instance, add a constraint that will take up forces in all directions, whereas in reality the support might only take up forces in compression. However, many topology optimization software are limited to conducting linear analyses, where, for instance, compression only supports may not be available. In those cases, special care needs to be taken to ensure that the supporting area is sufficient for the loads during validation.

As most structures will be subject to several different loads during operation, it is important to make sure that all major loads that may act on the part are represented. If one is missing, the optimization will typically recommend a design that is weak in that direction. A good strategy may be to add a new load case for each force acting on the structure.

5.3.5 Define Constraints and Objectives

There are a number of possible constraints and objectives that may be set up for TO. The most commonly available objectives include minimizing the compliance (*i.e.*, maximizing the stiffness) and minimizing the mass. These objectives will obviously not generate useful design by themselves and need to be coupled to constraints. For instance, minimizing the compliance is often linked to a constraint on the percentage of the volume that should be retained. Minimizing the mass is often linked to a constraint on the stresses or deformation of the part. As knowing beforehand what the optimal design should weigh is impossible, it is recommended to experiment with several percentages. It is also worth mentioning that stresses calculated during TO are only rough estimates, and do not necessarily correspond to the results calculated during validation. The topology optimization can remove or change the mechanical properties of individual elements which makes it difficult to accurately predict the stresses. Moreover, the mesh density that is suitable for TO is not necessarily suitable for stress calculations. While research is being done into how to get more accurate stress values, it is recommended to add additional constraints to the optimization, such as deflection, to get more robust results.

Apart from structural constraints, many software vendors have added support for taking AM-specific manufacturing constraints into account. One can, for instance, reduce the need for support material by adding an overhang constraint, which limits the number of surfaces with an angle below the defined support angle and build direction. As the build direction may not initially be known, however, it may be beneficial to run optimizations in several build directions to evaluate the difference in build height, amount of support material, and part performance. It common for the overhang constraint to be contradictory to the structural objectives, and thus there is often a need to compromise between the amount of support material and the part performance, depending on whether cost or performance is more important.

5.3.6 *Define Optimization Settings*

Most software will allow the user to define parameters such as mesh density and minimum feature size. The mesh size affects the level of detail that the resulting geometry will have, and of course the computation time. In theory, the finer the mesh, the more optimal the results (as for instance Michell structures shown in Fig. 5.10), however, computational limits and production constraints will typically mean that the mesh size is fairly coarse, compared to traditional FEA meshes. This also means that traditional TO is not suitable for generating structures with the typical lattice structures, and other approaches are needed for generating them.

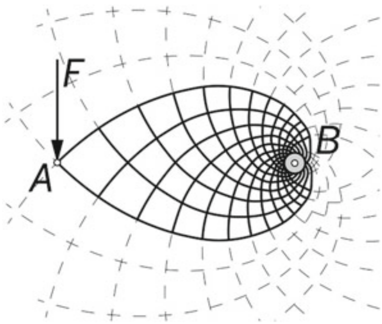

Fig. 5.10 A Michell structure (Courtesy of Arek Mazurek). https://commons.wikimedia.org/wiki/File:MichellCantilever.jpg

5.3.7 Solve

Solution time will go up with the number of load cases and the mesh density. While reducing the number of load cases to reduce the computational time may be tempting, doing so will yield results that are not useful. Reducing the number of elements, on the other hand, will not typically affect the overall distribution of material, but will only have local effects. For initial optimization of concepts, it is therefore recommended to adjust the number of elements.

5.3.8 Interpret the Results

The results from a topology optimization is most commonly in the form of a mesh-based model, although there are a number of experimental methods that aim to make the process from optimization to manufacturing more streamlined. While it could be possible to directly print this part, doing so is often not preferred, as the mesh from the TO is quite coarse, may have many stress concentrations, and may not fit well with interfacing components. Due to this, there is a need to remodel the mesh-based result to make it suitable for manufacturing and use. There are three main approaches for this, as illustrated in Fig. 5.11:

1. Mesh-based smoothing
2. NURBS interpretation
3. Manual re-design.

Mesh-Based Smoothing

There are several tools for smoothing the facet-based result and many smoothing algorithms. While this may produce satisfactory results for one-off prints, the facet-based model will not have any link to the initial CAD model, and it will be difficult and time consuming to do parametric changes to it, such as increasing dimensions.

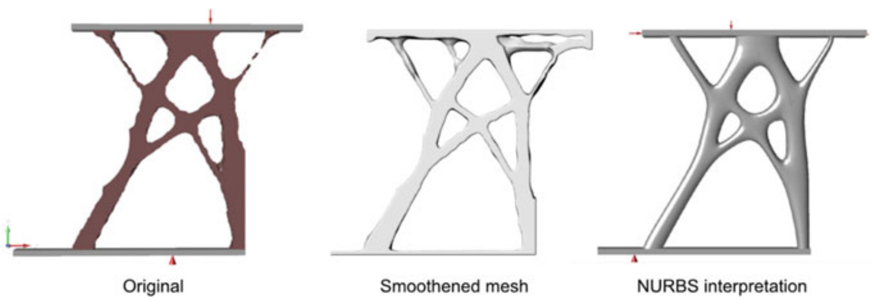

Fig. 5.11 Approaches for post-processing the topology optimization result (Courtesy of Axel Nordin)

NURBS Interpretation

There are several tools for reverse engineering a facet-based model into a parametric model, as discussed earlier. Some require manual input, and some are more automated, but all will require some amount of manual manipulation to get good results. Although these tools generate parametric models, the complexity of them is often very high, with few planar or cylindrical/spherical surfaces. Moreover, the model is "dead" and there is no information about the features or design intent. This makes it difficult and time-consuming to continue working with the model in standard CAD-packages, and the models are not easily parametrically controllable, if changes to the dimensions need to be done or if one wants to conduct a size optimization.

Manual Re-design

This method is obviously the most time-consuming, but also generates a model with high parametric controllability and design intent. If the model is to be further adapted for manufacturing or optimization, manual re-design is usually the most straight-forward option.

5.3.9 Validate

A design validation always needs to be done on the reinterpreted model as the results reported during the TO are not usually very accurate.

5.3.10 Topologic Design with Altair Software

1. **Software Selection**

Once the initial geometry evaluation for PBF-EB/M technology is completed, it is time to optimize the geometry using the computer tools. The software selected is Altair Inspire and the main reasons for this selection are explained below:

– It is an easy computer tool to navigate in its menus and it has a very intuitive interface.
– It is useful to obtain the first approximation to the optimized shape. The optimization process is complex and needs the model to be able to evolve in different phases and taking into account diverse factors.
– It allows obtaining fast results, avoiding the difficulties of selecting types of elements and meshing. As will be seen, this is both an advantage and a handicap when there are problems associated to the automatic mesh.

Figure 5.12 exhibits the workflow of Altair Inspire: geometry setting, case loads assignment, analysis and optimization, results evaluation and CAD model translation.

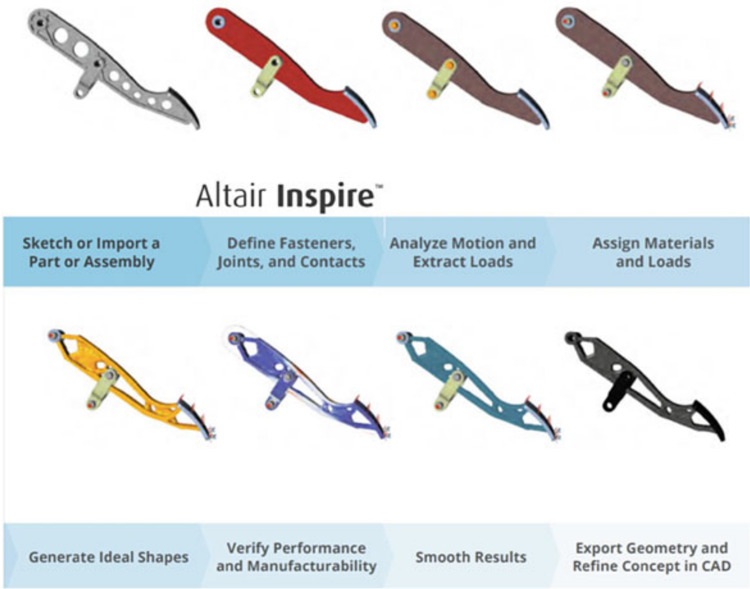

Fig. 5.12 Workflow of Altair inspire (https://www.altair.com/inspire/) (Courtesy of Altair)

2. **Geometry**

First of all, it is important to learn the available abilities to create and modify the models. It is crucial to develop the initial geometry and widen the software´s optimization options. Generally, all the space available inside the maximum volume of the part should be included in the optimization process unless there are technical reasons not to, such as mounting space or interferences with other parts in its normal function (Fig. 5.13).

Simplifications are also required with these kinds of tools. In order to speed up the calculations, it is recommended that all the small fillets, rounds or chamfers that are not necessary in the structural behaviour should be deleted. This deletion should pay special attention to not include simplifications that can introduce significative errors in the results. Nonetheless, the final optimized shape should be validated afterwards through a new analysis.

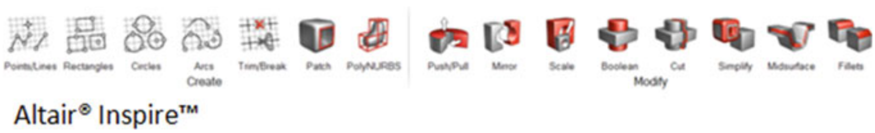

Fig. 5.13 Altair inspire geometry tools (https://www.altair.com/inspire/) (Courtesy of Altair)

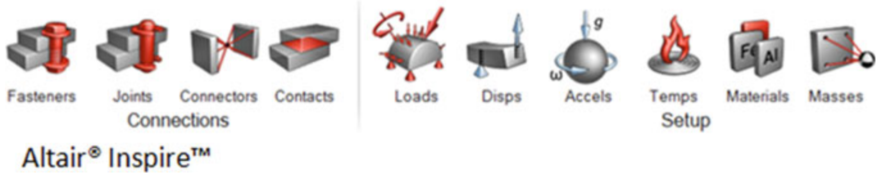

Fig. 5.14 Altair inspire case setup tools (https://www.altair.com/inspire/) (Courtesy of Altair)

Linked to the optimization process and the software layout, a distinction between design parts and non-design parts is required. Therefore, all parts that will have loads or constrains must be defined as non-design parts. To meet this requirement, the user should adapt the model using the geometry tools.

3. **Load Cases Setup**

After completing the geometry modifications, the load cases that will feed the software must be set in order to obtain the optimization. The typical tools to set loads such as forces, pressures or torques and constrains in any freedom degree can be easily found and applied in this software (Fig. 5.14), as in many other CAE software. Furthermore, in most cases, it is also necessary to set fasteners, joints or connectors to bond the parts.

Other less usual conditions that the selected software (Altair Inspire) allows us to add are imposed displacements, accelerations, temperature conditions and concentrated masses.

Contact definition between parts can also be found in this section and it offers us the possibility to define the faces in contact as bonded, contacting or without contact.

In this section, the material properties to the components also need be set. The more accurate these properties are, the more trustworthy the results will be. However, it is also important to know that this software does not allow anisotropic materials setting and this is a significant deficiency because additive technologies normally require this material behaviour. The way to compensate this deficiency and assure safety is to consider the weaker properties. That is, the structural problem is solved as an isotropic material. Again, it should be mentioned that this optimization is a first stage and the final design will need to be validated.

4. **Analysis/Optimization**

On one hand, an option to perform structural analysis is included. Before the analysis can be launched, the user has to set the analysis parameters. The software chosen includes only a few parameters that can be modified: mesh size, contact's type and accuracy. This is due to the simplicity and navigability of the software concept.

The analysis can be completed before and after the optimization. It is good to analyse it prior to the optimization to know the stress level or the model behaviour, in order to help the user, set the parameters in the optimization set up. The analysis is performed after the optimization to check the proposed shape in the different load cases. However, this second analysis can display high levels of stress concentrated in specific points because the raw model shape has imperfections that will be removed in the final model.

On the other hand, the optimization analysis offers different approaches depending on the objective. It can maximize the stiffness or minimize the mass. For the stiffness maximization, the program needs the mass target. For the mass minimization, the safety factor is required.

All of these analyses require the parameters of mesh size (defined as thickness constraints), level of accuracy (faster/more accurate) and contact's assumption (sliding only/with separation). In case of error, the user can modify the size mesh. Reducing it can help avoid meshing problems due to geometry imperfections. An alternative option is suggested: to check and correct the geometry imperfections, since this reduces the work time increase that would result if a smaller mesh size were used.

Finally, the user can select what load cases are used in the optimization. It is not possible to assign different weights to each load case directly. Different weight assignments need to be made through new load cases modifying the load.

5. **Results/Comparison**

The results should be evaluated visually first. Some cases can give us incomplete shapes with reinforcing linking elements that are not fully developed. If it happens, there are two options: (1) the user can modify the result directly, increasing the mass with a slider tool included in the software, or (2) the optimization can be recalculated, increasing the level of mass or the safety factor.

The junction between design and non-design spaces is usually a week point and also needs to be evaluated to decide if it would meet the structural requirements. These issues can be pointed out as difficulties, even if they are accepted, they should be checked in the next phases (Fig. 5.15).

The next step is to establish the goals and to select the results that allow the evaluation and comparison in the different optimized models. The most used results are the stress level, the safety factor and the displacement. The software has utilities

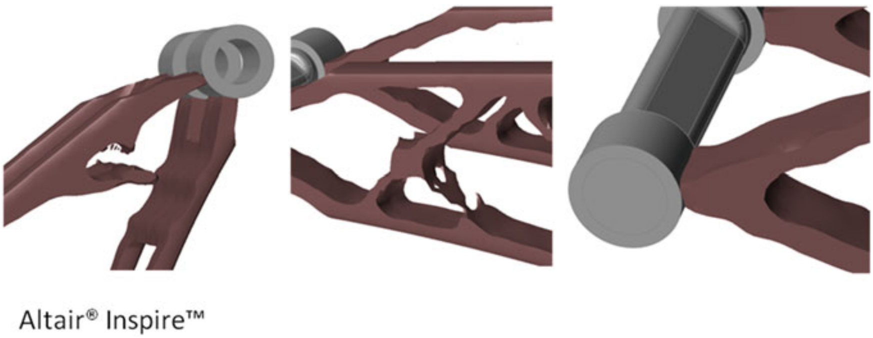

Fig. 5.15 Optimization issues (https://community.altair.com/community) (Courtesy of Altair)

Fig. 5.16 Comparison results (https://community.altair.com/community) (Courtesy of Altair)

to assist us in the comparison process, by displaying the selected outcomes in every optimization case (Fig. 5.16).

The user has to be aware that models include the imperfections generated in the optimization process and that the surface roughness is not considered. These two points can lead to an overestimation of the model in fatigue cases. This is a common issue in PBF-EB/M technologies because they have considerable surface roughness. A validation check is strongly suggested to be carried out considering this factor after the optimization.

6. Conversion From Optimized Result to Buildable Geometry Model

The conversion of the selected optimized model to a buildable geometry model can be done in the proposed software by three means:

- Save as STL model and design it in the CAD Software.
- Normally, it is not possible to save the optimized model directly as a parametric model. Therefore, it can be saved as a STL model which can be treated by the CAD software. The user can build a smooth and buildable model following the shape of the STL model.
- Use polinurbs tools to acquire a parasolid.
- The software used (Altair Inspire) includes the option to build a parametric model directly. It does not offer the usual tools of CAD software and sometimes the process can be time consuming and does not offer the same freedom to modify the model. However, this option is recommended if you do not have other software or it is a small and easy model.
- Use the automatic adjustment.
- The new version of this software offers the option to automatically adjust the resulting shape to a polinurbs model. It is fast and produces a buildable parametric model. However, it sometimes creates a large quantity of faces to adapt to the initial shape. It can be a problem to manage or modify the model but saves the time in the production of the initial adaptation (Fig. 5.17).

Fig. 5.17 Automatic adjustment tool (https://community.altair.com/community) (Courtesy of Altair)

7. Key Observations

The use of the proposed software offers a good approximation of an optimized structure in a reasonable time. However, depending on the use, the final design may need to pass an additional structural analysis.

The user should take into account that AM may leave a considerable surface roughness and that fatigue is not considered in this optimization process, for the applicable cases.

There are multiple options to achieve an optimization and it can be difficult to manage all the results and evaluate them. It is recommended to define the selected measurable factors first.

The tools to adapt the optimized shape to a CAD model are being improved. Nonetheless, the adaptations might still be complex when the user tries to translate the model between the different software.

Lattice structures can help lighten the SLS study models, but they may increase the difficulties in their use on the CAD software and the 3D printer machine.

5.3.11 Topologic Design with Altair Software for PBF-EB/M

As PBF-EB/M is a technology that needs to build supports, the software has a specific tool to set a limit and optimize the geometry adapted to this manufacturing process. This tool is applied if the model exceeds the slope degrees limit from the fusion bed. This tool is called Overhang shape control in Altair Inspire software. It allows users to set a maximum degrees/angle from the baseline prior to the analysis, however, this requires a decision on the building direction and this decision will condition the result (Fig. 5.18).

This tool is very useful for PBF-EB/M because the use of supports can be avoided. The main limitations include: that the user has to define the building direction; once set, the tool will not consider the use of supports and this can entail a heavier result. If one of the main goals is mass reduction, this option will probably not be

Fig. 5.18 Altair inspire overhang tool (https://www.altair.com/inspire/) (Courtesy of Altair)

the appropriate approach. For mass reduction the material should be used to build supports instead of reinforcing the model.

A suggested workflow to optimize the use of this tool would be to try each piece with and without the tool and subsequently, check if adding supports uses a lesser amount of material.

- **Example 1. Topological optimization of a demo bracket for Ti6Al4V processed by PBF-EB/M**

This is an example of topological optimization for a structural AM part suitable for the aeronautical sector. Figure 5.19 shows the original bracket, the optimization result and the polynurbs geometry.

Different options of topological optimization are represented in Fig. 5.20.

Fig. 5.19 Topological optimization. Bracket for PBF-EB/M technology (*Source* Skin Project—AIDIMME)

Fig. 5.20 Different options of topological optimization. Ti6Al4V bracket processed by PBF-EB/M (*Source* Skin project—AIDIMME)

5.3.12 Topologic Design with Altair Software for PBF-LB/P (SLS)

Since PBF-LB/P technologies do not need supports in the building process they offer flexibility in regard to the model shape. The only shape restriction will be to consider the spaces required to ensure the dust removal. The available utility to create lattice structures can be interesting in this type of manufacturing technologies due to its capacity to lighten the model even more.

The process of optimization with lattice geometries follows the same premises aforementioned, but adds an additional optimization using the model generated by the first result. Apart from the objective and contact parameters, the user has to set the percentage of lattice structure, the target length of the bar elements and the minimum and maximum values of the bar elements' diameter. The software will provide a result substituting the base material by bar elements following the lattice structure percentage given (Fig. 5.21).

On the contrary, the use of lattice structures with too many bars may be a problem for the CAD software or the file management by the 3D printer machine.

As a reminder of the material properties, the user has to be aware that the results do not take in account the surface roughness in case of fatigue loads. Therefore, the model needs to be validated properly.

- **Example 1. Topological optimization of a demo bracket for PA12 processed by PBM-LB/P (SLS)**

Same example as PBF-EB/M case. Figure 5.22 shows the original bracket volume together with three optimization results where a volume reduction up to 87.62 % can be found.

Optimized AM parts processed in polyamide by PBF-LB/P technology can be observed in Fig. 5.23. After production, mechanical testing are performed to evaluate the mechanical behaviour.

Fig. 5.21 Altair inspire lattice optimization (https://community.altair.com/community) (Courtesy of Altair)

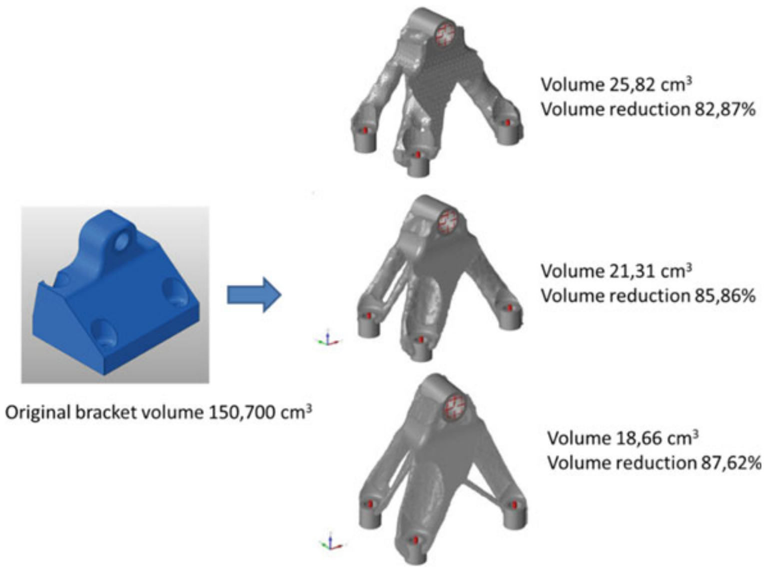

Fig. 5.22 Topological optimization of a bracket for PBF-LB/P technology—volume reduction. (*Source* Skin project—AIDIMME)

5.4 Lattice-Based Topology Optimization

As traditional TO is typically not suitable for generating very fine structures with high complexity, hybrid methods have been developed. There are different approaches,

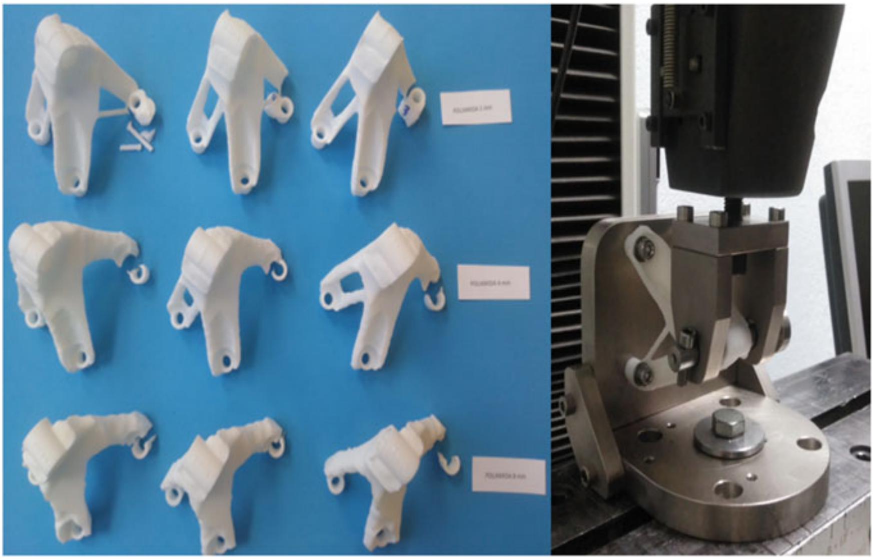

Fig. 5.23 SLS optimized parts in polyamide and mechanical testing (*Source* Skin project—AIDIMME)

some create a free lattice structure from the underlying geometry, and some rely on a cell-based approach. The cell-based approaches first determine an optimal pseudo-density field within the design space, and based on this density field, a lattice geometry can be generated. The general workflow is to define the lattice type, define the cell size, define the wall/strut thickness, define the minimum/maximum density, solve, interpret the results and validate.

5.4.1 Lattice Type

The lattice type can range from simple lattices like cubic trusses to more complex shapes like gyroidal or other triply periodic minimal surfaces. The lattice shape should be chosen with respect to the type of loading the part will be subject to, and with respect to printability and build orientation. One should be especially careful to avoid lattice types which require support material in larger cell sizes.

5.4.2 Define the Cell Size

The cell size will determine the dimensions of each lattice cell. While small cell sizes may be useful for creating self-supporting structures, larger cell sizes will be computationally more efficient to generate and validate. Moreover, large cell sizes may be beneficial for getting loose powder out after printing.

5.4.3 Define the Shell Thickness

As many applications require a smooth outer surface, it is usually possible to define a shell thickness of the geometry where the lattice structure is excluded. The choice of thickness depends on the application, but in order for the lattice structure to have any effect, it should be chosen as small as possible.

5.4.4 Define the Minimum/Maximum Density

The density will affect how thick the walls/struts in each lattice cell are. As a very low density may result in non-buildable wall thicknesses, it is important to set a minimum density requirement. Exactly what the lower limit should be depends on the machine and on the software, so some experimentation may be required. Additionally, a very high density will lead to lattice cells with very small openings, which, in turn, make powder removal difficult. Therefore, a maximum density should also be set. A good starting point may be 20% minimum density and 80% maximum density.

5.4.5 Interpret the Results

The results from the optimization is either a geometry or a density field, but there will typically be built-in tools for converting the density field into a facet-based model. As the lattice-structure itself should not need any further manipulation, it does not need to be converted into a parametric format. Depending on the software and output lattice structure, some sort of mesh smoothening may be beneficial to reduce stress concentrations.

5.4.6 Validate

Validation of lattice structures is difficult as the complexity is very high, the models are typically facet-based, and depending on the lattice shape, there could be many stress concentrations (Fig. 5.24). Moreover, as lattice structures do not lend themselves to easy post-processing, the surface finish can be rough and be detrimental to fatigue life. Therefore, lattice structures in critical applications, especially where cyclic loading will occur, is not recommended without physical validation.

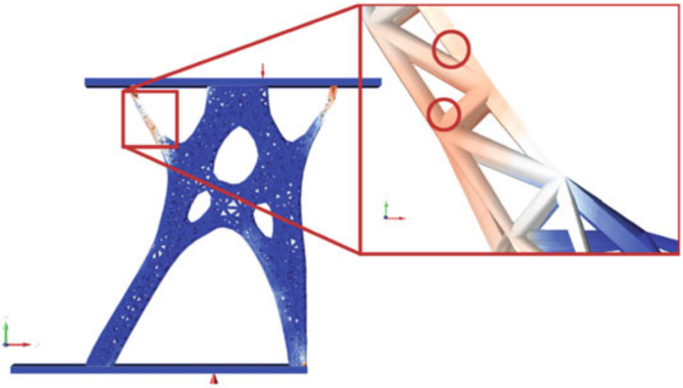

Fig. 5.24 Stress concentrations in lattice-based design (https://community.altair.com/community). (Courtesy of Axel Nordin)

5.5 Non-parametric Mesh Modelling

Non-parametric modelling normally starts from the 3D data obtained from a scanned object. A laser scans an object in three dimensions. The result is points is space, or rather a “point cloud”. This point cloud is triangulated into a mesh before the non-parametric modelling starts. Common formats are the obj (object) and the stl (stereo lithography)-formats. The mesh may later be cleaned, repaired and altered according to the operators’ demands. The scanners that are the easiest and fastest to operate are normally the scanners that are intended for the consumer market. Some of these are handheld and can for example be attached to an iPad, see Fig. 5.25. Football sized objects can easily be scanned by turning the object by hand or by simply waking around the object. The disadvantage with these scanners is the low scanning precision. The precision is, in practice, at best $+-2$ mm. The top end of the handheld scanners operate in a similar fashion, but with higher precision, they are however more complex to operate and the entry level price is about 7000 €.

The number of different types of scanners on the market is immense, they may scan everything from wear and tear on small mechanical parts to the topography of entire landscapes. Another type of scanners are the ones that are not handheld. What they all have in common is that the scanning unit is fixed or mounted on an axis controlled by for example a step engine. These scanners can offer precision up to about $+-0.01$ mm depending on the circumstances. Some of these scanners have the appearance of a box with a door and with a rotating plate to place the object to be scanned at the bottom. Naturally they come in different sizes. One drawback is that they have to have rather large dimensions if one, for example, intend to scan a human head or a human limb for later prosthesis manufacture.

The non-parametric manipulation of a mesh let the user change the density of the mesh according to his or her demands. Ideally, the mesh is made as light and with as few vertices and triangles as possible without jeopardizing the description

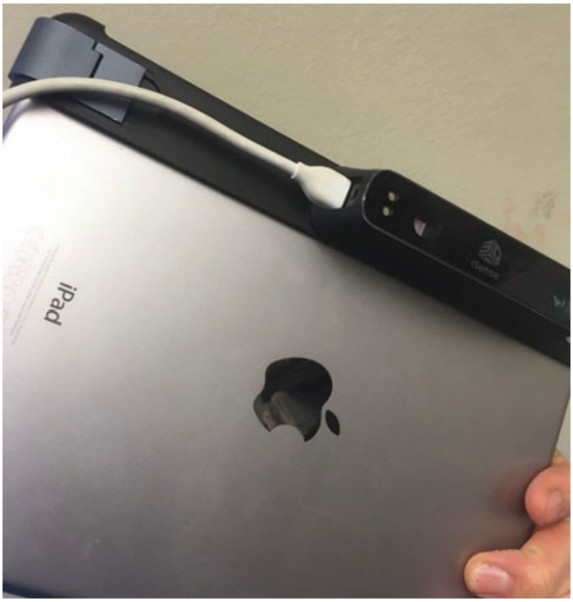

Fig. 5.25 An iSense scanner attached to an iPad (Courtesy of Per Kristav)

relevant for the surface at hand. The minimal number of triangles to describe a perfectly straight rectangular surface is two. Double bent surfaces require a far greater number of triangles, and hence a more dense and complex mesh to be described with sufficient accuracy. Non-parametric mesh modelling will however let a user to add and reduce the complexity of the mesh locally according the requirements on the surface accuracy.

Normally when an object has been scanned or a CAD file has been saved in order to be able to print the object one loses some of the information. The scanned object is no longer identical to the fully defined measurements of the product, and its original CAD/Step file. This causes problems if one wants to continue to manipulate a scanned object or want to return a 3D print file to parametric software. A solution to this shortcoming is to deploy non-parametric modelling. Exact measurements may, in some circumstances, be of marginal importance. The purpose may for example be to print a human bone, or an object with a purely aesthetical purpose. In these cases, only the scale, level of detailing and quality of the surfaces are important. Another example is if one wants to print or make a mould from for example a scanned branch from a three, or a seashell.

When one has turned such objects to digital data for further form manipulation one has, as mentioned, converted the original surface into a mesh. This mesh can be kept as a mesh surface or be converted into a solid mesh body. There are however several mesh formats. What they all have in common is that they triangulate the surface of a volume into a triangular mesh. First, when this has been done, one may let 3D printer software slice this mesh into slices. This process is however, an obligatory and last step also for parametric CAD models to be able to print in 3D.

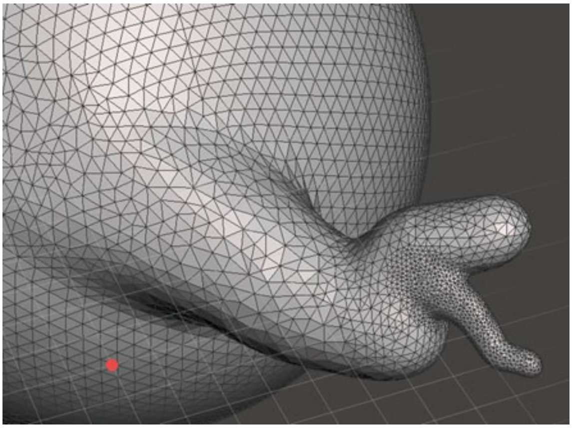

Fig. 5.26 An example of a mesh that has been manipulated non-parametrically by drag and inflate tools (Courtesy of Per Kristav)

Non-parametric CAD-programs such as, for example, MeshMixer and MeshLab let the user manipulate a mesh as in Fig. 5.26 rather than like parametric CAD software as, for example, Creo and SolidWorks that normally produce the mesh only as a last conversion strep to facilitate 3D printing. One may nowadays however, import a mesh in some traditional parametric CAD software, but it is still a delicate, restricted process that require a mesh of limited complexity.

The actual manipulation of the mesh can in some cases be described as working in real clay, but on a 2-dimentinal computer screen. The main tools in Meshmixer and Meshlab could be divided into three main types. One type is filters. Meshlab have a great selection of different mesh filters. A typical function of a filter is to repair a mesh with undesired holes, reduce mesh complexity with a mathematical formula, or make a "ruff" mesh more complex or smoother. Another type of tools are different sculpt and brush tools that let the operator manipulate the mesh locally. A typical function of such a tool let the operator to drag, inflate, smoothing, flatten or move a selected part of the mesh as in Fig. 5.27. The last type are tools that let the operator offset, duplicate, transform, shell, solidify and merge/subtract different mesh bodies from each other. There are numerous software on the market for the manipulation of meshes. Some focus on repairing and "cleaning up" damaged meshes, some focus on optimizing mesh complexity whilst others let the operator create new interesting forms with for example "un-proportional scale" and "sculpt" tools.

The drawback with the mesh format is that it will always present a soft double bent surface as a number of straight triangles, and the claylike manipulation will not result in fully defined surfaces as in parametric software. The strength is that a user may create amazing organic forms that would be next into impossible or very time consuming to create with parametric modelling by deploying extrusion of two-dimensional sketches, this is exampified in Fig. 5.28.

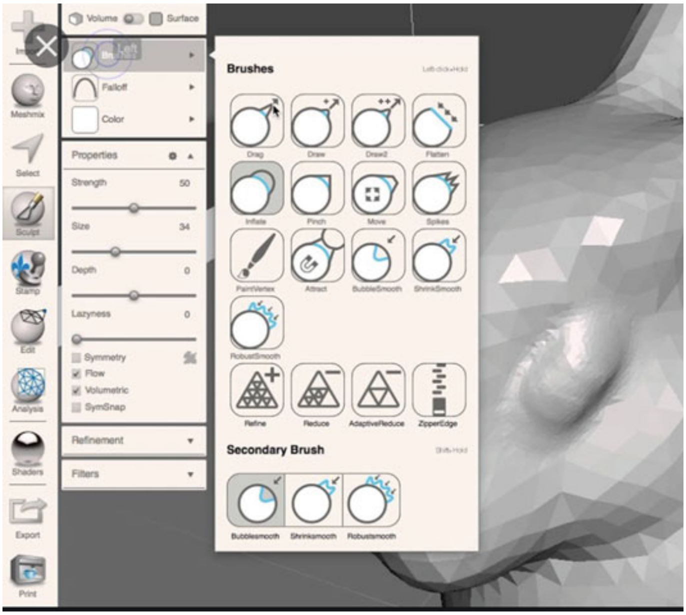

Fig. 5.27 The brush tools for non-parametric modelling in MeshMixer (Courtesy of Per Kristav)

Fig. 5.28 An example of a result a of non-parametric mesh modelling (Courtesy of Per Kristav)

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Chapter 6
Applications of AM

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6.1 AM in Tool Making Application

Application of AM in toolmaking can be historically considered as a second wave of AM application (so-called Rapid Tooling). Although AM processes are mainly considered as a process for final production, their potential can be used for making tools for conventional production processes (e.g. injection moulding of polymers). Processes of design and production of complex tools such as moulds for injection moulding of polymers are typically the bottlenecks in development and production process of final products and strongly influence their time-to-market.

One of the trends at the market is shifting from mass to custom production which requires more flexibility in tool production processes. Therefore, the main objectives of AM in toolmaking application is to reduce lead-time required to make the tools, as well as to improve the efficiency of the tools (shortening the production cycle time and improvement of parts produced in the tools).

At the end of 20th and in the beginning of twenty-first century there was a lot of excitement about AM application for toolmaking, but requirements for the tools for serial or mass production (e.g. for injection moulding) and AM possibilities are not in accordance. AM in toolmaking applications is exposed to very strict demands because of common processing parameters for such tools (e.g. pressures, temperatures, impact loads, abrasion, etc.) which must be wear resistant, with very narrow dimensional tolerances and with high surface quality.

Injection mould inserts have to fulfil combination of three main requirements:

- strength $\geq$ 500 N/mm^2

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- dimensional accuracy ≥ 0.01 mm
- surface roughness (R_a) ≥ 1 μm.

At the moment, the mentioned requirements (especially the last two ones) have not been achieved on the market of the AM equipment and materials. However, all the companies in the field are continuously trying to meet these requirements. This refers especially to the speed of the manufacturing, precision of dimensions and forms, and the number of materials that can be processed by AM technologies. Also, the properties of usable materials are being continuously improved, contributing to the improved properties of final products. In this way, the differences between traditional procedures of mould production and alternative AM technologies are expected to be reduced in the future.

AM application for toolmaking can be realised in three ways:

- production of *short-run tools* (mainly polymer (soft) tools)—10–100 shots
- production of *bridge tools*—up to several 1.000 shots
- production of *hard tools*—up to several 100.000 shots.

In case of short-run tools, only a few moulded parts can be produced within such tools before moulds are worn or damaged. Example of this type of tools is silicone mould (Fig. 6.1). The main advantage of this tooling approach is that such tools can be produced within one day, the process is very simple and the costs are relatively small.

A small-batch production of a hundred to a few thousand parts can be run with so called bridge moulds (Fig. 6.2). Final number of produced moulded parts depends on applied materials (paper, metal, polymers, etc.). Bridge moulds can also be produced in relatively short time (from one day to few days), which also depends on applied materials and additive technologies. Bridge tools for injection moulding are not intended to be replacement for soft or hard tools used in mid- and high volume production. Instead, they are intended to fill the gap between soft and hard moulds as well as a substitute for 3D printed prototypes.

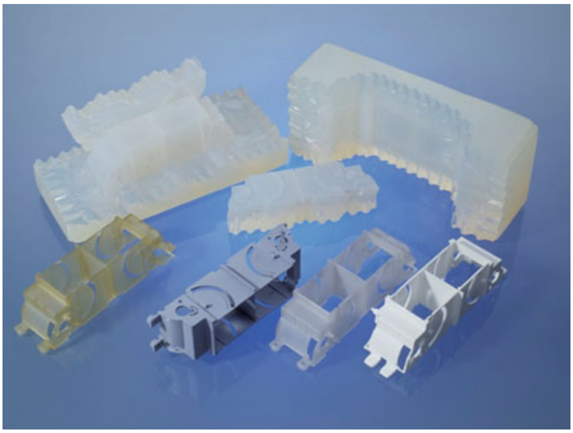


Fig. 6.1 An example of AM silicone mould: left—original 3D printed part, top—4-piece silicone mould, bottom—3 mouldings in different materials (www.scott-Am.com, Courtesy of Ronald Simmonds, photographer Giulio Coscia)

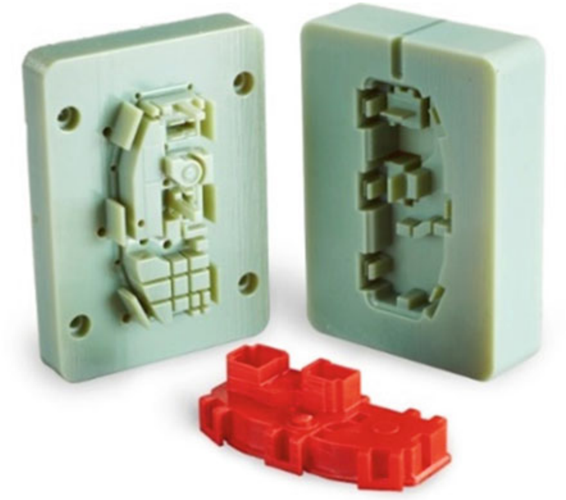


Fig. 6.2 An example of AM PolyJet (bridge) mould (Courtesy of Stratasys)

Finally, with *hard moulds* (Fig. 6.3) it is possible to produce up to a few hundred thousand moulded parts. Their durability is similar to the conventional moulds. They require much more time and expenses for production, compared to the soft and bridge moulds.

Figure 6.4 shows relations of moulds produced with *PolyJet* technology and moulds produced with classic technologies from common mould materials and AM technologies for production of metal bridge/hard moulds. It has to be stressed that A and B processed materials (e.g. unreinforced polyolefines) are far less aggressive, and C and D groups are more aggressive materials regarding mould cavity wall wearing (e.g. reinforced polymers).

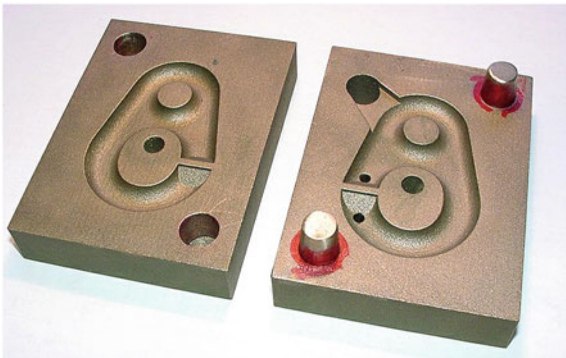


Fig. 6.3 An examle of AM hard mould (Courtesy of SIRRIS)

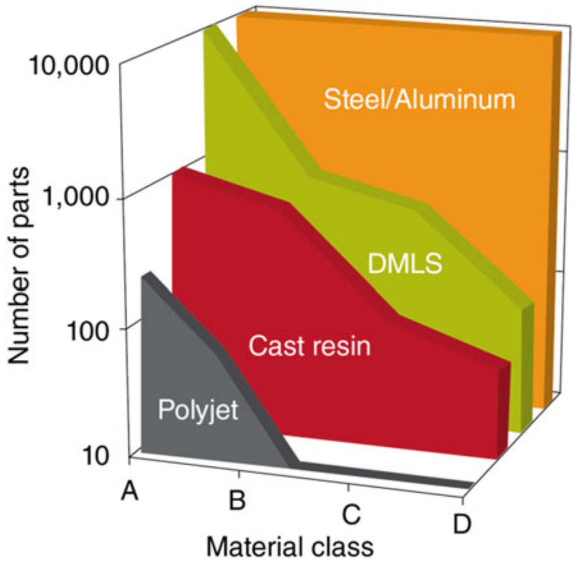


Fig. 6.4 Anticipated number of produced parts depending on the type of the mould and material class (Courtesy of Stratasys)

6.1.1 AM Silicone Short-Run Moulds

Silicone short-run moulds can be considered as AM moulds when master models (patterns) are produced with one of the AM technologies. Generally, the process consists of three main steps: master model making (AM), master model preparation for casting (definition of mould parting plane, definition of mould runner system, etc.) and silicone casting around master model for production one- or two-piece moulds. After the silicone casting and curing, silicone block is removed from the frame, master model is removed from the mould cavity and the mould is prepared for casting materials such are ABS, polyurethanes or polyamides into the mould cavity (Fig. 6.5) (Fig. 6.6).

In case of two-piece silicone mould (Fig. 6.7), two-step process is applied. In first step, lower half of the box is filled with modelling clay and silicone is poured into the upper half of the box creating the first half of the mould. After silicone curing, the box is rotated 180°, the clay is removed from the box, parting plain is coated with separation agent and the process is repeated to create the second half of the mould.

In case of the production of more complex mould geometry, within a silicone mould, different metallic or polymeric inserts can be used. Those inserts can be a good replacement for thinner silicone mould parts, and they can prolong mould durability.

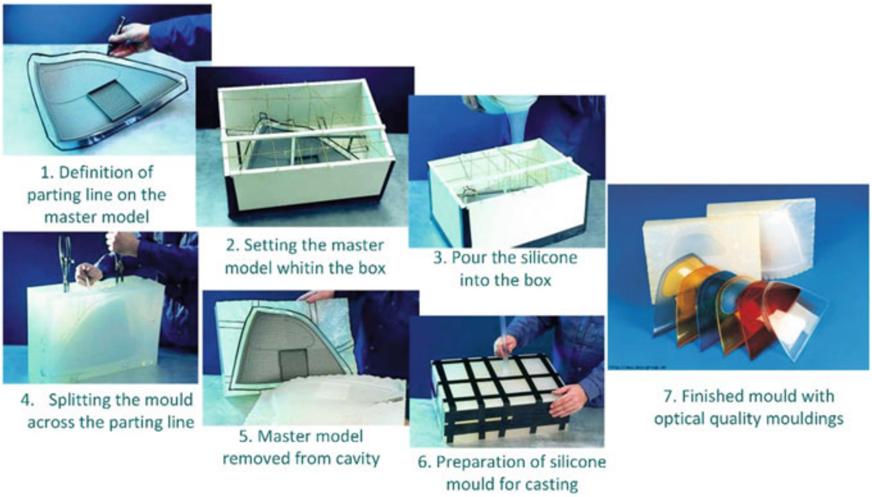


Fig. 6.5 Production process of one-piece silicone mould (www.scott-Am.com, Courtesy of Ronald Simmonds, photographer Giulio Coscia)

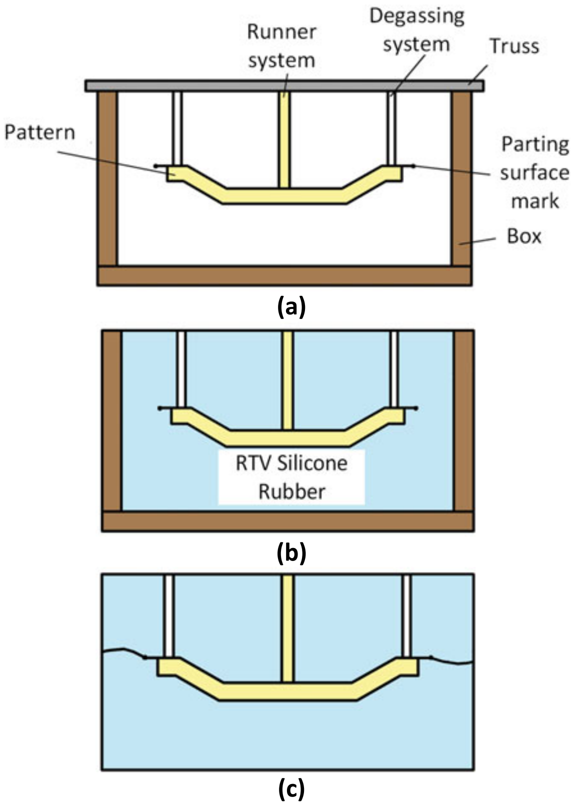


Fig. 6.6 Production process of one-piece silicone mould: **a** setting the master model, runner systems and degassing system, **b** pouring the silicon into the box, **c** finished silicone mould (Courtesy of Andreas Gebhardt)

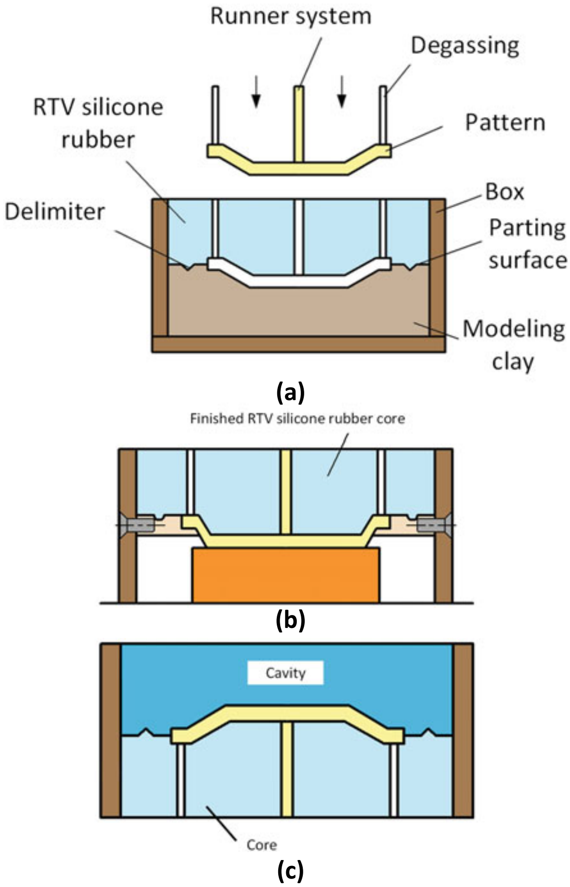


Fig. 6.7 Production process of two-piece silicone mould: **a** setting the master model, runner systems and modelling clay system, **b** ouring the silicon into the box (core production), **c** box rotation, pouring silicone into the box (cavity production)—finish (Courtesy of Andreas Gebhardt)

6.1.2 AM PolyJet Bridge Moulds

PolyJet and *PolyJet Matrix* processes enable application of more than hundred different materials based on acrylic resins, which can mimic the properties range of the materials from elastic to rigid. For manufacturing bridge moulds, mould materials have to be strong enough (tensile, flexural, compressive and bending strength), tough, and resistant to high temperatures in order to maintain mould cavity dimensions. Four materials can be selected as the most appropriate for the *PolyJet* bridge mould manufacturing: *RGD 525* (white high-temperature material), *RGD 5160-DM*, *RGD 5161-DM* and *Digital ABS plus* (ABS-like green materials). Table 6.1 shows some basic mechanical and thermal properties of those materials.

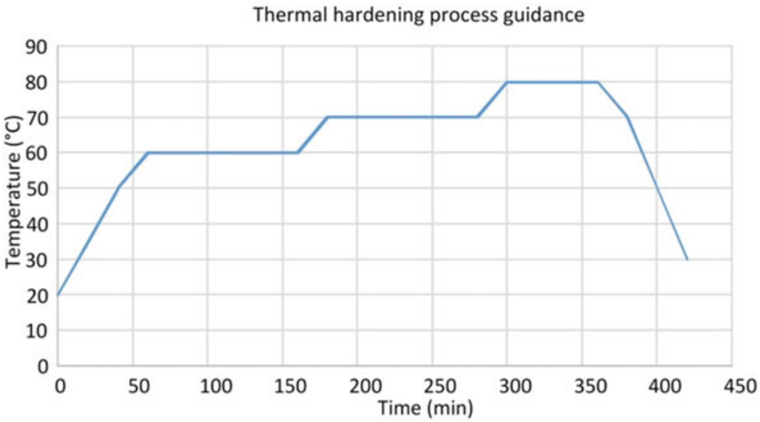


Fig. 6.8 Process of ABS-like mould insert hardening (Courtesy of Stratasys)

Table 6.1 Properties of PolyJet materials suitable for mould production

Property/(unit)	RGD 525	RGD 5160-DM RGD 5161-DM	Digital ABS plus
Tensile strength/(MPa)	70–80	55–60	55–60
Tensile modulus/(MPa)	3200–3500	2600–3000	2600–3000
Flexural strength/(MPa)	110–130	65–75	65–75
Flexural modulus/(MPa)	3100–3500	1700–2200	1700–2200
Izod impact strength/(J/m)	14–16	65–80	90–115
Heat deflection temperature/(°C)	63–67	58–68	58–68
Heat deflection temperature (after hardening)/(°C)	75–80	92–95	92–95

Material RGD 525 is the strongest material, but its toughness is 5–7 times lower compared to the other materials. RGD-5160-DM material is suitable for production of details with wall thickness down to 1.5 mm, while RGD-5161-DM for wall thickness down to 1.0 mm. If high impact resistance and shock absorption are requested, Digital ABS plus is the most appropriate. By hardening process in furnace (), heat deflection temperature can be increased for all materials up to 30%. Increasing the heat deflection temperature is very important for mould inserts for injection moulding, where mould material is heated in cycles as hot polymer melt fills the mould cavity (Fig. 6.8).

6.2 Design Rules for Bridge PolyJet Moulds

In design of bridge *PolyJet* moulds it is possible to apply basic guidelines for design of classic moulds for injection moulding. Nevertheless, because of specific properties *of PolyJet* materials for production of bridge moulds, it is necessary to make some modifications in design concept. This is necessary because of compensation of mechanical, thermal and dimensional characteristics of such plastic moulds. Some of the basic rules for design of *PolyJet* bridge moulds are:

- increase the draft angles for easier moulded part ejection (Fig. 6.9),

- add minimal radius at all sharp edges,
- in case of inserting 3D printed mould into classic mould base, add at least 0.2 mm in height at back face to enable better mould closing and avoiding of flush (Fig. 6.10),

- add minimal radius at all sharp edges,
- in 3D printing of core pin, height/width aspect ratio of 3:1 is recommended (for larger aspect ratios it is recommended to use exchangeable metallic pins),
- for making holes, minimal diameter is 0.8 mm,
- classic side, film, tab and ring gates are recommended in mould gate design (avoid tunnel and pin gates) (Fig. 6.11),

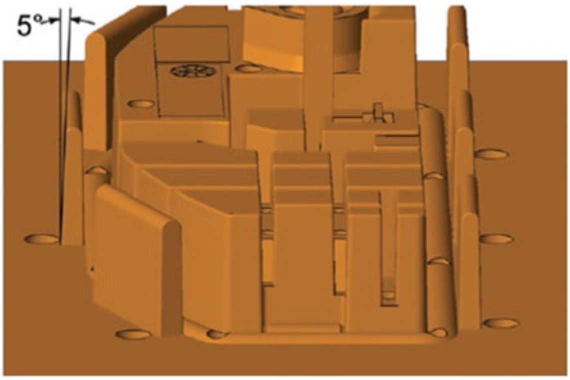


Fig. 6.9 Increased draft angles (Courtesy of Stratasys)

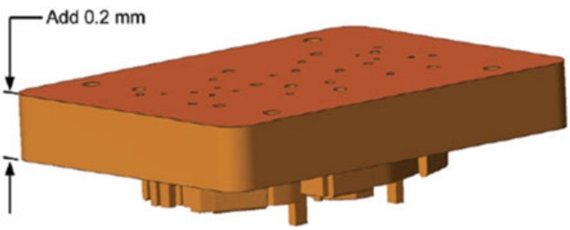


Fig. 6.10 Extension of the back face of the core/cavity (Courtesy of Stratasys)

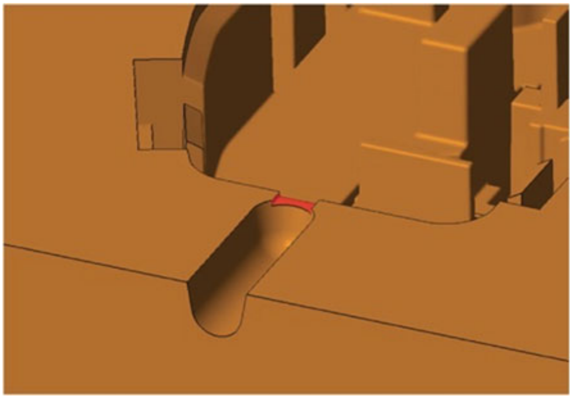


Fig. 6.11 Typical bridge mould side gate (Courtesy of Stratasys)

- gate dimensions have to be 2–3 times larger than gate dimensions in classic steel moulds,
- gate thickness has to be equal or larger than maximal moulded part wall thickness,
- metallic sprue has to be built in the plastic mould, in order to avoid direct contact of the plastic mould with hot injection moulding machine nozzle,
- classic ejector pins that are not placed on distance smaller than 3 mm from mould cavity edge have to be built in (otherwise, the mould can be damaged) (Fig. 6.12),

- decrease the ejector holes diameters by 0.2–0.3 mm and adjust them while mounting the ejector in the mould insert with classic machining,
- complex mould cavity geometry has to be split into multiple mould inserts (Fig. 6.13), in order to achieve appropriate mould cavity venting through tolerances in inserts contact,

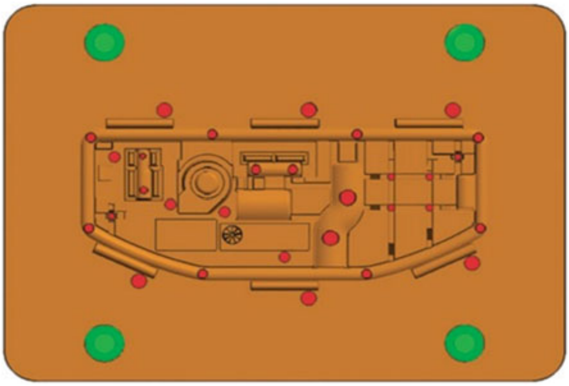


Fig. 6.12 Moulded part ejection system (Courtesy of Stratasys)

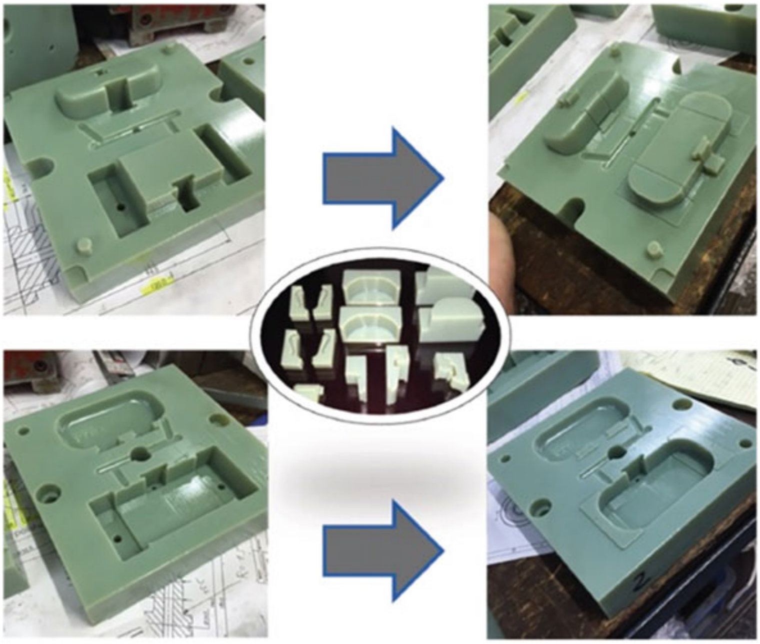


Fig. 6.13 Multiply mould inserts (Courtesy of Stratasys)

- although, because of the poor thermal conductivity of *PolyJet* materials classic mould tempering by cooling channels and water as a coolant is not efficient, it can contribute to prolongation of mould durability (expected up to 20%) (Fig. 6.14),
- more effective cooling is by blowing of compressed air on mould parting plane,

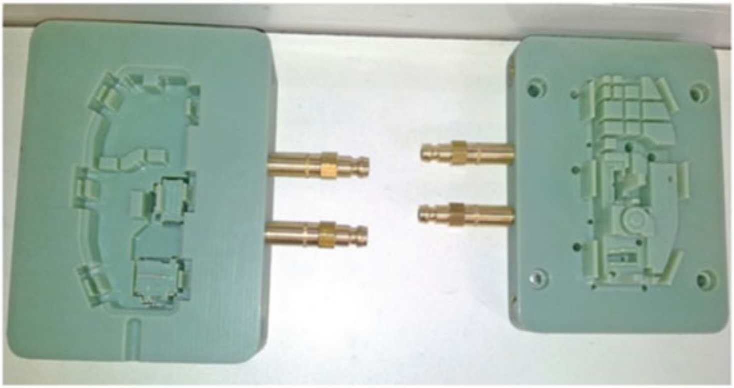


Fig. 6.14 Cooling channels plugs (Courtesy of Stratasys)

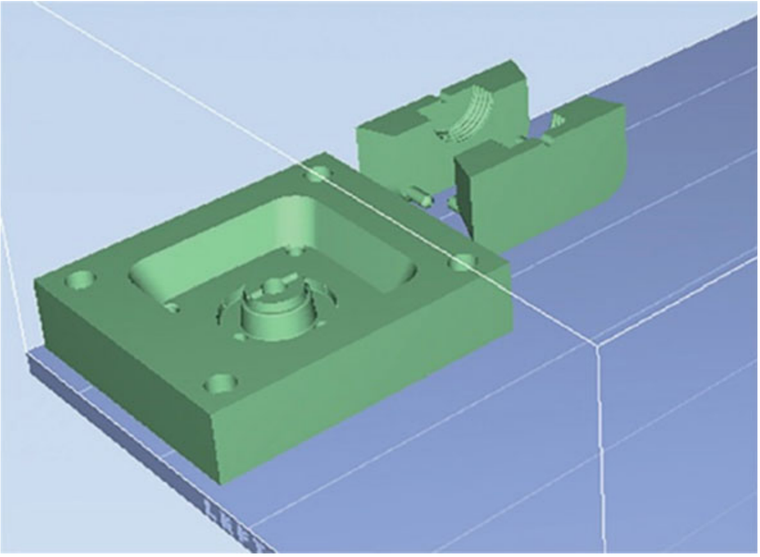


Fig. 6.15 Orientation for glossy surface without support material (Courtesy of Stratasys)

- while preparing for 3D printing, mould insert should be oriented so that mould cavity is up-oriented (glossy surface without support material), which will result in smoother mould cavity surface (Fig. 6.15),
- mould insert should be oriented on building platform with larger dimension in line of printing head moving direction (print lines) because in such orientation the material is better cured—it is exposed to the UV light longer (Fig. 6.16).

In application of bridge *PolyJet* mould inserts, several approaches of embedding in standard mould bases or their independent application are possible. In case of smaller injection moulded parts it is possible to independently use *PolyJet* bridge moulds. Depending on the usage of manual or mechanical injection moulding machine (Fig. 6.17), it is necessary to adjust *PolyJet* moulds dimensions correspondingly.

When *PolyJet* moulds are used on mechanical injection moulding machines, it is necessary to adjust mould dimensions to the injection moulding machine clamping plates and tie bars, as well as to the rest of the mould base. Also, it is necessary to enlarge the thickness of mould plates, compared to the moulds aimed to operate with manual injection moulding machines, in order to avoid creation of cracks on the mould plates (Fig. 6.18).

In case of production of large amount of moulded parts on larger injection moulding machines, *PolyJet* mould inserts have to be embedded into a steel mould base (Fig. 6.19).

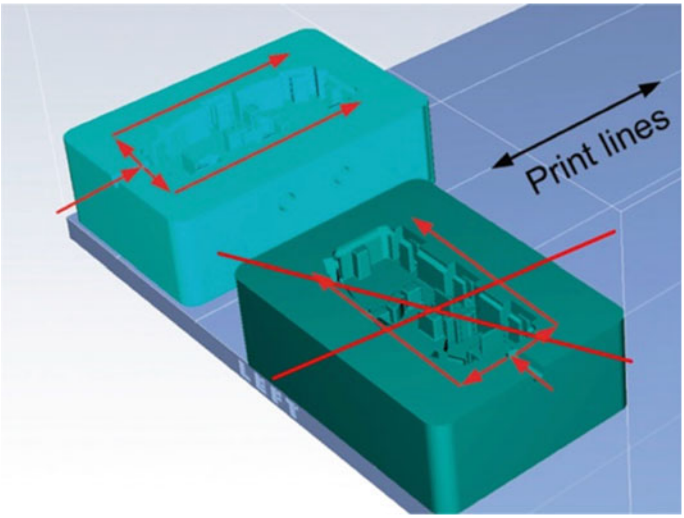


Fig. 6.16 Orientation along printing line (Courtesy of Stratasys)

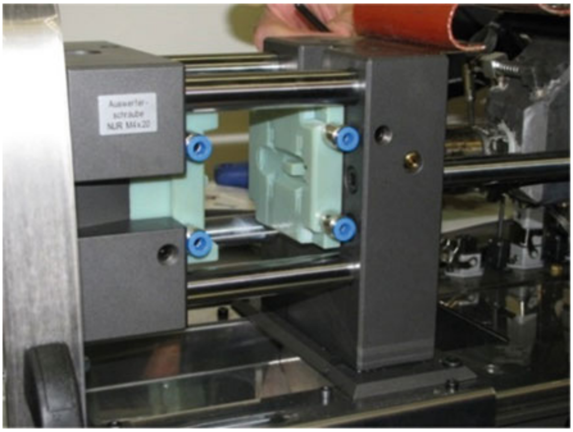


Fig. 6.17 Bridge mould on injection moulding machine (Photo by Damir Godec)

6.2.1 AM (Steel) Hard Moulds

For a long-run tooling, AM hard moulds/tools are required. AM hard moulds are mainly made through direct AM processes such as PBF-LB/M (e.g. SLM) and DED. The primary concerns when making AM mould inserts for long-run tooling are surface roughness, dimensional accuracy and wear. Most of AM processes can provide only partial solutions to those requirements mainly because of higher surface roughness and lower dimensional accuracy than it is required for mould inserts.

Two different strategies can be applied in order to achieve required mould insert properties. First is application of common AM systems for production near-net shape

Fig. 6.18 PolyJet mould plate with cracks (Photo by Damir Godec)

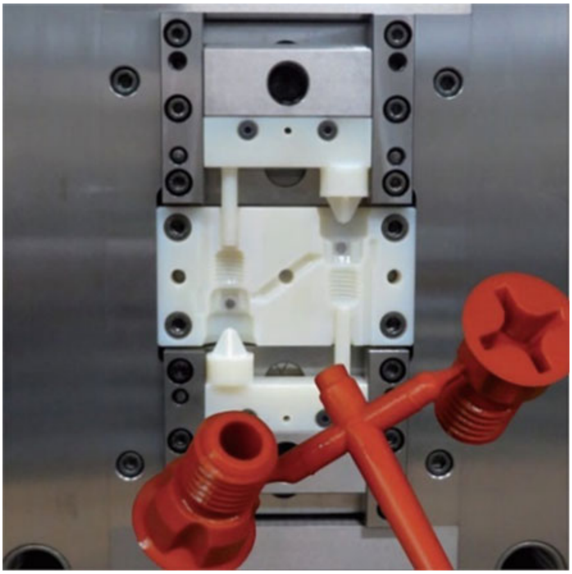


Fig. 6.19 PolyJet mould inserts embedded into steel mould block (Courtesy of Stratasys)

inserts. Achievable surface roughness of near-net shape inserts is in R_a range 12–20 μm, and with dimensional tolerances in range ±0.1 mm, which is not acceptable for the most tooling applications. Therefore, additional subtractive operations have to be applied (e.g. shot peening, milling etc.)

Second approach is application of hybrid technology which combines both AM and subtractive technologies in one machine. The example is Laser Deposition Welding (AM-DED) and milling (subtractive process) (Fig. 6.20), or PBF-LB/M (SLM) with High Speed Cutting (Fig. 6.21) presents differences in mould insert surface roughness after PBF-LB/M phase and after CNC HSC machining (Fig. 6.22).

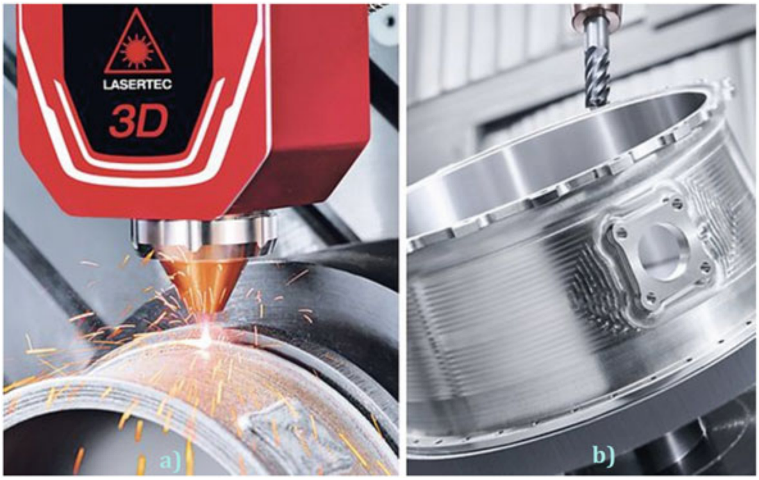


Fig. 6.20 Hybrid manufacturing process: **a** Laser Deposition Welding (DED), **b** milling (Courtesy of DMG MORI)

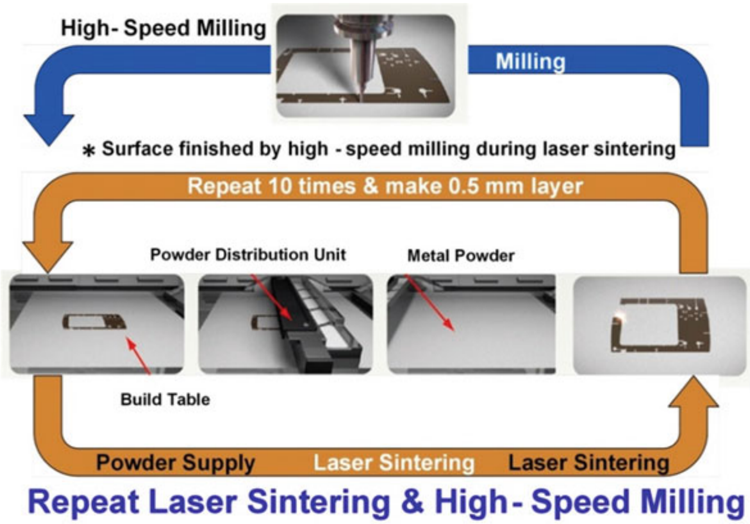


Fig. 6.21 Hybrid manufacturing process—PBF-LB/M (SLM) & HSC (Courtesy of Matsuura)

Because of the need for additional processing with CNC in order to achieve required dimensional accuracy and surface roughness (in both scenarios), during mould insert design phases it is necessary to predict excess material in critical areas of AM mould insert. It is also advisable to design a fixture points to AM mould

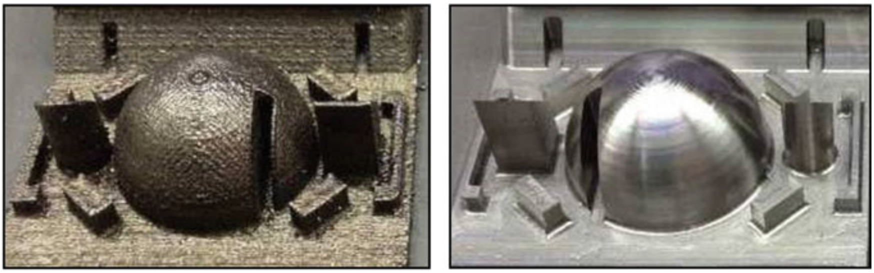


Fig. 6.22 AM mould insert—after PBF-LB/M process (left) and after HSC machining (right) (Courtesy of Matsuura)

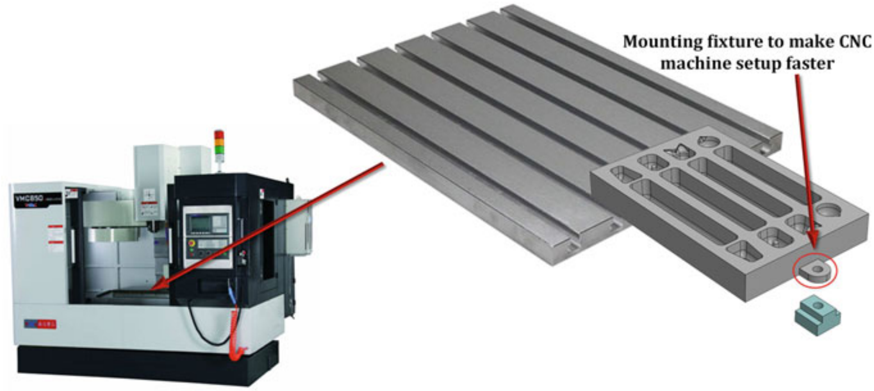


Fig. 6.23 Additional fixtures on AM mould inserts (Courtesy of Olaf Diegel)

inserts for easier mount of AM mould insert on CNC machine bed (Fig. 6.23) for the finishing operation.

A range of AM tool steel powders are available for the production of AM hard moulds/tools:

- Maraging 300
- Tool Steel H13
- Stainless Steel CX
- Stainless Steel 316L
- Stainless Steel 15-5PH
- Stainless Steel 17-4PH.

Maraging 300 alloy steel is a very high strength iron base, molybdenum, cobalt and nickel alloy with excellent properties, workability and heat treatment characteristics. This kind of steel is characterized by having excellent strength combined with high toughness. The parts are easily machinable after the building process and can be easily post-hardened to more than 50 HRC. They also have excellent polishability. Maraging alloy provides a high value for critical parts in aerospace, structural, component and tooling applications.

Tool Steel H13 works excellent at high temperature and can withstand drastic cooling rates. These properties, together with abrasion resistance and machinability, makes it ideal for high-temperature tooling and wearing resistant parts, like mould inserts.

StainlessSteel CX is a tooling grade steel with a good corrosion resistance combined with high strength and hardness. This material is intended for injection moulding tools and tool parts and other industrial applications where high strength and hardness are required. Parts built of StainlessSteel CX can be machined, shot-peened and polished in as-built or heat-treated status.

Austenitic stainless steel 316L, with high strength and corrosion resistance, can be reduced to low temperature in a wide range of temperatures. It is applied in various engineering applications such as aerospace and petrochemical, as well as toolmaking, food processing and medical treatment.

Martensitic stainless steel 15-5PH, also known as Martensitic aging (precipitated hardening) stainless steel, has high strength, good toughness and corrosion resistance, is a further hardening of the ferrite-free steel. At present, it is widely used in aerospace, petrochemical, chemical, food processing, paper and metal processing industries.

Martensitic stainless steel 17–4 PH still has high strength and high toughness under 315 °C, and strong corrosion resistance and can bring excellent ductility as the laser machining state.

Main advantages of AM application for tooling can be summarized as:

- production of mould inserts with complex geometry in shorter time
- production of mould inserts with improved efficiency (conformal cooling/multi-material).

Generally, AM allows production of very complex geometries with very low cost or without increase of the costs for production. In case of conventional mould/tool production, complex mould insert geometry is very often split into a few simpler mould inserts, which means longer production times as well as more potential problems with multiple tolerances. In case of AM, very complex mould insert geometry can be produced from one piece and thus in shorter time. Figure 6.24 presents a project of production of complex mould with DMLS technology. The whole project of mould design, production and injection moulding was realised within 15 days which cannot be accomplished by conventional tooling.

6.2.2 Efficient AM Moulds—Conformal Cooling

Improperly designed mould cooling systems (cooling channels) often result in two undesirable outcomes. Firstly, moulded part cooling and injection moulding cycle times are much longer than what could have been achieved. Secondly, significant temperature gradients arise across the mould, causing differential shrinkage and

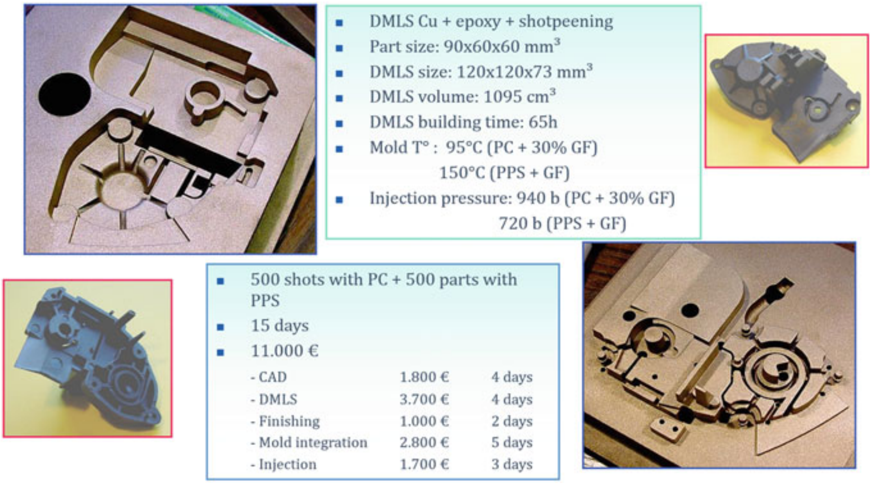


Fig. 6.24 Project of DMLS mould production for injection moulding (Courtesy of SIRRIS)

warpage of the moulded parts. To operate effectively, cooling systems must be carefully designed to manage the heat flow throughout the mould without incurring undue cost or complexity.

When we are speaking about moulds for mass production, saving in injection moulding cycle time of just a few seconds means huge savings in total production. Injection moulding cycle consists of few phases: mould closing, polymer melt injection, packing pressure phase, moulded part cooling, mould opening and moulded part ejection (Fig. 6.25). Moulded part cooling is the most important part of the injection moulding process for two facts: it consumes from 50 to 80% of the injection moulding cycle time and it has the strongest influence on achieving required quality of injection moulded parts (Fig. 6.26).

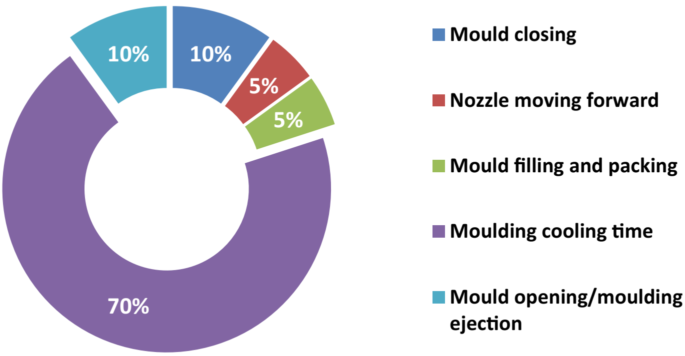


Fig. 6.25 Injection moulding cycle time analysis (*Source* Damir Godec)

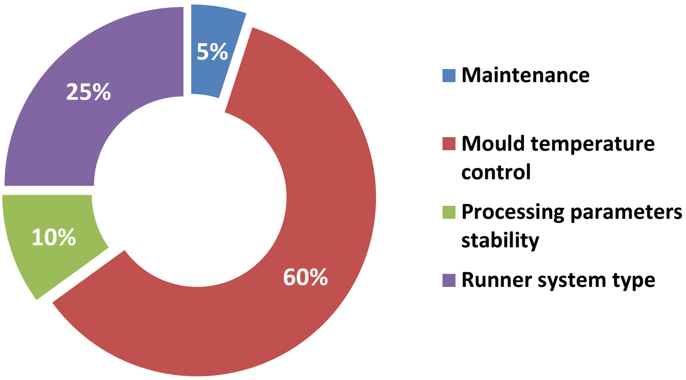


Fig. 6.26 Influencing factors on quality of injection moulded parts (*Source* Damir Godec)

In order to remove a moulded part from the mould, the material must be sufficiently cooled to provide ejection without distortion. Adequate mould cooling can be considered to have occurred if the part surface is hard enough to prevent ejector pins from penetrating. Cooling channel placement determines cooling efficiency and uniformity. Positioning the channels too close to the cavity surface can cause cold spots and uneven cooling. If they are too far away, cooling becomes more uniform but less efficient. As shown in Fig. 6.27, uneven distances to the cavity surface lead to an uneven heat exchange.

Cooling efficiency is particularly dependent on cooling channel characteristics such as proximity to the mould cavity, cross-sectional area, length, route and surface roughness. However, the design of conventional drilled cooling channels in injection moulds is limited by traditional manufacturing constraints such as the linear nature of the drilling process, which restricts the ability to conform the channel to the contour of the mould cavity (Fig. 6.28a). Variation in the proximity of cooling channels to the mould cavity results in uneven heat dissipation, leading to: increased cycle time, part warping and sink marks, internal part stresses, and reduced tool life due to thermal stresses.

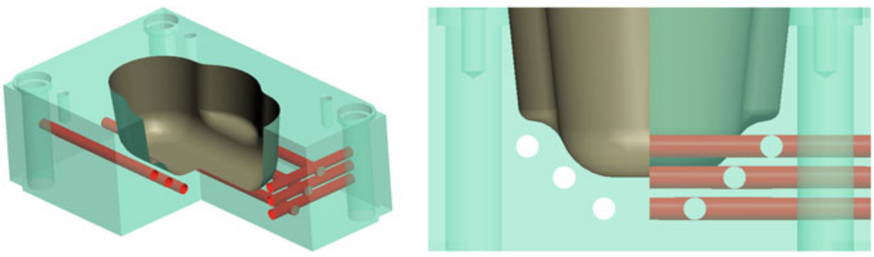


Fig. 6.27 Conventional tooling mould temperature control (uneven distances to the cavity surface or impossibility to reach some cavity areas) (*Source* Damir Godec)

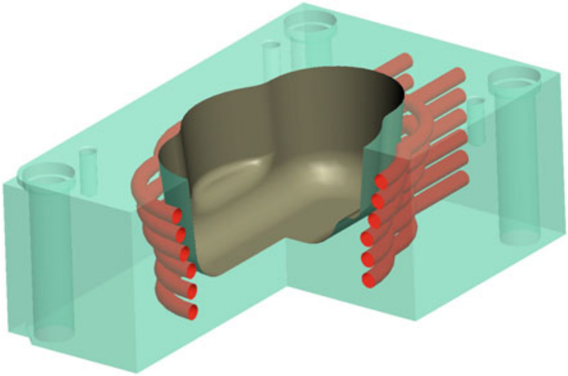


Fig. 6.28 Conformal mould cooling channels (*Source* Damir Godec)

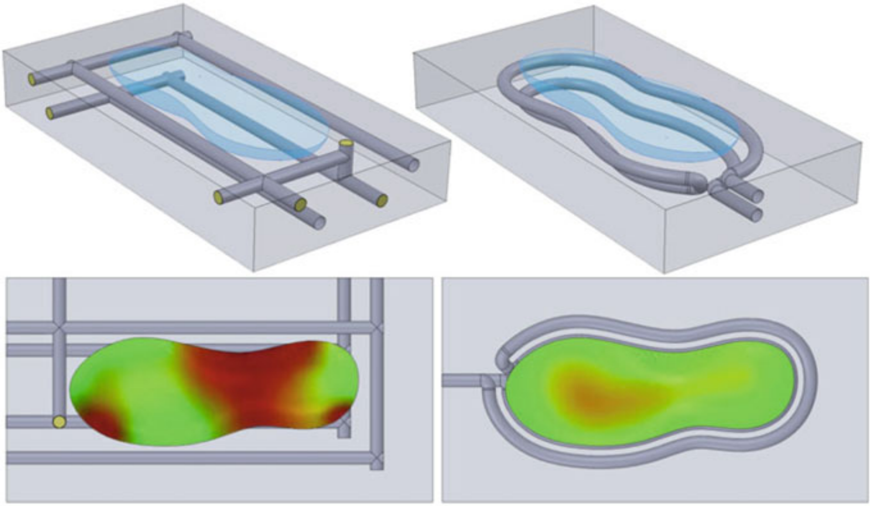


Fig. 6.29 Heat distribution comparison between conventional and conformal cooling channels (Courtesy of Olaf Diegel)

In case of moulds for mass production, the injection moulding cycle time is much more important than the time and the costs necessary for mould production. Therefore, a lot of toolmakers apply new strategies in mould design and production. Most of them are focused on optimisation of heat exchange in the moulds in order to reduce injection moulding cycle time as well as to improve moulded part quality and to extend the mould lifetime. AM tooling with conformal cooling is the possible answer to those requirements.

AM mould inserts can be built with internal cooling channels that follow the contour of the cavity beneath the surface (Fig. 6.28b). Because the form of the channels follows the contour of the mould, the method is called conformal cooling. Due to the more intensive heat exchange, the productivity of a polymer injection mould can be increased significantly. Conformal cooling channels, applied with no engineering simulation or analysis will, generally, result in about a 10% cycle time improvement. On the other hand, conformal cooling channels, applied with engineering simulation and analysis will, generally, result in cycle time improvements from 20 to 40%.

The use of conformal cooling channels also optimizes the moulding process by providing a constant temperature gradient and thus more even heat distribution throughout the mould (), while increasing the total surface area of the cooling circuit. This also results in savings in manufacturing the inserts. When plastic cools evenly, internal stress is minimized. This results in a higher quality parts with less warping or sink marks. The more controlled cooling offered by conformal cooling channels allows you to precisely control how the plastic solidifies in the mould and, therefore, to minimize part distortion and shrinkage (Fig. 6.29).

The ultimate objective in optimisation of the injection moulding cycle time and moulded part quality is the creation of a mould temperature control system, which enables a constant and adapted temperature level for the polymer material, during the running injection moulding process on each point of the moulding surface. In order to achieve this result, when applying conformal cooling, appropriate coolant flow strategy and cooling channel shape have to be determined. The general opinion is that, when designing conformal cooling channels, it's always recommended to use an injection moulding simulation software package (CAE) in order to identify different temperature zones within a mould so that the conformal cooling channels can be separated and optimized within each region. CAE software can successfully assist in evaluating the effectiveness of cooling layout designs and verify potential design problems at early stage.

When designing conformal cooling channels, the first decision that needs to be made is which coolant flow strategy to use. There are three different strategies: zigzag pattern, parallel channel design and spiral channel design (Fig. 6.30). A zigzag pattern, also known as a series cooling path (Fig. 6.30a), has part regions cooled one

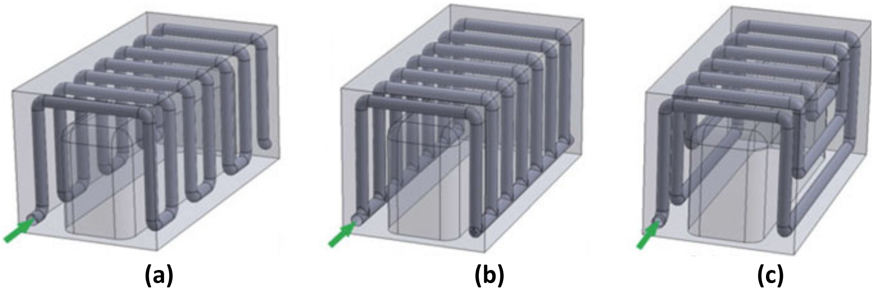


Fig. 6.30 Types of cooling strategies that can be employed with conformal cooling: **a** zigzag, **b** parallel, **c** spiral (Courtesy of Olaf Diegel)

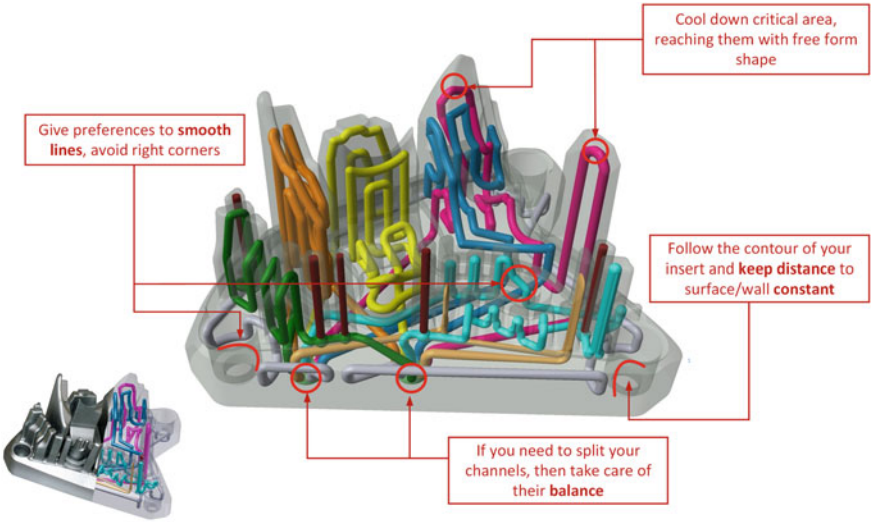


Fig. 6.31 Conformal cooling of complex mould insert (© Copyright Renishaw plc. All rights reserved. Image is reproduced with the permission of Renishaw)

after the other rather than at the same time. Cooling in series is generally not preferred unless parts are small enough that the delay is negligible. A parallel channel design (Fig. 6.30b) allows for different areas of the mould to be cooled at the same time. The main drawback of the parallel cooling method is that it requires a lot of coolant. A spiral conformal cooling channel design (Fig. 6.30c) is often used with parts that have curved or spherical elements.

On complex tools, one can sometimes combine cooling strategies where, for example, part of the tool uses a zigzag type of strategy, while the rest of the tool employs a parallel strategy. For very complex mould inserts specific rules have to be employed for optimal cooling (Fig. 6.31).

When considering coolant channel shapes produced with AM, one must be aware of the effect of the ability of the AM system to effectively produce them, as well as their effect on cooling efficiency. The design guidelines used for conventional cooling circuits can also be applied to conformal cooling channels. Some of the recommended dimensions are given in the schematic in Fig. 6.32 and the recommended channel diameters based on the average wall thickness of the moulded plastic part are shown in Table 6.2.

Generally, the optimal cooling channel diameter is usually between 4 and 12 mm (depending on the design and the material of the moulded part). The diameter should, however, be carefully chosen depending on the AM system being used. It must also be taken into account that round horizontal channels, for example, will require internal support material if their diameter is above 8 mm.

The freedom offered by AM opens a lot more possibilities when it comes to optimising the coolant flow in the cooling circuits. One of those possible optimisations is

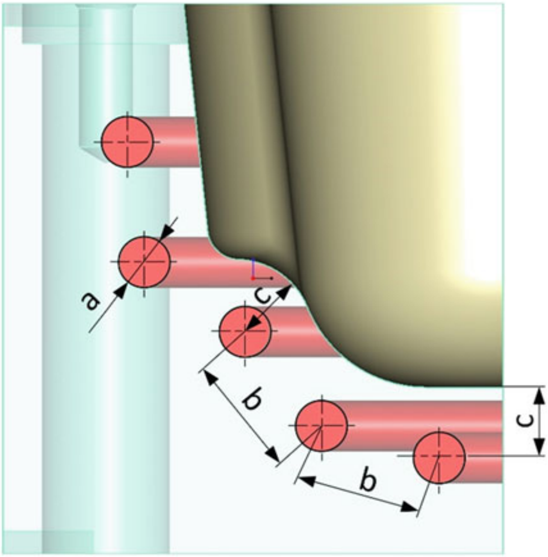


Fig. 6.32 Conformal cooling channels—recommandations for design (*Source* Damir Godec)

Table 6.2 Conformal cooling channel diameter and spacing based on moulded part wall thickness

Moulded part wall thickness (mm)	Channel diameter (mm) *b*	Centreline distance between channels *a*	Distance between channel centre and cavity *c*
0–2	4–8	(2 ÷ 3) · b	(1.5 ÷ 2) · b
2–4	8–12	(2 ÷ 3) · b	(1.5 ÷ 2) · b
4–6	12–14	(2 ÷ 3) · b	(1.5 ÷ 2) · b

to change the cross section of the channels in order to improve the coolant flow. The most common channel shape is, generally, round but, on occasion, vertical elliptical holes, or house-shaped or teardrop-shaped channels are also used (Fig. 6.33).

The cooling performance can, sometimes, also be increased by ribbing the shape of the channel which causes an increase of channel perimeter as well as increase in the expected turbulence in the channel (higher Reynolds number), which thus increases cooling (Fig. 6.34).

Figure 6.35 shows conformal cooling channels with different cross sections and their characteristics.

As alternative to application of single channels, mould designers for a mould cooling employ a whole hollow surface structures beneath the cavity wall. Two main types of hollow surfaces are mostly applied. One structure consists of large number of consecutive knots which run through larger inlets or outlets (Fig. 6.36). Consecutive knots configuration guarantees volume flow large enough for efficient mould insert cooling. Small channel diameter enables cooling of very small details in mould insert

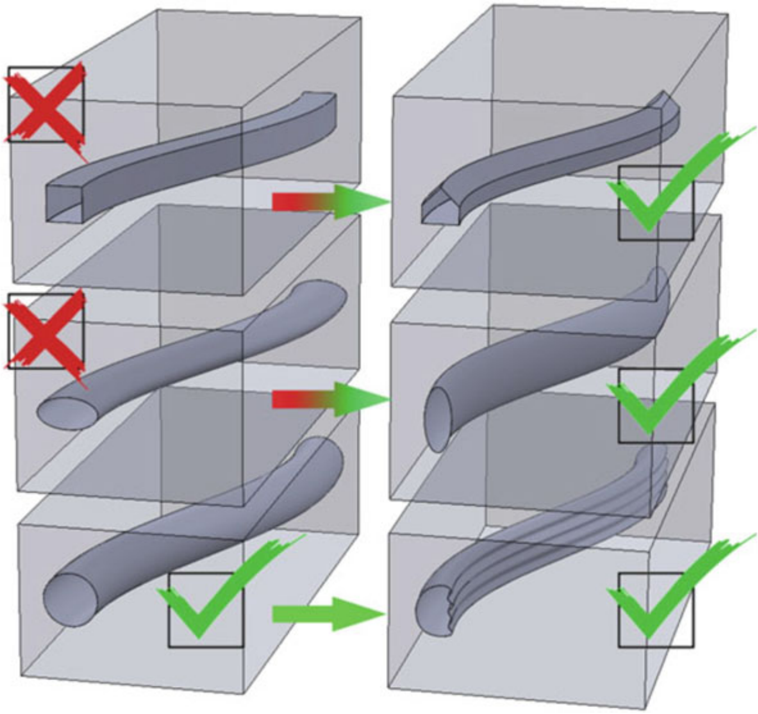


Fig. 6.33 Recommended shapes of conformal channels cross section (Courtesy of Olaf Diegel)

(width of only 4.5 mm). In this case, a dome-shaped structures with dimensions from 4.5 · 5 mm and larger, are also available.

Second structure type consists of mesh surfaces for mould insert cooling placed only 2 mm beneath the mould insert cavity wall and must achieve a large coolant volume flow. Small distance from mould insert cavity wall enables very efficient cooling, and very short cycle times. Mould insert temperature can be controlled locally over the insert and thus decrease (or even remove) unwanted moulded part thermal deformation and achieve target moulded part shrinkage. Mesh surface can be combined with insulation layer, which enables rapid temperature changes in moulded part cooling time phase in the mould cavity (Fig. 6.37).

6.2.3 Efficient AM Moulds—Optimised Build Time in Tooling

Tooling is a typical application in which the bulk of the tool is a large mass of metal which serves little purpose. It is there because by CNC machining we try to minimize the amount of cutting that needs to happen. AM provides the opportunity of creating

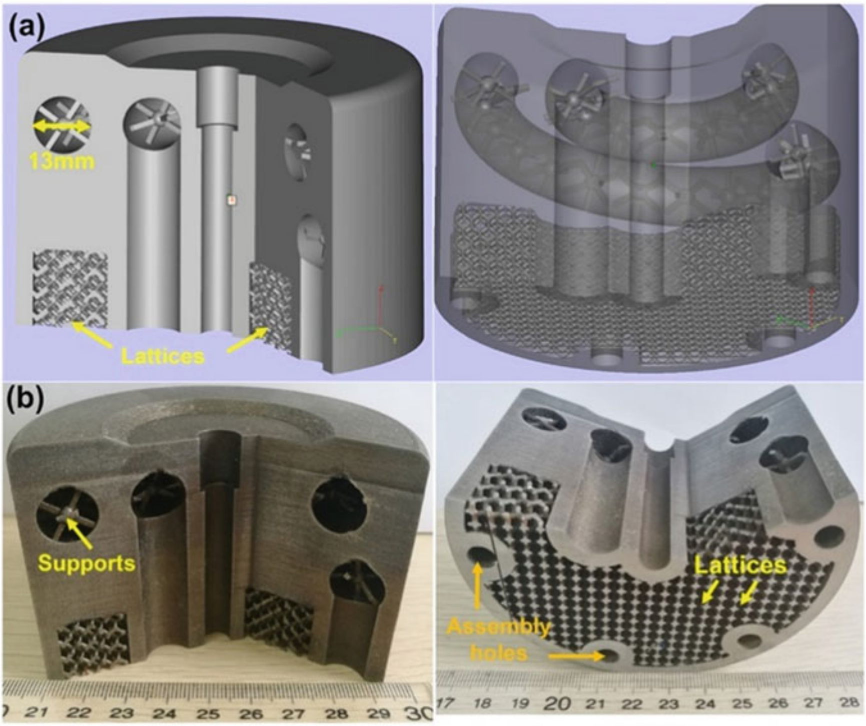


Fig. 6.34 Novel Conformall cooled mould insert: **a** CAD models of novel conformal coolled mould insert, **b** the corresponding mould insert processed by PBF-LB/M (Reprinted from Materials and Design, Vol. 196/109147, Chaolin et al. [10], Copyright 2021, with permission from Elsevier)

much lighter tools that have an even metal wall thickness and take less time and cost to manufacture.

Using the tool for a shoe insert (Fig. 6.38), we can see that the vast bulk of the tool is a solid mass of steel. AM application in tooling offers a possibility to reduce the amount of the material used. Whether this can be done will of course depend on many factors such as the pressure the tool will be subjected to, etc. But, in many applications, a wall thickness of 10–20 mm is more than adequate, and still leaves enough material for conformal cooling channels.

Other option to achieve a similar goal would include filling the inside of the tool with a honeycomb structure (Fig. 6.39), or a lattice (Fig. 6.40). Lattice structure also has the influence on the mould/tool insert elasticity. Lattice structures should have sufficient strength to withstand the injection pressure, but at the same time enough flexibility for the surface to expand and retract during the cycle. The elasticity of lattice structures can be made highly anisotropic in laser powder bed fusion process. Generally, a lattice structure containing large cells will give a higher elasticity than a structure with smaller cells. Figure 6.40 illustrates a mould insert where a large portion of the mould insert consists of lattice structures. This means that much less

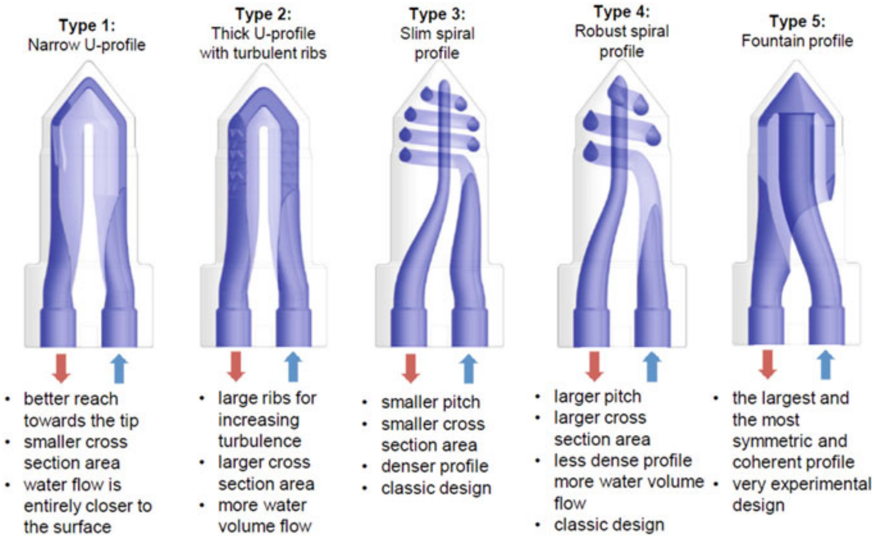


Fig. 6.35 Different types of conformal cooling channels cross sections (Courtesy of ABB Oy)

material and shorter machine time is needed to produce the mould insert. In addition, the structural flexibility is higher which could reduce thermal fatigue. The cooling channels are placed at some distance from the wall of the insert. With this design, cracks in the insert wall will not propagate into the cooling channel, causing leakage of coolant into the mould cavity. Another point is that the thermal fluctuations in the cooling channels will be low, as there is slower heat transfer to the channels.

The problem is that there will not be much thermal conductivity between the lattice structure and the cooling channels. One solution to such a problem is to make the elements of the lattice structure thicker towards the edges, or to make the structure smaller with larger connections. Both proposals increase the melted mass between the surface and the cooling channels. For faster/cheaper production it is also possible to entrap powder in the section between the cooling channel and the surface, since entrapped powder has much more thermal conductivity than air.

6.3 AM Application in Medicine

The medical industry is one of the fastest-growing sectors within AM, and is used for a range of applications, from patient-specific implants to realistic functional prototypes and advanced medical tools. AM provides extensive customisation as per the individual patient data and requirements for medical applications. Individual patient models are in three-dimensional (3D) sections developed through customised software. These include implants, soft tissue, foreign bodies, vascular structures,

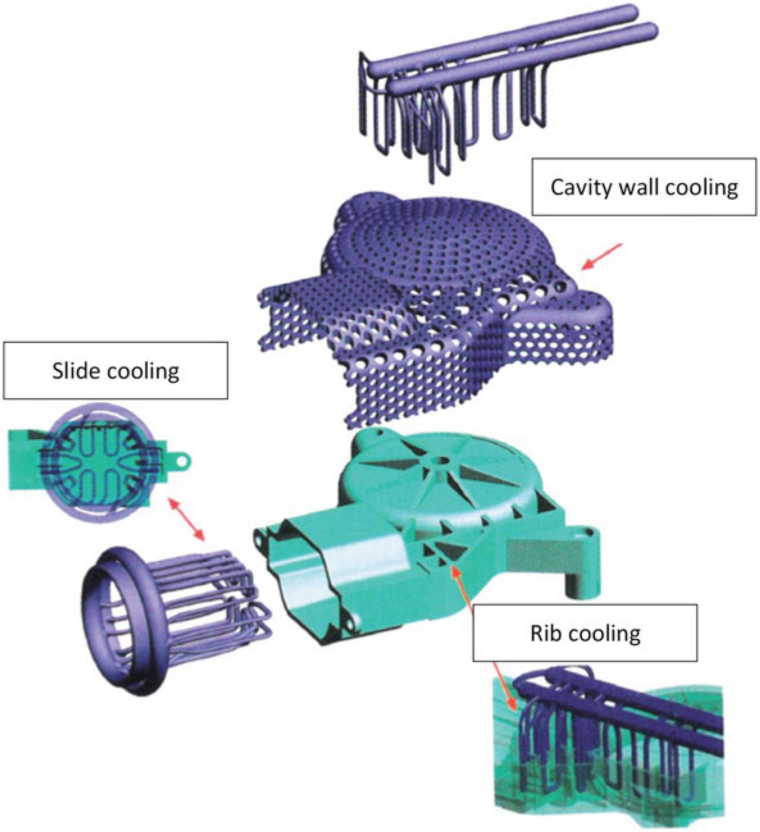


Fig. 6.36 Surface hollow structures for efficient mould cooling (Courtesy of GE Additive/Concept Laser)

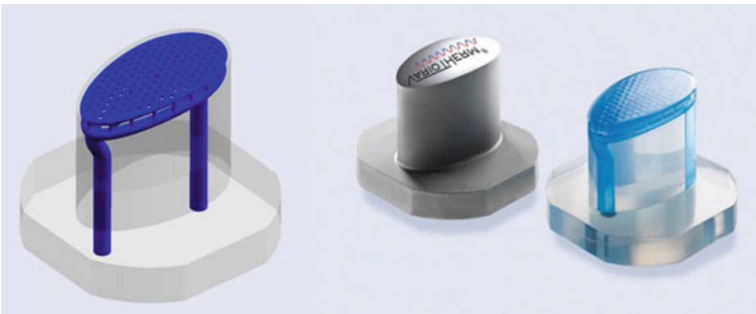


Fig. 6.37 Mesh surface for efficient mould insert cooling (Courtesy of GE Additive/Concept Laser)

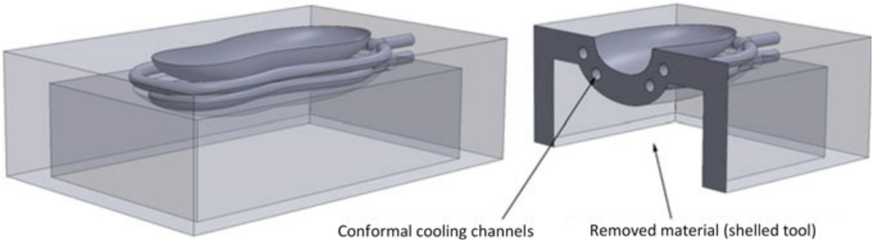


Fig. 6.38 Example of improving the print time and cost of a tool by shelling its interior (Courtesy by Olaf Diegel)

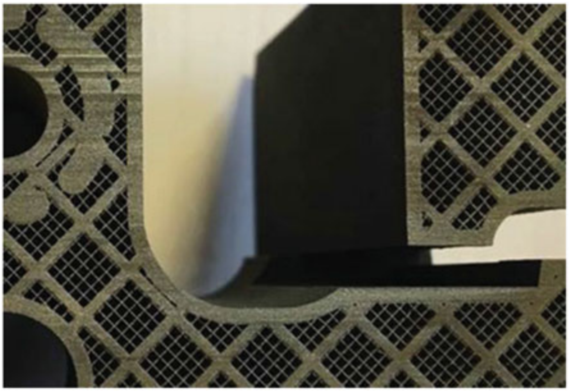


Fig. 6.39 Honeycomb structure used on inside of sheet metal tool to reduce its print time and cost (Courtesy by Olaf Diegel)

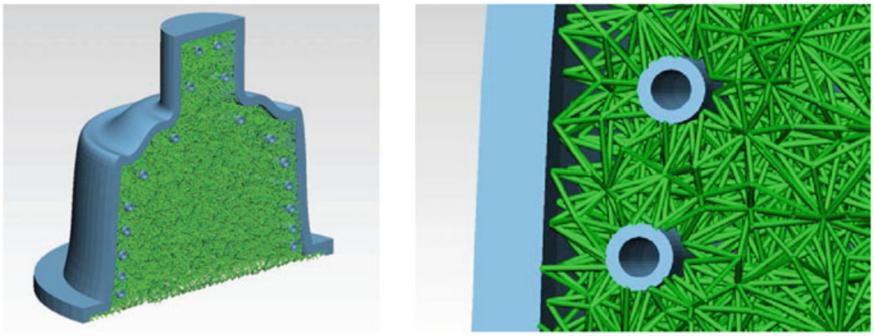


Fig. 6.40 A split mould tool with internal lattice structures (Reprinted from Procedia CIRP, Vol 54, Brøtan et al. [9], Copyright 2021, with permission from Elsevier)

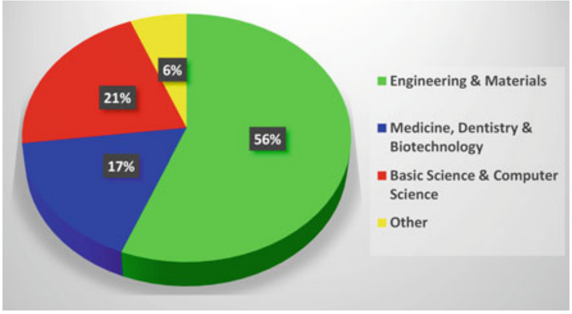


Fig. 6.41 Medical application of AM (Javaid and Haleem [34], Courtesy of Mohd Javaid)

etc. Magnetic Resonances Imaging (MRI) technology or Computerised Tomography (CT) are usually used for capturing model data.

Application of AM in medical sectors can be divide into a few areas:

- medical research and development
- preclinical testing and planning
- production of medical devices
- pharmaceutical application
- bioprinting/tissue fabrication.

6.3.1 Medical Research and Development

AM models can greatly contribute to medical research by providing realistic anatomical models and prototypes. And as AM speeds up the product design cycle, biomedical engineers can now create very complex models and prototypes that much faster.

Share of AM in medical applications is shown in Fig. 6.41. Engineering and materials have significant contribution in this area which is 56%. Medicine, dentistry and biotechnology have 17%, basic science and computer science have 21%, and other fields have 6% contribution in this particular area. It indicates that engineering and materials areas have demonstrated a great potential in this field, because this is tool-less production which produces complex shapes quickly, in lesser time.

6.3.2 Preclinical Testing and Planning

AM models allow physicians to visualise patient's anatomy and assess complex pathologies directly, overcoming the challenges of digital images which lack 3-dimensional realism. And thanks to advances in multi-material AM (e.g. PolyJet technology), additively manufactured models made up of different materials can be create to replicate characteristics of human tissues and bones. This method can help surgeons plan an operation in advance and improve surgical precision and postoperative outcomes.

Generally, development and production of models for medical testing and planning can be divided into a three main groups:

- general application
- anatomical modelling (patient-matched)
- surgical planning.

General application medical models

In case of general application, non-personalized models, instruments or prototypes are produced (Fig. 6.42). Mostly it is about plastic or metal specializes instruments for hospital/surgical use, for testing parts built with new materials or for prototypes used for iterative design processes.

Anatomical medical models

When the aim of AM models is anatomical modelling, they are used for patient-matched anatomical models from medical imaging studies (CT/MRI). This type of models have numerous application such as: models for surgical preparation (Fig. 6.43), simulation (Fig. 6.44), models for teaching or training (Fig. 6.45), models for communication with patients and colleagues (Fig. 6.46), demo models to test fit and fixation of an instrument, etc.

Medical models for surgical planning

AM is also used for different types of templates, guides, and models, after preparing a patient-specific, surgical plan in a software environment (AM items are brought into operating room). Guides can be divided into a group that does not need cutting

Fig. 6.42 Example of AM medical device (general medical model) for prototyping and testing (Courtesy of Formlabs)

Fig. 6.43 AM model for surgical preparation (surgery time reduction up to 75%) (Dr. Mickey Gidon and Department of Neurosurgery at Soroka)

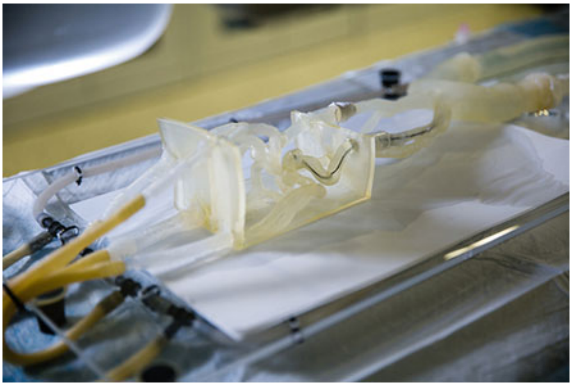


Fig. 6.44 AM model for simulation (aneurysm simulation) (Courtesy of Stratasys)

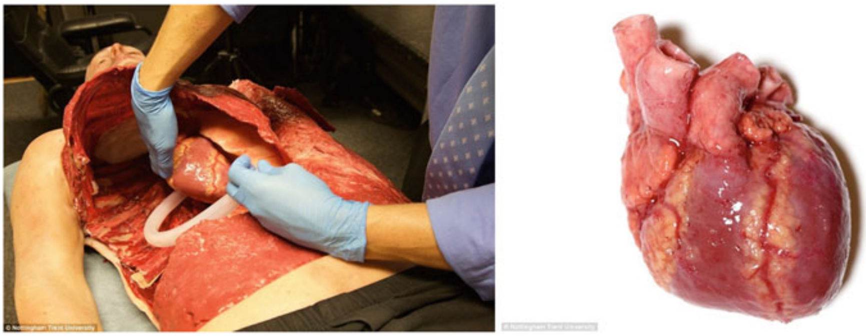


Fig. 6.45 AM model for teaching/training (Courtesy of Richard Arm)

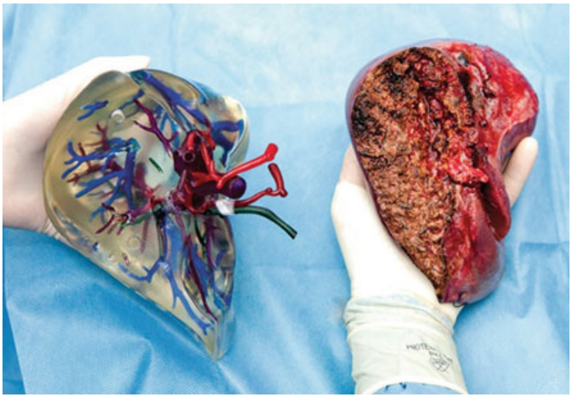


Fig. 6.46 AM model for communication (Courtesy of Stratasys)

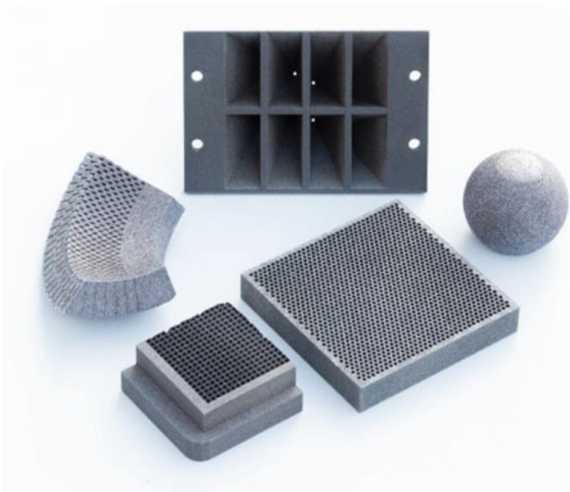


Fig. 6.47 Examples of complex AM tungsten models (e.g. collimators) for advanced medical imaging (Courtesy of M&I Materials Ltd.—Wolfmet 3D)

or injection for marking (surgical marking guides, implant placement guides, radiation shields (Fig. 6.47), imaging frames) and a group of cutting/drilling guides for surgical injection/instrumentation (surgical saw guides, surgical drill guides (Fig. 6.48), guiding osteotomies in the bone).

6.3.3 Production of Medical Devices

With the global market for AM produces medical devices expected to reach more than 1.0 billion EUR by 2026. (Future Market Insights), AM offers significant value to produce customised medical products. From complex-shaped implants, personalised prosthetics and hearing aids to fit-for-purpose tools, additive manufacturing enables

Fig. 6.48 Examples of AM surgical drill guide (dental application) (Courtesy of Formlabs)

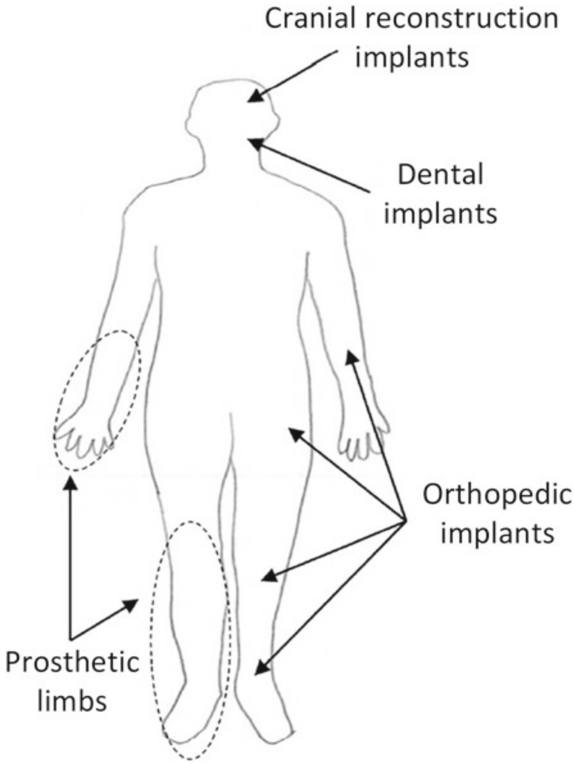


Fig. 6.49 Examples of AM in current medical models with AM major influence (Courtesy of ASME)

the production of one-off devices that would be impractical to manufacture using traditional manufacturing.

In case of AM of medical devices, there are three main groups of products (Fig. 6.49):

- personalised (precision) prosthetics
- temporary/permanent implants
- wearable (active) devices/covers.

AM is making a huge impact in the production of affordable yet highly accurate prosthetics. Using traditional manufacturing methods, it can take weeks to create a device matching a patient's requirements. Today, this is no longer the case, as AM prosthetics is significantly less time-consuming and, in many cases, can be produced at a fraction of the cost of traditionally fabricated prosthetics. In this case AM has been used for a patient-matched prosthetics/orthotics that can be in direct contact with mucosal surface (e.g. complex facial (Fig. 6.50) and cranial prosthetics, dental (Fig. 6.51) and orthodontic (Fig. 6.52) applications), as well as without direct contact with mucosal surface (e.g. glasses, body braces (Fig. 6.53), hearing aids (Fig. 6.54), prosthetic limbs and attachments (Fig. 6.55), etc.) and different type of assistive devices.

According to a recent report by SmartTech Publishing, the dental market will reach 9.5 billion EUR by 2027. Today, dental labs can additively manufacture bridges, aligners, crowns, orthodontic appliances and stone models, which can be customised to fit the patent.

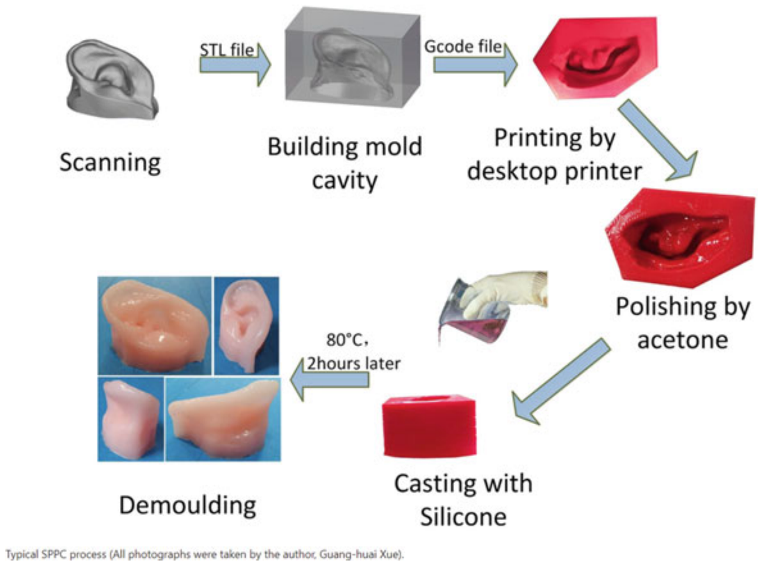


Fig. 6.50 Examples of AM fabrication of silicone ear (He et al. [27] 2014—licenseds under CC BY-NC-ND 4.0)

Fig. 6.51 Example of AM CoCr dental crowns (Schweiger et al. [71], 2010.—licensed under CC BY 4.0)

Fig. 6.52 Example of AM orthodontic application (aligner) (Courtesy of Stratasys)

Over 10,000,000 people are now wearing 3D printed hearing aids with more than 90% of all hearing aids globally now being created using AM. Not only has AM technology significantly reduced the cost of custom hearing aids when compared to traditional manufacturing but the ability to produce the complex and organic surfaces required for a hearing aid has reduced returns because of bad fit from 40 to 10%.

It is important to note that in any application of AM in medical production it is advisable to adhere to the Technical Considerations for Additive Manufactured Medical Devices/Guidance for Industry and Food and Drug Administration Staff (5th December 2017) as well as The European Union Medical Device Regulation—EU MDR, Regulation (EU) 2017/745 (5th April 2017). As the requirements for medical production are very high, it is necessary to take into account quality control and it is necessary to adopt ISO 13485: 2016 procedures and certainly regulate the research or production activities of AM for medicine.

One of the fastest growing segments within medical AM is implants production. Advances in AM have enabled the production of implants made to match the patient's anatomy. Furthermore, with biocompatible materials such as titanium and

Fig. 6.53 Examples of AM orthotics: **a** Forearm static fixation, **b** hand prosthesis, **c** Spinal brace, **d** Ankle–foot orthosis (Barrios-Muriel et al. [6] 295.—licensed under CC BY 4.0)

Fig. 6.54 Examples of AM hearing aid (Courtesy of Formlabs)

cobalt chrome alloys, AM orthopaedic and cranial implants can be manufactured with the right surface roughness, resulting in reduced rejection rates. The possibility of creating topologically optimised designs also means that an implant can be designed with complex organic geometry and reduced weight. This AM area is used for production of "off-the-shelf" (ability to create fine details easily, such as porous structures/surfaces) and patient-matched implants.

Fig. 6.55 Examples of AM prosthetic covering (Courtesy of Anatomic Studios, photographer Stefan von Stengel)

There are two main groups of implants: serialised implants which can be temporary or permanent (metallic implants—titanium (Figs. 6.56, 6.57), titanium alloys, cobalt chrome alloy and polymeric implants—PEEK/PEKK implants (Fig. 6.58)) and patient-matched reconstructive implants (small quantity implants—limb salvage, oncology cases, spinal implants, temporary/removable implants—nasal stents, permanent implants: non-dissolvable—knee/bone implant (Fig. 6.59) or dissolvable—tracheal splint).

Beside direct AM of implants, there is also possibility of indirect AM application for implants production. In first step it is necessary to produce appropriate AM mould (Fig. 6.60), which is in second step used for implant production.

Wearable (active) devices are devices that include electronics or other active element. This group of products involves wearable sensors, lab on a chip, microfluidics (Fig. 6.61) and electronics for active devices.

Design for AM of medical models

When developing and production medical models either for preclinical testing and planning, or for applications such are implants, prosthetics, orthoses, etc. medical process chain can be divided into eight major steps (Fig. 6.62). Data varies from patient to the patient. We need imaging and scanning, which is produced through various scanning procedure such as CT convert data in the 3D digital form.

Fig. 6.56 Example of AM titanium cranial implant (Sun and Shang [82]—licensed under CC BY 4.0)

The process chain starts from diagnosis. For the application of AM in medical models development, images and scanned data of patients are required as input data (Fig. 6.63).

Computer data of the patient can be obtained in three ways:

- by scanning with laser or optical scanners in case that only patient outer body surface is necessary (e.g. for production of different types of orthoses and prosthesis);
- by application of medical diagnostic procedure (Computed Tomography—CT or Magnetic Resonance Imaging—MRI) which results with so called DICOM data format (Digital Imaging and Communications in Medicine) used for obtaining a CAD model of patient bones (e.g. for production of medical customised implants, for production of customised surgical guides etc.) (Fig. 6.64);
- by application of medical diagnostic procedure CT or MRI (DICOM data format) for obtaining CAD models of patient soft tissue (e.g. internal organs and tissue for complex surgical planning, for organs production by AM of living cells—bioprinting, etc.).

Procedure of 3D scanning with laser or optical scanner is relatively simple and similar to obtaining models in technical area. However, procedure of getting patient CAD data from DICOM data is very complex and requires specific knowledge on human anatomy as well as for understanding and interpreting results obtained through medical diagnostic procedure and application of specialised software (Fig. 6.65).

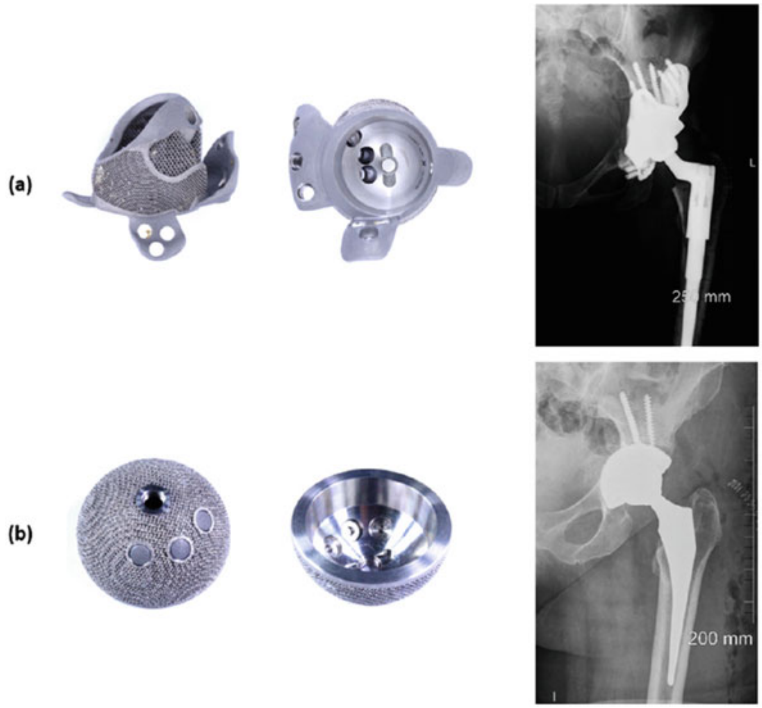


Fig. 6.57 Example of AM titanium hip implant: **a** custom, **b** of-the-shelf (Dall'Ava et al. [12] 729.—licensed under CC BY 4.0)

For success realisation of medical model development, a cooperation among medical and technical experts is necessary. The result of medical diagnostic procedure is file with point cloud which represents a geometry of the patient in three-dimensional space. With specialised software it is possible to segment total point cloud into a several point clouds and separates the cloud that represents specific part of the patient body for which it is necessary to develop CAD model (Fig. 6.66).

After segmentation of point cloud of specific patient body part/organ, it is necessary to generate surfaces that connects points from the cloud, which results with initial CAD model of patient body part/organ in STL file format necessary for AM. In next step, it is necessary to customise initial CAD model to adjust it for the application and patient (e.g. modelling of implant fixation system).

In following step AM helps to transform the original design of the customised implant to the physical model. There is the importance of biomechanical simulation to determine the strength of the medical model. In case of implant production, after all simulation has done, regulatory approval is must before manufacturing. After building the model, post processing is compulsory for increasing strength and surface finish quality. Final steps, in case of implants, are sterilisation and surgery (Fig. 6.67).

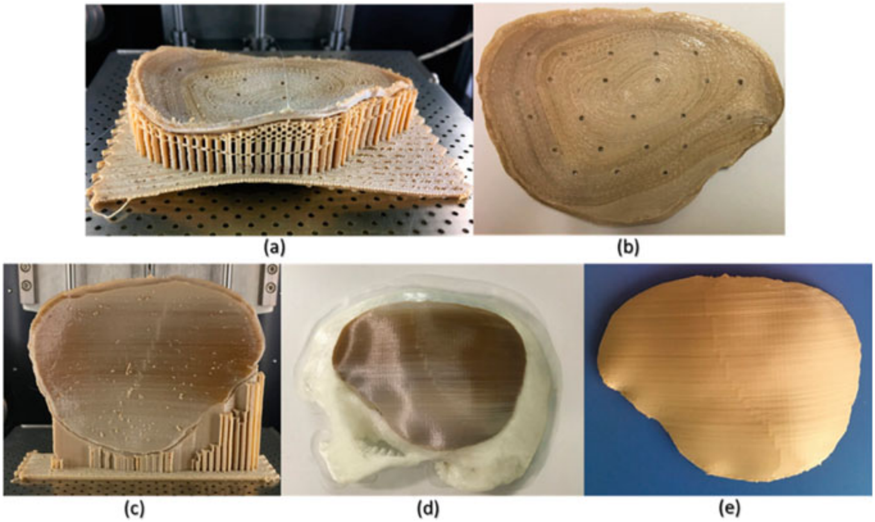


Fig. 6.58 FFF PEEK 3D printed cranial implant in different orientations. **a** horizontally printed cranial implant showing raft; **b** horizontally printed cranial implant—internal surface; **c** vertical printed cranial implant; **d** 3D printed skull biomodel; **e** annealed vertically printed cranial implant displaying (Sharma et al. [73] 2818.—licensed under CC BY 4.0)

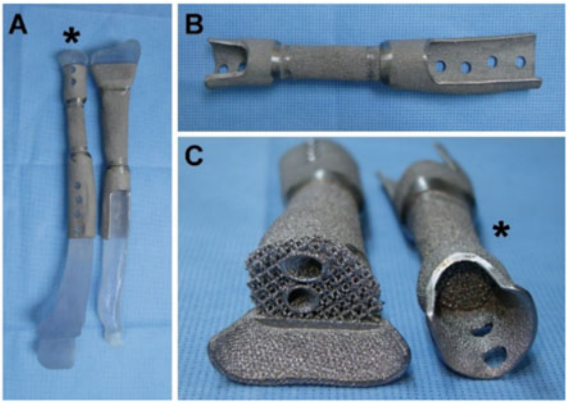


Fig. 6.59 AM metallic bone implant: **a** 3D-printed implants of both forearm bones with the host bone models, **b** a volar view of the ulnar implant, **c** the mesh-structured junctional area of the implants (Park et al. [58], 553.—licensed under CC BY 4.0)

In the future AM will have a better capability of enhancing product customisation and usage with reasonable cost. AM has disrupted all the traditional fabrication of medical models. This technology fabricates implant with its specific geometrical dimensions, and it replaces conventional scaffold fabrication methods. This technology is beneficial in surgical planning; the models provide surgical and physician team with a visual aid to make surgery planning better. It has potential to fabricate customised fixtures and implants; complex geometry is also fabricated in short time. This is needed for designing and manufacturing of surgical aid tools,

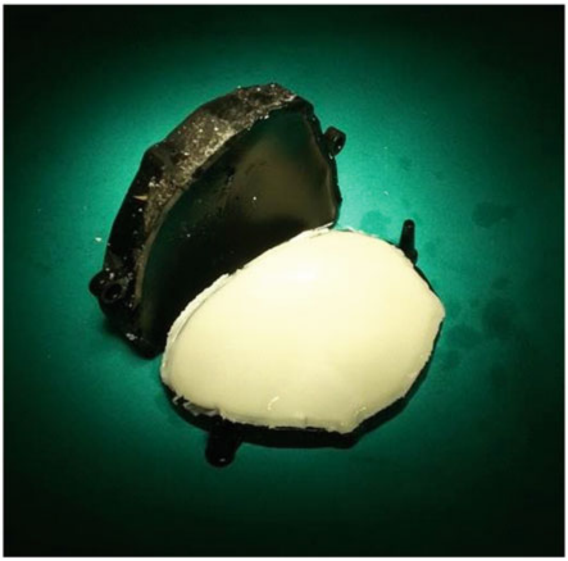


Fig. 6.60 Example of AM (PolyJet) mould for production of bone cement cranial implant (*Source* AdTec SME project—UNIZAG FSB)

bio-models, implants, various scaffolds for tissue engineering and development of multiple medical devices and surgical training models. In future medical will have to work in close collaboration with AM researchers and commercial product developers.

6.3.4 AM Pharmaceutical Application

There are several different AM approaches that have potential for pharmaceutical production (Fig. 6.68). However, only a few methods have been successfully explored with the purpose of producing pharmaceuticals. The primary AM techniques that have been applied toward pharmaceutical manufacturing thus far include Binder Jetting, Material Extrusion, and Material Jetting.

Widespread commercialization of AM of pharmaceuticals has the potential to disrupt the supply chain used by the healthcare industry worldwide with the cost-saving potential of minimizing waste related to unused, expired medications. But despite the potential of this technology, many clinical and regulatory challenges will need to be addressed prior to large-scale implementation of AM fabricated therapeutics for precision medicine applications.

One main advantage of using AM for pharmaceutical manufacturing is that pharmaceuticals can be easily tailored for each patient. This is achieved through changing the release profile of the pharmaceutical, which essentially means adjusting when and for how long the active agent is released into the body. This can be adjusted by changing the relative quantities of the active and inactive form of the constituents or

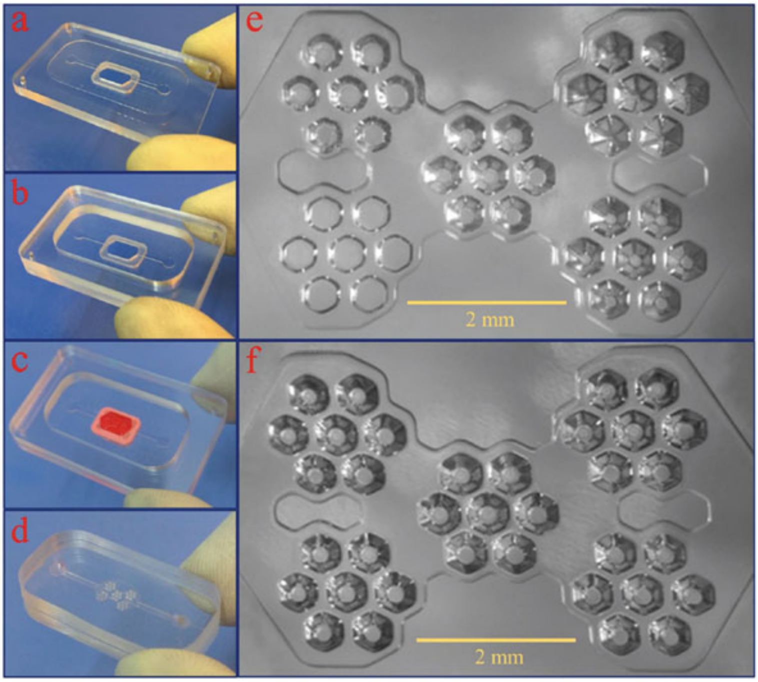


Fig. 6.61 Microfluidic device—Steps to produce the master mold and casting with PDMS. **a**, **b** Two CNC milled parts are bonded to each other permanently using a solvent bonding method. **c** The 3D printed mold is assembled on the CNC mold and fixed with reusable putty adhesive. **d** The cover and microwell PDMS layers bonded together using the plasma bonding method to produce the microwell chip. **e**, **f** The optical micrographs of PDMS layers with the variable and constant depth (300 μm) microwells (Behroodi et al. [7]—licensed under CC BY 4.0)

by compartmentalizing or layering the tablet to change how drugs are released in the patient's body.

Another main advantage is the potential for on-demand drugs. In an emergency situation, it will be much easier to produce medicine for a patient as it can be printed in a hospital environment, rather than relying on the stocks containing a drug with the correct dose and release profile.

Long term stability of a drug would be less important (expire date), as they can be printed as soon as they are needed, so it would be possible to design more effective drugs with faster action, as they don't need a long shelf life.

All of these changes would normally be impossible or very difficult to achieve through conventional methods, as it would involve changing the entire manufacturing process.

While there are many benefits to the incorporation of AM to the facilitation of precision medicine in healthcare practice, there are significant obstacles, which must be overcome in order for this to occur. Of those obstacles, a few have been explored in the literature and are stated here. The first obstacle is the question of legal license over

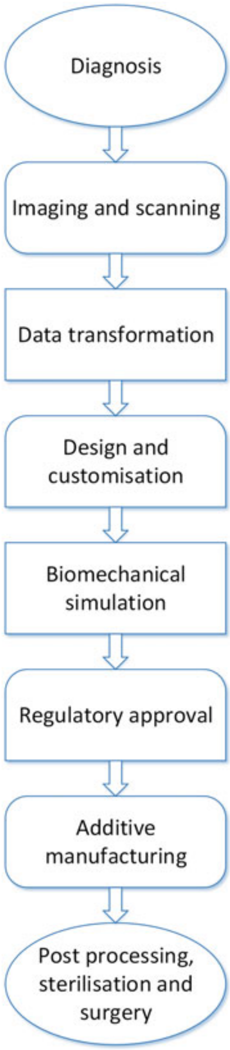


Fig. 6.62 Process chain development in medical application of AM (Javaid and Haleem [34], Courtesy of Mohd Javaid)

the active ingredients in many current medications. The second obstacle is the cost of printing a polypill compared to the cost of currently available mass manufactured medications for use in chronic disease states. The third obstacle is the establishment of new clinical guidelines, which facilitate provider prescriptions for chronic disease states.

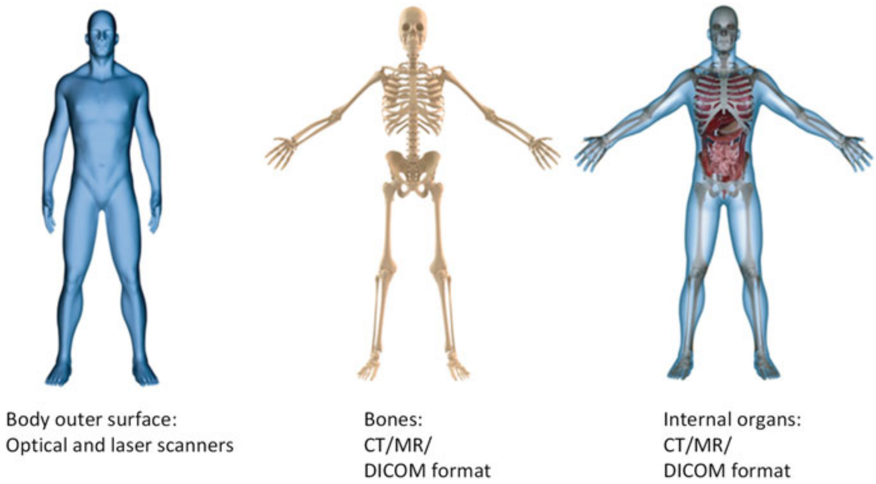


Fig. 6.63 Input data types for AM development of medical models (*Source* AdTec SME project—UNIZAG FSB)

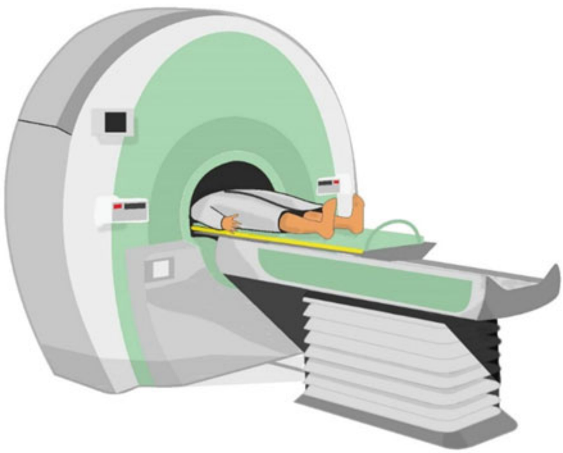


Fig. 6.64 Application of medical 3D diagnostic procedure (CT or MRI) for obtaining DICOM data (Courtesy of Miodrag Katalenić)

6.3.5 AM for Bioprinting/Tissue Fabrication

Bioprinting is an additive manufacturing process where biomaterials such as cells and growth factors are combined to create tissue-like structures that imitate natural tissues.

The technology uses a material known as bioink to create these structures in a layer-by-layer manner. The technique is widely applicable to the fields of medicine and bioengineering. Recently, the technology has even made advancements in the production of cartilage tissue for use in reconstruction and regeneration.

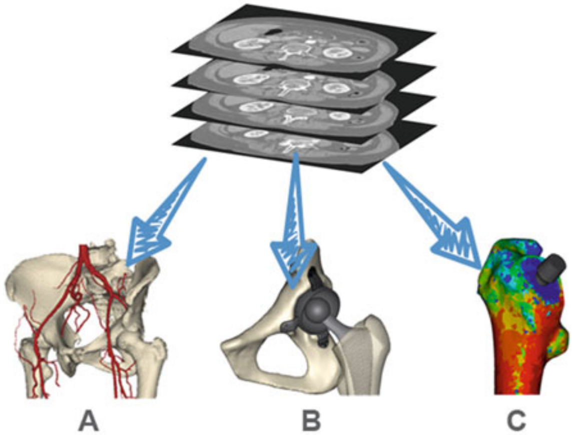


Fig. 6.65 Application of specialised software for DICOM data transfer (*Source* AdTec SME project—UNIZAG FSB)

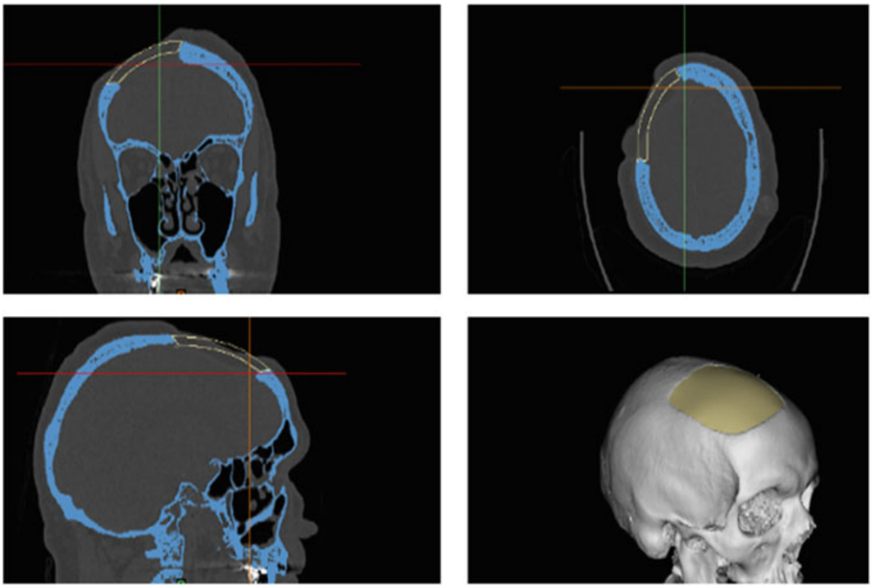


Fig. 6.66 Procedure of DICOM data segmentation (Courtesy of Miodrag Katalenić)

In essence, bioprinting works in a similar way to conventional AM. A digital model becomes a physical 3D object layer-by-layer. In this instance, however, a living cell suspension is utilized instead of a thermoplastic or a resin.

For this reason, in order to optimize cell viability and achieve a printing resolution adequate for a correct cell–matrix structure, it's necessary to maintain sterile printing

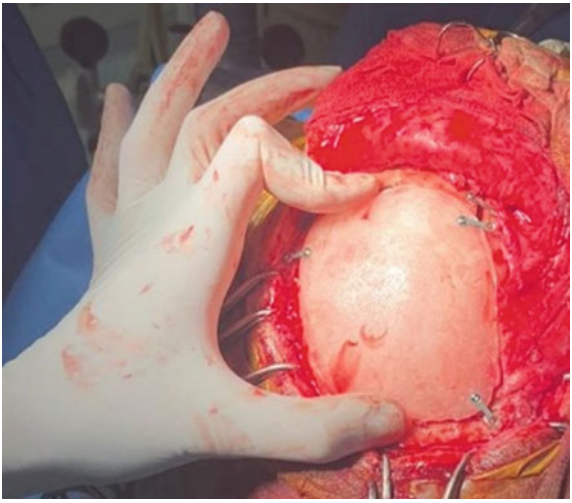


Fig. 6.67 Medical model customisation—surgery and implant fixation (Photo by Miodrag Katalenić)

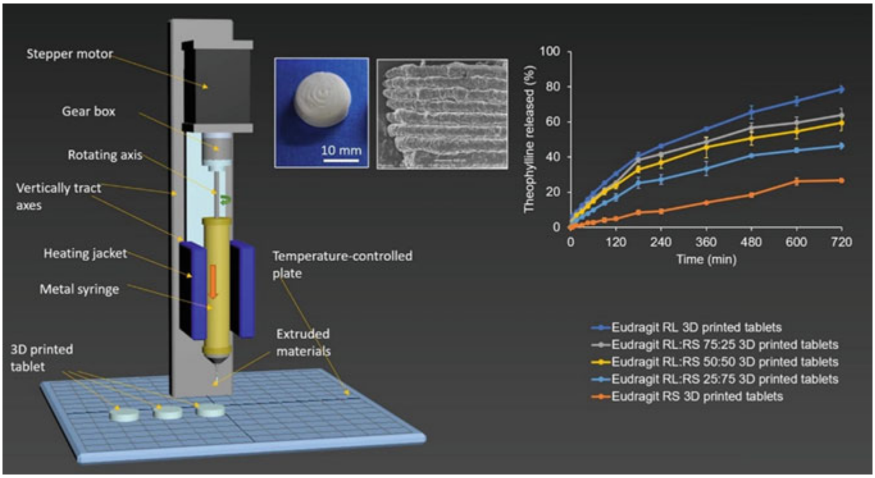


Fig. 6.68 AM of tablets: **a** Set-up for direct extrusion 3D printing. The printer is equipped with a metal syringe surrounded by a temperature-controlled heating jacket. The syringe is fitted with a luer-lock stainless steel needle, and the pharmaceutical ink (compressed powder) is added. The ink is then extruded by a piston pushed by a computer-controlled stepper motor equipped with gear to produce 3D-printed tablet. **b** Top and **c** side photographs of 3D-printed tablets based on Eudragit RL: RS: 100:0, 75:25, 50:50, 25:75, and 0:100. (Abdella et al. [1], 1524,—licensed under CC BY 4.0)

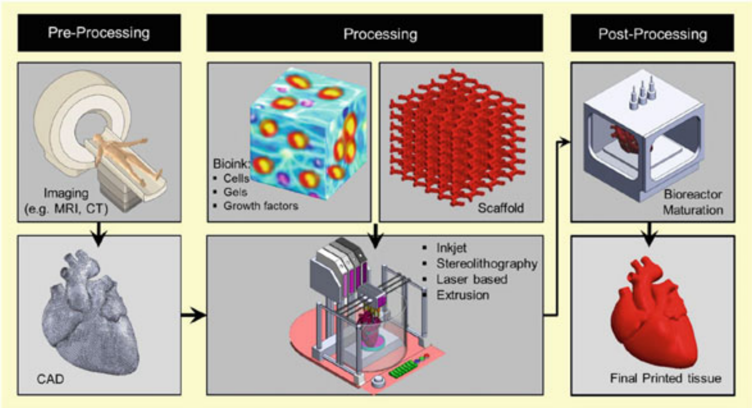


Fig. 6.69 Overview schematic of the bioprinting processes Copyright © 2021 Ramadan and Zourob [63], 648.—licensed under CC BY)

conditions. This ensures accuracy in complex tissues, requisite cell-to-cell distances, and correct output.

The process principally involves preparation, printing, maturation, and application. This can be summarized in the three key steps (Fig. 6.69):

- *Pre-bioprinting* involves creating the digital model that the printer will produce. In first step 3D imaging is necessary to get the exact dimensions of the tissue (CT or MRI scans). 3D imaging should provide a perfect fit of the tissue with little or no adjustment required on the part of the surgeon. In second step a 3D modelling is necessary for generating a CAD model of part to be printed.
- *Bioprinting* is the actual AM process, where bioink is prepared, placed in a printer cartridge and deposition takes place based on the digital model. Bioink is a combination of living cells and a compatible base, like collagen, gelatin, hyaluronan, silk, alginate or nanocellulose. The latter provides cells with scaffolding to grow on and nutriment to survive on. The complete substance is based on the patient and is function-specific. After preparation AM process of depositing the bioink layer-by-layer can start. The delivery of smaller or larger deposits highly depends on the number of nozzles and the kind of tissue being printed. The mixture comes out of the nozzle as a highly viscous fluid.
- *Post-bioprinting* is the mechanical and chemical stimulation of printed parts so as to create stable structures for the biological material. As deposition takes place, the layer starts as a viscous liquid and solidifies to hold its shape. The process of blending and solidification is known as crosslinking and may be aided by UV light, specific chemicals, or heat. Once the printing is complete, the printed structure is then placed in growth media to grow and mature. During this maturation period, the biomaterial loaded into the Bio-ink disintegrates allowing the cells to interact more with each other. This increased cell–cell interaction creates stronger bonds between the cells, which consequently allows for stronger shape formation.

3D bioprinters can be commonly classified into four groups based on their working principles. In this section, we introduced seven types of bioprinters: (1) inkjet-based, (2) extrusion-based, (3) laser-assisted, (4) stereolithography, (5) acoustic, (6) microvalve, and (7) needle array bioprinters.

The greatest importance of bioprinting lies in the resulting tissue-like structures that mimic the actual micro- and macro-environment of human tissues and organs. This is critical in drug testing and clinical trials, with the potential to drastically reduce the need for animal trials.

Here are a few of the main application areas of bioprinting (Fig. 6.70):

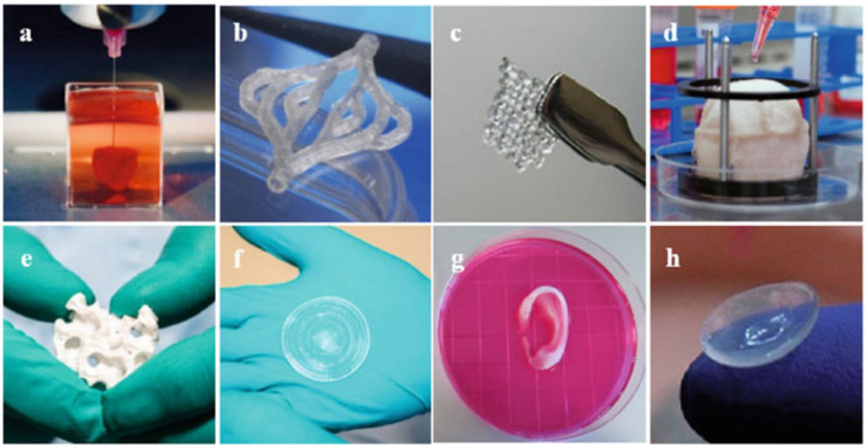


Fig. 6.70 Examples of 3D bioprinted tissues: **a** heart, **b** blood vessels, **c** ovarian cells, **d** bladder, **e** bone, **f** skin, **g** ear, and **h** cornea (Saini et al. [69], 4966.—licensed under CC BY 4.0)

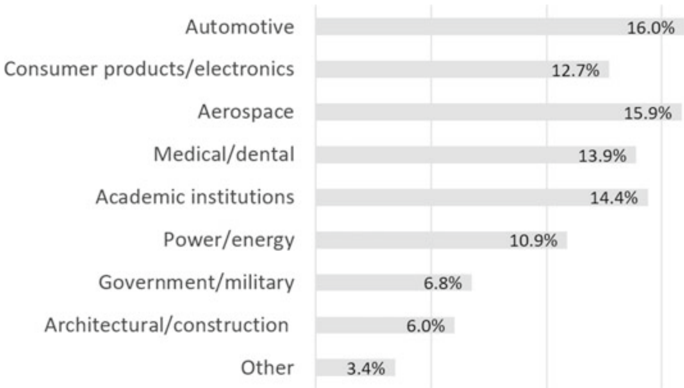


Fig. 6.71 AM Industry sector use percentages (Courtesy Wohlers Associates, generated by Olaf Diegel)

- *Artificial organs* are one of the greatest drivers of the technology due to the high rise of vital organ failure. Availability of AM produced organs helps to solve organ-related issues faster and quicker.
- Development of tissues for *pharmaceutical testing*, when AM, is a more cost-effective and ethical option. It also helps in identifying side effects of drugs and allows recommended drugs to be administered to humans with validated safe dosages.
- *Cosmetic surgery*, particularly plastic surgery and skin grafting, also benefits from the technology. In this particular application, bioprinted skin tissue could be commercialized. Some AM produces tissues are already being bioprinted for research on therapeutic purposes.
- *Bone tissue regeneration* as well as prosthetics and dental applications.

There are various other uses and applications of bioprinting, including producing foodstuffs such as meat and vegetables.

6.4 AM Applications in the Transport Industry

6.4.1 Aerospace Industry

The advantage of additive manufacturing (AM) has made the aerospace industry a substantial user of AM. In 2019 the aerospace sector represented approximately 15% of the overall AM market (Wohlers Report 2020) (Fig. 6.71).

A good example of aerospace industry adoption is the GE GE9X engine, manufactured by GE Aviation, used on the Boeing 777X that was recently certified by the FAA, and is the most fuel-efficient engine in its class (Fig. 6.72). The engine has over 300 AM manufactured parts, including 3D-printed titanium aluminide turbine blades and fuel nozzle tips.

The aerospace sector was an early adopter of AM, with companies such as Boeing and Bell Helicopters using AM to produce non-structural polymer parts since the mid-1990s. Since then, Boeing has installed over 60,000 production parts on 16 different commercial and military aircraft. Other heavy users of AM include Airbus, the European Space Agency, Honeywell Aerospace, Lockheed Martin, NASA, Northrup Grumman, and SpaceX (Fig. 6.73).

While prototypes for aerospace components can be made from a range of plastic materials, the main interest from the industry is in end-use functional parts for aerospace applications, and these must meet stringent requirements. Top-quality flight-certified materials are, therefore, necessary to 3D print functional parts. The selection of flight-worthy materials is still relatively poor but is growing rapidly. There is currently a choice of engineering-grade thermoplastics (Polyethylenes such as ULTEM 9085 and ULTEM 1010, and polyamide compounds such as: Nylon 12

Fig. 6.72 GE9X engine used on the Boeing 777X (Courtesy of Boeing and GE)

Fig. 6.73 Spark igniter manufactured using AM in Inconel 718 (Courtesy of NASA Marshall Space Flight Center, Photo by Olaf Diegel)

FR) and metal powders (high-performance alloys, titanium, aluminium, stainless steel, and nickel-based alloys, for example).

Reduced production times and speed to market

AM can substantially reduce production times and therefore increase speed to market, which can represent competitive advantage to companies. An example of this is the MGTD-20 Gas-turbine engine which is used on a Russian UAV. By using AM the engine was reduced to half the cost and was 20 times faster to produce.

Light-weighting

In the Aerospace industry, the amount of scrap material generated in production is referred to using the buy-to-fly ratio, which is defined as the ratio of the weight of raw material used to manufacture the part to the weight of the final part. With conventional manufacturing titanium aircraft components, for example, may have a buy-to-fly ratio between 12:1 and 25:1. This means that 12–25 kg of raw material is required to produce 1 kg of parts. This means that up to 90% of the material is machined away. In contrast, metal additive manufacturing can reduce this ratio to between 3:1 and 12:1. This is because metal AM typically use only the necessary amount of material needed to create a part, with only a small amount of wastage for support material. It is this comparatively low buy-to-fly ratio that makes AM so critical to the aerospace industry and has seen this industry become its most vital proponent.

Any reduction in overall aircraft weight results in considerable fuel saving, so the lighter parts enabled by AM produce considerable savings for the aerospace companies. In addition, any consumer products that have to be shipped around the world by air benefit by being lighter and both costing less to ship as well as also aiding in reducing the aircraft fuel consumption.

Weight savings are highly relevant to space applications too. Every kilogram that needs to go up to space will cost around US$20,000 to get there so, again, any reduction in weight can result in substantial cost savings. An example of this is the Atos titanium satellite mounting bracket with weight reduced by over 950 g (the original component weighed 1454 g, the new component AM made weighed only 500 g) or a 70% weight reduction over the conventionally manufactured part.

A similar example of such weight reduction is Swiss company RUAG, where they were successful in redesigning a Sentinel satellite bracket for AM in which the minimum stiffness requirements were exceeded by more than 30%, while its weight was reduced by 40% and met all space industry requirements tests.

Part consolidation

Part consolidation is another advantage made possible by AM. Part consolidation is about taking a product that was conventionally manufactured by assembling many simple parts into a product made of much fewer parts. Fewer parts means fewer production steps and labor, fewer chances of assembly faults, fewer joints to lea and, in most case, also represent substantial weight reductions.

Fig. 6.74 Leap fuel nozzle (Courtesy of GE Additive)

An example of this that has seen a lot of press is the GE LEAP engine fuel nozzle, in which the company was able to bring the number of components needed down from 20 to just 1 (Fig. 6.74).

Repairs and maintenance

Although AM largest area of growth is in final-part production, its use in non-direct part production should not be ignored. The last decade has also seen AM being used a great deal for the production of jigs and fixtures, as well as in many production and maintenance tools.

Maintenance and repair are extremely important functions in the aerospace industry. The average lifespan of an aircraft ranges between 20 and 30 years, making maintenance, repair and overhaul, if it can be aided or ameliorated through the use of AM a critical advantage.

6.4.2 Railway Industry

The railway industry is an exciting field to watch when it comes to the adoption of additive manufacturing. Various companies have begun deploying the technology for use in the production of on-demand spare parts. Below follows an account of a small number of operators, but it is reasonable to assume that similar needs and procedures to fulfill these needs are valid also to a greater number of operators. One of the leaders in adopting AM technology is Siemens Mobility Services, which work with the printer manufacturer Stratasys to print maintenance parts for the for the German and UK rail industries.

Dutch Railway is using 3D printing to produce spare parts. Not only is the railway industry growing, but so is 3D printing spare parts for trains, which will also segue into producing end parts. GE Transportation merged with industrial train part manufacturer Wabtec in 2018, which then bought GE's H2 metal binder jetting system with the plan to use it in the production of up to 250 components by 2025. Additive manufacturing enables Siemens Mobility Services to keep original parts available for rail traffic over decades and improve their designs—all based on 3D data and without a need for tools. What Siemens is offering is called Easy Sparovation Part. It opens new possibilities for replacing and modernizing system parts and upgrading vehicles with new components. For example, it provides spare parts equipped with newly integrated functions and significantly fewer individual components. With Easy Sparovation Part from Siemens Mobility Services, spare parts are manufactured as required—based on prepared CAD component data. One of the many advantages is the rapid availability of spare parts produced by AM technology—ideal for sporadic demand that cannot be scheduled, such as parts needed due to accidents or vandalism. Additive manufacturing enables Siemens's customers to incorporate new insights gained from practical applications and materials technology, implement ergonomic improvements, and integrate additional functions—turning spare parts into "improved parts". An example on how Siemens have expanded their business with AM technology is that they have bought two Stratasys Fortus 450mc systems to produce spare parts for its Russian business, just as Siemens Mobility have been awarded a contract to build 13 high-speed Velaro trains for RZD, a Russian train company (2019). Siemens will not only construct the vehicles but maintain and service them over the next 30 years. Siemens has already installed two new Fortus systems in its Siemens Mobility locations in St. Petersburg and Moscow. There, the 3D printers will be used to execute the German multinational's Easy Sparovation Part network, in which 3D print parts from a digital inventory allow for in-house production of spare parts. This contract allows Siemens to service 16 existing trains and an additional 13 over the next 30 years using AM technology. The Fortus 450mc systems may print using industrial-grade materials that can operate in the extreme temperatures that Russia is known for. Stratasys also offers materials that meet the regulatory certifications necessary for 3D printing interior cabin parts.

Raise3D is an innovative manufacturer of AM technology. They visit depots and locomotive repair plants; these visits have produced a list of scarce pieces and other products with delivery problems. This could be discontinued component parts or products with lost documentation. If necessary Raise3D scan parts or create 3D models in software for reengineering. They have recently made a sleeper transfer, which is intended for transfer rail tracks, using their 3D printers.

Also, Bombardier is no stranger to 3D printing. Bombardier Transportation is a global mobility solutions provider. Its lead engineering site for the region Central and Eastern Europe and Israel is in Hennigsdorf, Germany. This location is responsible for pre- and small-series production of mainline and metro projects, as well as design validation to enable the large-scale manufacture of passenger vehicles at other Bombardier Transportation sites around the world. In May of 2019, they adopted the Stratasys F900 3D printer to be used for 3D printing end-use rail parts. They have also stated in the past they would like to install a 3D printer in every engineering department for prototyping parts.

For Bombardier Transportation, the printer F900 marks a shift in service. Bombardier Transportation is now building a digital inventory, ensuring spare part needs are fulfilled on-demand regardless of the train model or its age. By simply storing 3D scans of parts, Bombardier Transportation bypasses the physical storage of parts. When a part is needed, Bombardier Transportation uses the F900 to build it from the digital CAD file. A significant benefit of the F900 is the way it enables the team to quickly recreate digital parts into certified train-ready parts, leading to fast and direct service for its customers. According to Marco Michel, Vice President Operations at Bombardier Transportation, the integration of Stratasys additive manufacturing at the Hennigsdorf-based facility has enabled the company to manufacture certain customized spare parts on-demand via digital inventory at significantly lower cost.

CAF, a Spanish manufacturer of railway vehicles, equipment, and buses, has also succeeded in using 3D printing for production of spare parts and functional components. Since September 2016, CAF is said to have produced around 2 400 3D-printed parts for use in its rolling stock, including cup holders, radio brackets, window frames, wiper covers, and door supports. The company also uses large-scale 3D printing to produce external parts measuring up to several meters. Among such parts are front-end components, 3D-printed for an Urbos tram. CAF names the ability to produce parts, with different dimensions and complex geometries, as a key benefit of 3D printing technologies. The company says it helps them to break the dependency on molds and original patterns when producing components, reducing the time to market for a new part.

AM technology provides SJ (Swedish Railways) with a simpler production, cheaper spare parts, and higher quality. The AM effort at SJ is an important part in their new program for digitalization. The program is intended to strengthen long term competitiveness by providing better punctuality of the trains and more satisfied customers. The first 3D-Printed spare parts at SJ are the further development of a toilet paper holder in plastics for the 3000-trains, air vents, electrical sockets, and a toilet door lock in metal. SJ focus on spare parts that are no longer available on the market that are expensive to replace. Anders Gustavsson, one of the heads of project managers at SJ claims that more and more spare parts will be printed for the

SJ trains. Anders Gustavsson argue that AM has an enormous potential from a range of different perspectives. He asserts that lead times, store holding, design, logistics and administration will all be positively affected. The most importantly for SJ is however to keep all the trains rolling. AM technology will contribute to this end by offering more effective maintenance and more “robust” trains. So far, only less critical parts have been printed. But SJ has recently started to consider printing also more challenging parts. The first part is a box lid for a bearing that must pass a thorough safety test. SJ collaborates with, for example, Postnord Stålfors who delivers AM services. SJ is also a part of an international network of leading digital enterprises where knowledge exchange drives the development of AM technology even further. Andreas Stjernudde, IT project leader at SJ, states that this is necessary as the 3D industry must work harder to lower the cost of 3D printing to make the technology competitive enough for a greater number of companies.

6.4.3 Maritime Transport Industry

The maritime transport industry has not adopted additive manufacturing at the same rate as aerospace or the automotive industries, but is gaining momentum on their own terms. The aerospace industry and automotive industry have had strong incentives to adopt early AM technologies, among others, the need for lightweight parts. The maritime transport industry is still discovering the different usages and benefits it can get from the technology. As of November 2020, the world fleet value is estimated to be worth USD 950 billion with an average annual capital allocation to new vessels estimated at USD 88.7 billion. The maritime transport industry, as virtually untouched markets, are very promising segments for additive manufacturing.

The structure of this industries is quite specific, especially the ship industry. It relies heavily upon a system of classification and certification by third parties, the classification societies, for ships to be sold, registered and insured. This is indispensable to assure that ships can sail months at sea under harsh conditions, and to assure the safety of persons and goods. Introduction of new technologies, materials and components in the ship industry depends on this classification and certification system. The classification societies have been central to the ship industry under a long time. The first classification society, Lloyd’s register (LR) has been established in 1760, Bureau Veritas (BV) in 1828, American Bureau of Shipping (ABS) in 1861, Registro Italiano Navale (RINA) in 1861, Det Norske Veritas (DNV) in 1864, Germanischer Lloyd (GL) in 1867. All these classification societies still exist today (GL has merged with DNV in 2013 to form DNV GL; the society changed its name to DNV in March 2021). There are exceptions to this general scheme, for example components not critical to safety do not generally need to get certified, but the pace in which the industry is introducing AM is largely dependent upon the possibility to certify materials, components and products.

The boat industry has a more diverse organization, depending on the size of the boat and on the flag state. Very small boats or racing boats do not typically need such types of certifications. But in Europe, for example, pleasure boats from 2.5 to 24 m must comply to the Recreational Craft Directive, which imposes boats to be CE marked by a notified body, some of them being classification societies (RINA, DNV, BV). Safety concerns, cost and a conservative mindset in some boat segments are also delaying the introduction of AM.

The classification societies have started working on the challenges and benefits of AM very recently. LR and DNV, for example, started their investigations in 2014. However, the classification societies and the industry in general have worked systematically and at high speed. Relatively quickly, the first certification guidelines for the additive manufacturing technology have been published: LR published its *Guidance notes for Additive Manufacturing certification* in January 2016, DNV guidelines are from November 2017, and ABS guidelines are from September 2018. Since then, 3D printed products have started to be certified, along with manufacturing facilities. The latter is important because it accelerates the certifications of products manufactured in these sites. Examples of certified manufacturing facilities are AML Technologies (Australia) that became the first wire-arc additive manufacturing (WAAM) facility to get an LR certificate in 2018, and Thyssenkrupp, which became the first company certified for additive manufacturing and post-processing of austenitic stainless steel parts by DNV in summer 2019. The whole industry in general is multiplying research and joint industrial programmes to ease the development and diffusion and of the AM technology. Especially Singapore is aspiring to become an AM technology hub and has invested heavily in this segment. Most classifications societies and major industrial actors have AM facilities in the city-state. All in all, the ship industry strategic and disciplined work might well become a textbook case of a progressive, but systematic and fast, deployment of the AM technology, and is worth following up.

Industrially commercialized products are thus starting to appear, but most of the current products, even if fully functional and installed on ships, are part of feasibility study projects. The main focus of the industry is currently on spare and replacement parts. Spare and replacement parts represent USD 13 billion a year and older vessels suffers from part availability. In a market feasibility study performed by major actors of the industry and partly funded by Singapore, 100 parts were shortlisted and their potential for 3D printing analyzed, among the 600,000 parts ordered by the industrial partners in the last three years. This gives a direction for further application of the AM technology. Such inventories happen worldwide. U.S. Navy's Naval Sea Systems Command (NAVSEA), for example, has approved a total of 182 3-D printable parts (October 2020) and more than 600 more are undergoing engineering review.

The first certified 3D-printed propeller (verified by BV) was manufactured in 2017. A replacement part, it was developed by Promarin, manufactured by The Rotterdam Additive Manufacturing LAB (RAMLAB), in collaboration with Autodesk, Damen Shipyard Group and BV. It was fabricated with the WAAM technique, which is in essence a welding technique where the welding material are melt on top of each others layer by layer (Fig. 6.75). The printing took ten days; the 1.2 mm filament used was a nickel-aluminium-bronze alloy. Weighing 180 kg after post-processing

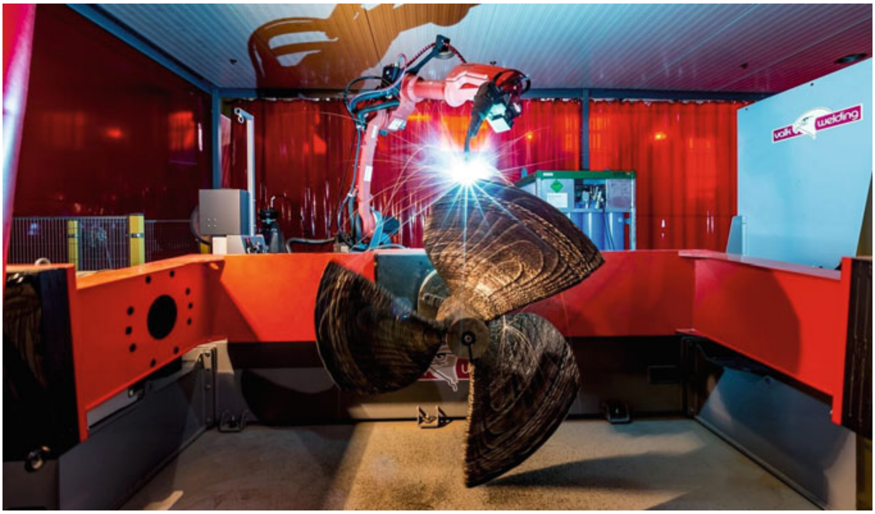


Fig. 6.75 Manufacturing of the WAAMpeller (Courtesy of RAMLAB)

(Fig. 6.76), it is installed on a Damen Stan Tug 1606, a 15.5 m long, 5.5 m broad tug with a 16-ton bollard pull (Fig. 6.77).

Wilhelmsen group, a products and services company for the merchant fleet, has partnered with Ivaldi group, a 3D printing company focusing on the marine industry, to redesign spare parts for its customers in an early adopter program to assess the possibilities and gains of AM for different components. Thus, a handwheel made of cast iron has been re-designed in polyamide/nylon. Polymer handwheels present the advantage of preventing damage to valve stems compared with traditional handwheels. Another product is the scupper plug, used to close drainage holes to prevent oil or contaminant spills. They do not exist in standard forms. 3D printed scupper plugs as spare and replacement parts have been developed for Berge Bulk, a major

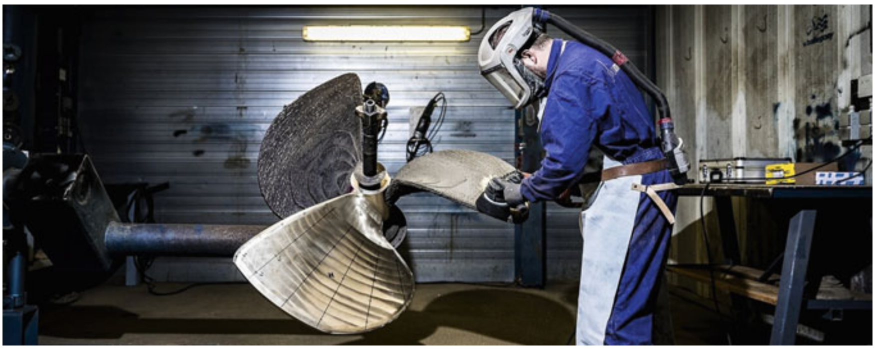


Fig. 6.76 Post-processing: grinding the WAAMpeller (Courtesy of RAMLAB)

Fig. 6.77 The WAAMpellers on the Damen Tug (Courtesy of RAMLAB)

dry bulk cargo owner. All the elements of the part had to be redesigned, the biggest challenge was making the insert expand without collapsing. The first scupper plugs have been delivered on the *Berge Mafadi* in 2020, see Fig. 6.78. A 3D pattern for sand casting of a guide bar has also been developed by Wilhelmsen group and Ivaldi group (Fig. 6.79). According to, the original manufacturing cost of the guide was USD 2000 with a lead time of twelve weeks; the current manufacturing cost is USD 1225 for a lead time of four weeks. The 3D printed pattern cost is of USD 22.74 (wooden pattern cost: USD575.00). All these components have showed shorter lead-time and cost benefits.

Sembcorp Marine, a large engineering marine company, and 3D Metalforge, a well-known metal printer manufacturer, together with the classification society ABS, have developed and installed working 3D-printed mechanical parts aboard the oil tanker *Polar Endeavor* (shipowner ConocoPhillips Polar Tankers). According to ABS, the replacement parts (see Fig. 6.80) are of higher quality than conventionally manufactured products.

The number of 3D printed spare parts in use is quite small and the number of new parts developed with 3D printing is even smaller. But not less impressive. One

Fig. 6.78 Left: Damaged scupper plug. Right: 3D printed scupper plug (Courtesy of Wilhelmsen group and Ivaldi group)

Fig. 6.79 Left: 3D pattern (bottom)/wood pattern (top). Right: Guide bar (Courtesy of Wilhelmsen group and Ivaldi group)

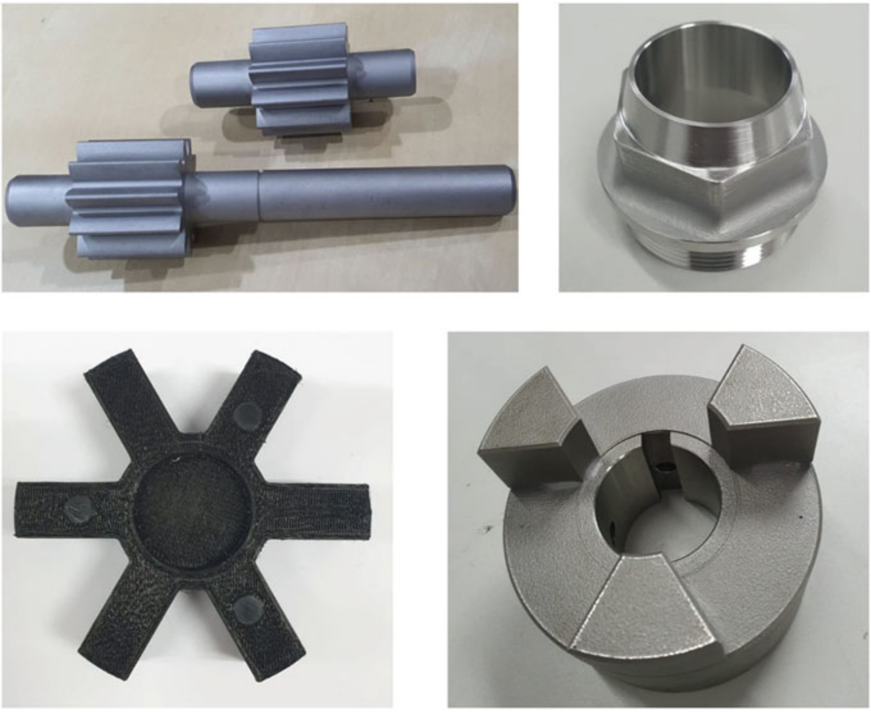


Fig. 6.80 Top left: Gear set with shaft for a centrifugal pump. Top right: nozzle for a combined brine/air injector. Bottom: full flexible coupling for an effluent pump (Courtesy of Sembcorp Marine and ConocoPhillips Polar Tankers Inc.)

example is the hull of the TAHOE T16, from White River Marine Group, a five-meter-long speedboat. 3D printing was used to create a pattern onto which the hull mold was cast. The hull mold was then used to manufacture several hulls. This is the same manufacturing principle as that of the fabrication of silicone molds, see Sect. 6.1.1. The pattern of the T16 hull has been manufactured with the help of a large-scale additive manufacturing technique (SLAM), by Thermwood. The development of the pattern has been done in collaboration with Techmer PM and Marine Concepts. The pattern, about 4 cm thick of 20% carbon fiber filled ABS was manufactured in six sections (Fig. 6.81). The printing took about 30 h. After printing, these sections were bonded together (Fig. 6.82) and machined. The trimmed pattern, with a weight of about 1500 kg, was sanded and polished. The fiberglass mold was then cast on the pattern (Fig. 6.83). The whole manufacturing process took about ten days. According to Thermwood, the process could be accelerated with the use of a vertical layer printer. A vertical layer printer, as the name indicates, prints the layers vertically instead of horizontally. This allows for a printing in one part instead of sections.

New parts developed with additive manufacturing in the ship industry are following a classical learning process, starting with re-design of existing products to take advantage of the cost effectiveness of AM for small, and rapid tooling, such as the hull patterns. The other advantages of AM, such as form freedom, reduction of components, have been very scarcely explored. The racing boat segment,

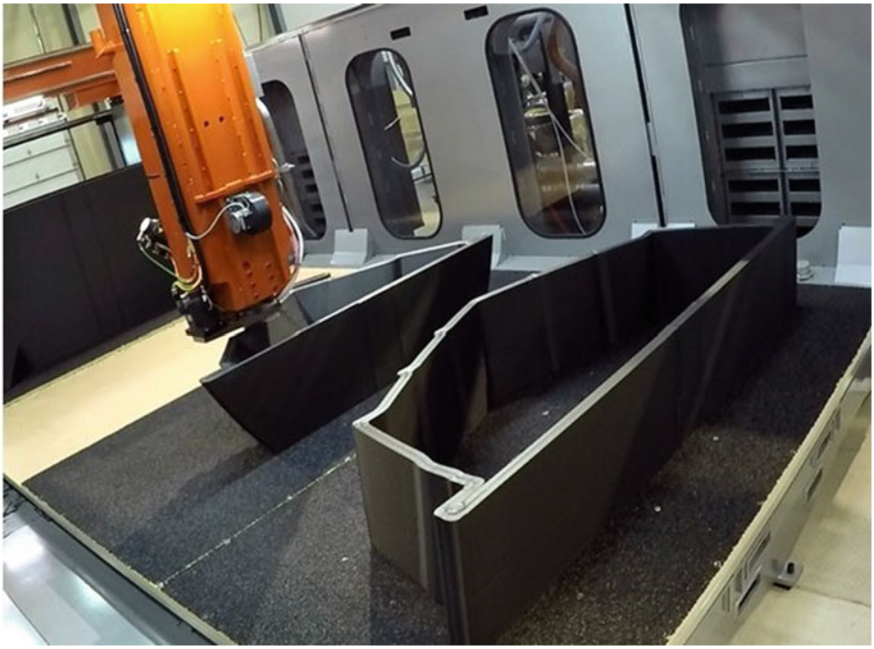


Fig. 6.81 Thermwood LSAM (3 m × 6 m) machine printing two of the six sections (Courtesy of Thermwood)

Fig. 6.82 Boat hull pattern after bonding together and before machining (Courtesy of Thermwood)

however, has some showcase of advanced 3D-printed components. Renishaw, a global engineering company, has developed manifolds for the Land Rover BAR, an America's Cup class yacht. The AM-based manifold is smoothing the hydraulic fluid flow decreasing power loss compared to a manifold manufactured with conventional methods (Fig. 6.84). Several other components of the Land Rover BAR have been designed with the AM process in mind (Fig. 6.85). The Land Rover BAR racing catamaran was one of the five participants to the 2017 Louis Vuitton America's Cup Challenger Playoffs, held to determine the challenger in the 2017 America's Cup (Fig. 6.86).

After the 2017 America's Cup Renishaw went on to work with INEOS TEAM UK in the 2021 America's Cup. Renishaw has developed, among several AM-based components, a mast ball for the T5 test boat (Figs. 6.87 and 6.88). The mast ball function is to transmit power from the rig into the foiling hull. Topological optimization was used in the design process, resulting in a stronger component than the original while weight was decreased by 20%.

As the ship and boat industries are rapidly adopting the AM technology, this review of current industrial applications is to become rapidly obsolete. Therefore, a glimpse of the very near future applications, for at least the most obvious application

Fig. 6.83 Removing fiberglass mold from boat hull pattern (Courtesy of Thermwood)

Fig. 6.84 Demonstration Land Rover BAR metal AM hydraulic manifold (Courtesy of Renishaw—© Copyright Renishaw plc. All rights reserved)

of 3D printing, is also presented. First, 3D printing is not only to be used for ships, but can also be used in ships. In the short run, printers on board could be used for printing simple spare parts. In the long run, they could be used as a mobile manufacturing centers, printing on the go or on sites where parts are difficult to obtain or are urgently needed (humanitarian crises or military operations). There are already 3D printers on ships: the *USS John P. Murtha*, a 200-m-long transport dock, has printers installed on board, with the possibility to print plastic parts. Maersk Tankers had also installed

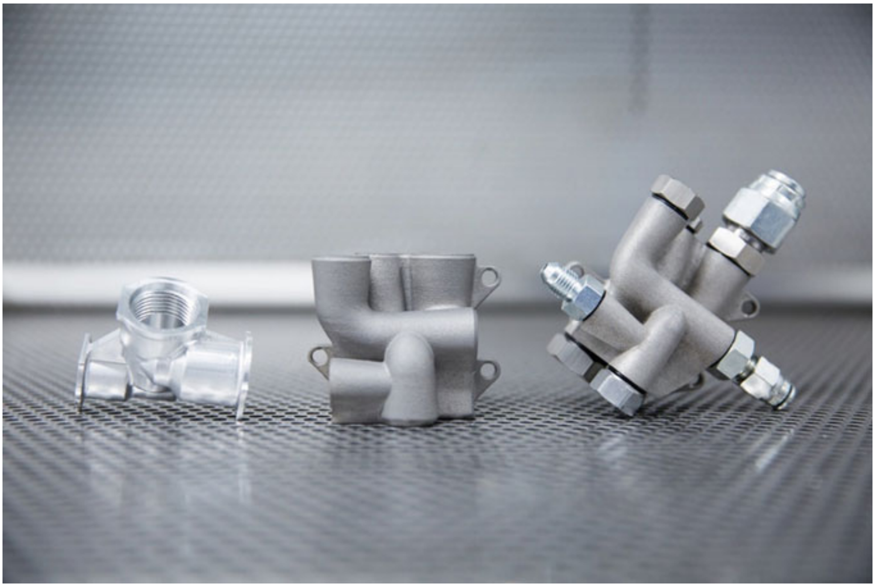


Fig. 6.85 Metal 3D-printed hydraulic system parts made by Renishaw for the Land Rover BAR yacht (Courtesy of Renishaw, credit: Harry KH)

Fig. 6.86 The Land Rover BAR racing catamaran (Courtesy of Renishaw, credit: Harry KH/Land Rover BAR)

nine tabletop printers on six ships and two rigs to test the possibility of printing spare parts, as part of a project from Green Ship of the Future, funded by the Danish Maritime Fund in 2017–2018. In this project, IP rights challenges were addressed, the printers being equipped with an encryption technology that ensured that the part models could not be re-used elsewhere. The constraints of a printer at sea (vibrations the rolling movements of the ship), the need for expertise and materials are currently limiting this technology to specific usages such as simple, non-critical parts with no

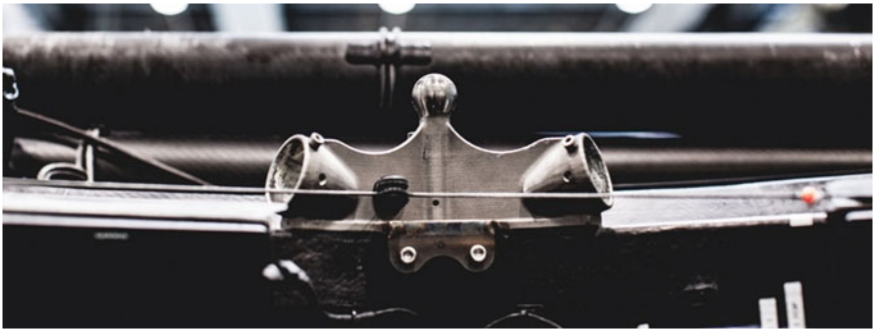


Fig. 6.87 T5 mast ball (Courtesy of Renishaw, credit: Harry KH/INEOS TEAM UK)

Fig. 6.88 The T5 test boat (Courtesy of Renishaw, credit: C Gregory/INEOS TEAM UK)

Fig. 6.89 DIN rail for relays and flexible couplings for IGG DO pump (orange is original), 3D printed on board (Courtesy of Maersk Tankers and Green Ship of the Future)

need of expertise. The following figures show examples of products printed on board during the project (Figs. 6.89 and 6.90).

The printing of molds for large ships (yachts) is also nearly feasible, such as illustrated with the figure below. Figure 6.91 shows two 1.5 m sections (screwed together) of a yacht hull mold, developed and manufactured by Thermwood. The material used is carbon fiber reinforced ABS thermoplastic.

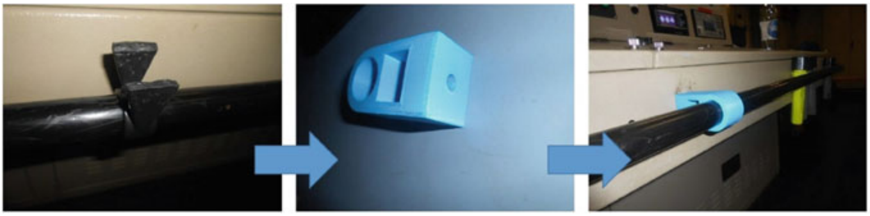


Fig. 6.90 Rail bracket replacement, 3D printed and installed on board (Courtesy of Maersk Tankers and Green Ship of the Future)

Fig. 6.91 Three-meter section from a 15-m-long yacht hull mold (Courtesy of Thermwood)

Last but not least, several boats have been directly printed. These are prototypes, still under test or development (one big concern is delamination of the printed layers), but quite near a fully functional product. The biggest one-piece printed boat is *3Dirigo* (Guinness World record), developed by Navatek, a ship design company, on the model of the Seablade 25, and manufactured in September 2019 by the UMaine Advanced

Fig. 6.92 3D printed boat from RISE and Cipax (Courtesy of RISE, Photographer Anna Hult AB)

Structures and Composites Center of the University of Maine. *3Dirigo* is 7.6 m long for 1350 kg. She was printed in plastics with 50% wood in 72 h with LSAM. She has been tested at the Alfond W^2 Ocean Engineering Laboratory, a facility equipped with a multidirectional wave basin and a wind machine. Another one-piece boat has been developed and manufactured by RISE Research Institute of Sweden, in collaboration with Cipax and other partners. Cipax is the company that owns the boat model, a Pioner 14 Active Dark Line. The boat is 4.2 m long. Seaworthy, she was launched in December 2020 in Gothenburg (Fig. 6.92). A significant advantage of a printed boat is the possibility to customize her for specific groups of users, such as law enforcement or fire service. There are still some challenges before 3D printed boats be able to fulfill the same specifications as conventionally manufactured boat. One is for example that the material for 3D printing is denser, which may require some specific requirements for maintaining floatability when the boat is full of water.

As an alternative to one-piece boats, Moi Composite, a company based in Italy, has developed a boat, the *MAMBO*, whose hull and deck consists of 50 printed parts (Fig. 6.93), made of continuous fiberglass and thermosetting vinyl ester resin, which have then been adhesively bonded and reinforced (laminated) fiberglass/polyester layer cored with PVC, before being sanded, primed and gel-coated. The continuous fiber manufacturing technology (CFM), patented, makes use of a robot depositing continuous fibers impregnated with thermosetting resin that is cured immediately (Figs. 6.94 and 6.95). Officially unveiled in October 2020, the *MAMBO,* 6.5 m long and of weighing 800 kg (1200 kg all equipped), is fully seaworthy, reaching a speed up to 26 knots (48 km/h). With curvatures that are impossible to manufacture conventionally, and no division between hull and deck, she is a telling example of the AM free-form possibilities for functionality and aesthetics (Fig. 6.96).

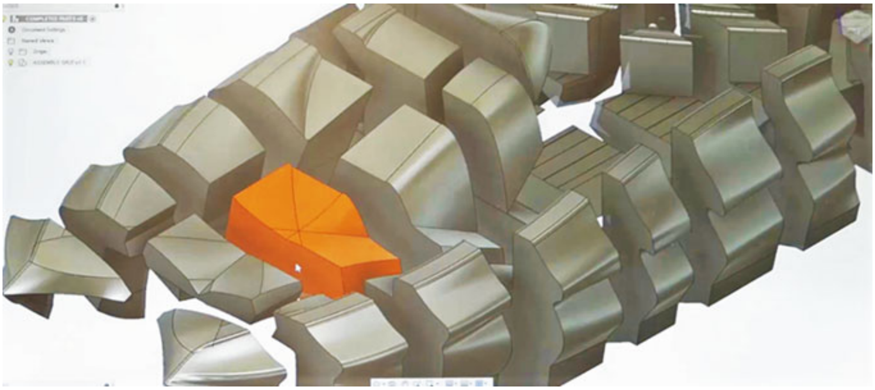


Fig. 6.93 CAD model of the boat section (Courtesy of Moi Composites)

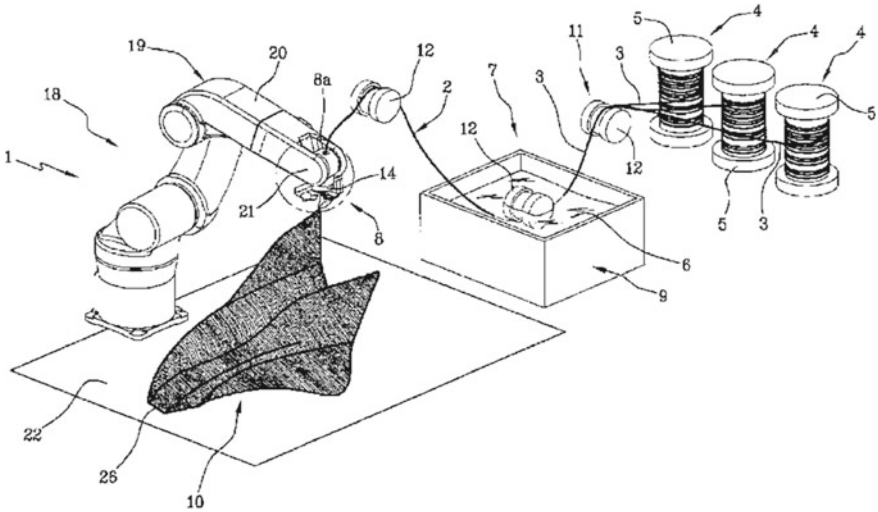


Fig. 6.94 The CFM technology

6.4.4 Automotive Industry

AM is rapidly growing technology that enable designers to create rapid prototypes as well as complex designs, which would not have been possible through traditional manufacturing processes. 3D printing in the automotive industry is expected to reach a market value of 2.5 billion dollars in the next 3 years. The novel technology provides innovative designs and design freedom. AM is used for testing, manufacturing, and assembling automotive parts and components with higher efficiency, optimization, and cost-efficiency.

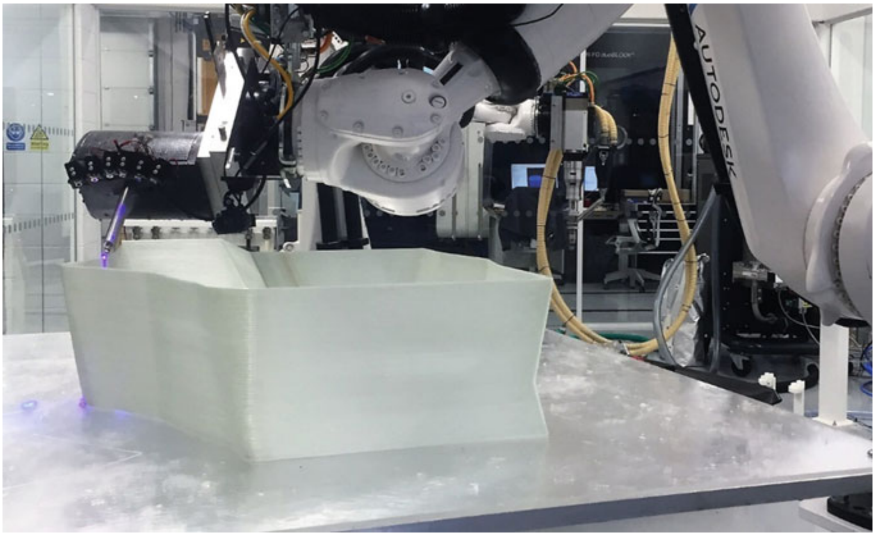


Fig. 6.95 Robot equipped with the CFM technology, printing of one boat section (Courtesy of Moi Composites)

Fig. 6.96 The MAMBO at sea (Courtesy of Moi Composites)

The role and importance of the additive manufacturing in automotive design and manufacturing stages can be split in 5 stages: Design, Validation, Pre-production, Production, and Customization (Table 6.3). The designs in the automotive industry usually start out as scale models that show the shape of a vehicle. The right models allow the design to progress smoothly and exhibit the general form of a concept. AM prototyping is common in the automotive industry. Moreover, AM enables the automotive industry to produce customized car parts quickly at low cost.

AM technology is not new to the automotive industry, it was recognized as an opportunity three decades ago. The developed and manufactured components range

Table 6.3 AM in different phases of automotive life cycle

Design	Designs in the automotive industry often begin as scale models showcasing the form of a vehicle. These are often also regularly used for aerodynamic testing. Accurate models allow design intention to be clearly communicated and showcase the overall form of a concept
Validation	AM is used a lot for different prototyping in the automotive industry. From a full size parts printed with low cost fused deposition modelling (FDM) to a detail, full color components. Some AM engineering materials allow testing and validation
Pre-production	AM is used most for the production of low cost rapid tooling for injection molding, thermoforming and jig and fixtures. Tooling can be quickly manufactured at a low cost and then used to produce low to medium runs of parts. This validation mitigates the risk when investing in high-cost tooling at the production stage
Manufacturing	AM is a viable option for many medium-sized production runs, particularly for higher-end automobile manufacturers with limited production numbers
Customisation	Parts can be tailored to a specific vehicle (custom, lightweight suspension arms) or driver (helmet or seat). AM enables part consolidation and optimize topography of many custom automotive components

from prototypes to small plastic mountings and highly complex metal chassis parts. Car manufacturers are always looking for new ways to reduce their product's weight. A lighter car consumes less fuel, which makes it more environmentally friendly. Lighter structures can be achieved with design patterns such as lattices or reduce the number of parts with optimized design of the components.

By eliminating the need for new tooling and directly producing final parts, AM cuts down on overall lead time, thus improving market responsiveness. Furthermore, AM-manufactured lightweight components can lower handling costs, while on-demand and on-location production can lower inventory costs. Finally, AM can support decentralized production at low to medium volumes. All these AM capabilities combined allow companies to drive significant change within the supply chain—including cost reductions and the improved ability to manufacture products closer to customers, reduce supply chain complexity, and better serve consumer segments and markets without the need for extensive capital deployment.

The most common uses of additive manufacturing in the automotive industry are still prototyping, tooling, jigs and fixtures. However, the last two decades delivered a big progress, and additive manufacturing in automotive is expanding beyond these applications. Here are several examples from well-known automakers using additive manufacturing, their efforts, goals and boldest applications.

Examples of additive manufacturing

BMW has several implemented printed parts to their vehicles such as the convertible's roof bracket which has a unique complex shape that is very hard to produce using traditional methods. BMW demonstrated the first installation of brake calipers with bionic design. The calipers are 30 per cent lighter than conventional components and were manufactured using a metallic 3D printing process. This masterpiece

Fig. 6.97 Developed by Bugatti: This eight-piston monobloc brake caliper is the world's first brake caliper to be produced by 3-D printer and also the largest titanium functional component produced by additive manufacturing. (*Image credits* (© 2018 Bugatti Automobiles S.A.S.)

is carried along by 20" BMW Individual light alloy wheels in 730i V-spoke design. Another application of AM technology is the brakes of the new BMW M850i Coupe Night Sky Edition.

The brake calipers of the Chiron sport car are produced using bionic principles on the basis of a natural model (Fig. 6.97). The new architecture combines minimum weight with maximum stiffness. The inspiration for the design and mode of operation of the brakes was taken from motorsports. This particular titanium alloy, with the scientific designation of Ti6AI4V, is mainly used in the aerospace industry, for example for highly stressed undercarriage and wing components or in aircraft and rocket engines. The material offers considerably higher performance than aluminum, it has a tensile strength of 1,250 N/mm^2. The brake caliper (410 × 210 x 136 mm) weighs only 2.9 kg; the weight was reduced by about 40%. The high-performance 3-D printer opens up the possibility of design and manufacturing complex structures which are significantly stiffer and stronger than would be possible with any conventional production process.

Audi is dedicated to the manufacture of sports cars. The PolyJet technology allowed Audi to develop and evaluate different prototypes before producing the parts of a vehicle such as wheel covers, grilles, door handles or even rear light cabs, which are usually made of transparent plastic (Fig. 6.98). With 3D printing, they were able to speed up design, meeting the demands of their customers, and creation of final parts.

Additive manufacturing has a key role in motor sport, enabling the design of lighter, stronger and more efficient parts in a much shorter time frame. Ferrari use an EOS machine and titanium powder. AM increases the number of possible iterations

Fig. 6.98 The PolyJet technology allowed Audi to develop and evaluate different prototypes faster. The J750 3D enable printing of transparent plastic such as rear light cabs (*Image credits* Audi)

and accelerate its prototyping phase. The manufacturer has also designed 3D printed brake pedals with a hollow structure.

General Motors has designed a 3D-printed seat support in stainless steel for its future electric cars. The seat support would consist of only one part, as opposed to 8 different parts using conventional methods, would be 40% lighter and 20% stronger (Fig. 6.99). Manufacturing times are also reduced as there is no assembly phase at all.

Lamborghini argues that AM offers more than just saved costs and rapid production. AM represents endless opportunities of customization. Lamborghini's Sian Roadster customers are able to have their initials integrated in the design of this car element. An example, the AM technology is used to make a textured fuel cap with the Urus label and a clip component for an air duct (Fig. 6.100). No further post-processing is required after the print.

Volvo Trucks produces many jigs and tools using AM, slashing the tool turnaround times by more than 94%. Previously these tools were produced in metal using traditional manufacturing methods. The production plant's overall efficiency and flexibility was improved, helping meet delivery times while reducing waste and costs.

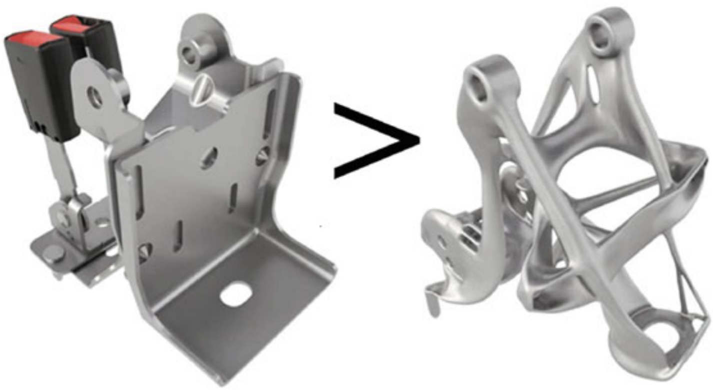


Fig. 6.99 3D-printed seat support in stainless steel for the General Motors future electric cars; designed in cooperation with Autodesk (*Image credits* General Motors and Autodesk)

Fig. 6.100 Lamborghini Urus Fuel Cover Cap digitally manufactured in EPX 82 epoxy resin (*Image credits* Lamborghini)

Different production tools include a range of different durable yet lightweight clamps, jigs, supports and even ergonomically designed tool holders that ensure a more organized working environment for operators.

Mercedes uses AM for truck parts made of metal. The components are more resistant, and cost-effectively production is enabled even for discontinued parts in small quantities. Mercedes is the first company to focus on 3D printing of spare parts for trucks.

Michelin, presented its AM prototype tire called UPTIS (Unique Puncture-proof Tire System), these tires have been designed to be airless in order to reduce the risk of flat tires and other air loss failures that result from puncture or road hazards. The wheel design was inspired by nature, with a honeycomb structure, and using only organic materials (Fig. 6.101). It gives strength to the wheel, as well as a very good resistance.

Porsche 3D printed engine pistons for the Porsche 911 GT2. The optimized pistons are 10% lighter than the traditionally manufactured ones. Porsche used a special aluminum alloy in order to obtain the best properties. Porsche dedicated to old and classic vehicles is using additive manufacturing for small series of spare parts. All parts meet the requirements in terms of fidelity, from a technical and visual point of view.

Renault Trucks Lyon Powertrain Engineering Department focused on using metal additive manufacturing for creating a prototype DTI 5 Euro-6 engine. Rocker arms and camshaft bearing caps were manufactured by metal 3D printing and successfully bench-tested for 600 h inside a Euro-6 engine (Fig. 6.102). The weight of a four-cylinder engine was reduced by 120 kg or 25%. The tests proved the durability of engine components made using AM. The number of components in the DTI 5 engine has been reduced by 25%, making a total of 200 fewer parts (Fig. 6.103).

Fig. 6.101 A prototype of Unique Puncture-proof Tire System (UPTIS) (*Image credits* MICHELIN—https://www.michelin.com/en/innovation/vision-concept/)

Fig. 6.102 A rocker arm manufactured by 3D printing on a bench test inside a Euro 6 engine (*Image credits* Renault)

Automotive parts often require internal channels for conformal cooling, hidden features, thin walls, fine meshes and complex curved surfaces. AM allows for the manufacture of highly complex structures which can still be extremely light and stable. One major benefit of additive manufacturing is that all printed parts can be post-processed in order to create a watertight and moisture resistant barrier. Part consolidation is a significant factor when considering how AM can benefit the reduction of material usage, thereby reducing weight and in the long run, cost.

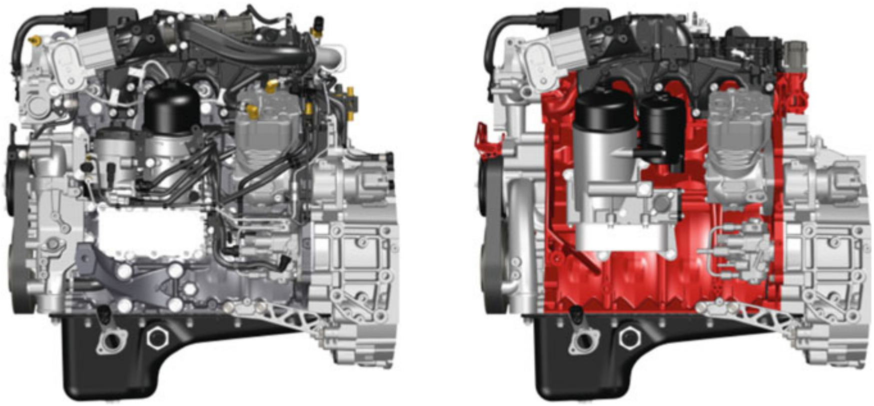
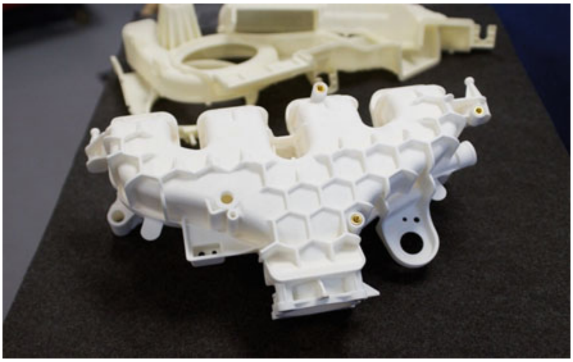


Fig. 6.103 Left: A conventional Renault Trucks DTI 5 Euro 6 engine, 841 parts. Right: the same engine exclusively designed using 3D metal printing to reduce weight and number of components (*Image credits* Renault)

By using PBF-LB/P to manufacture non-structural low volume parts for performance racing, highly optimized, and complex structures can be designed. SLS enables design in variable wall thicknesses and increase the strength to weight ratio through the application of structurally optimized surface webbing (Fig. 6.104).

Daimler AG has fully integrated 3D printing technology into the development process and series production for its commercial vehicles segment. Daimler Buses used 3D printing technology to quickly fulfill customers' individual wishes, replacement parts, and small series production. It takes a few days, from idea and design to production and delivery, to complete the entire process, which will be very economical for customers ordering small series and batch sizes from 1 to 50 units. Customers all over the world can quickly reorder any 3D printed part by looking up the specific part number, which can be found in the Daimler Buses order code lists and replacement parts catalogs. The component features multiple parts, including the lid and the handle, hinges and assembly clips, and interior compartments.

Fig. 6.104 A complex, functional ducting design printed in using PBF-LB/P nylon (*Image credits* Biehler 2014).



Formula Student Germany set out to design and build a reliable, lightweight axle-pivot (knuckle) with high rigidity (Fig. 6.105). The knuckle needed to withstand the dynamic loads that racing cars are subjected to while also reducing the overall weight of the car. The resulting design was a topographically complex single component, only capable of being manufactured using AM technologies. The final design was 35% lighter than the original design and improved rigidity by 20%.

3D Printing and the electric vehicles

As the industry moves away from the internal combustion engines toward electric vehicles, 3D printing rises as a solution that can speed up development and radically change the way we look at the design of car components. In electric vehicles, reduced weight reduces energy consumption and thus increasing driving range (Fig. 6.106).

The autonomous shuttle marks a substantial milestone in using 3D printing for EV production. The parts such as knuckle, upper control arm and a brake pedal, were

Fig. 6.105 The final optimized knuckle design (*Image credits* Uni Stuttgart, 2012)

Fig. 6.106 Arcimoto's FUV feature 3D-printed components. The use of 3D printing helped to reduce the weight of the vehicles (*Image credits* Arcimoto)

redesigned for 3D printing using generative design tool, achieving weight savings of between 34 and 49 per cent.

Applications of Additive Manufacturing in Automotive Electronics

Aside from mechanical components, additively manufactured electronic components are providing new ways to network vehicles, gather automotive data, and produce smart components. Additive manufacturing systems built for 3D printed electronics can reduce the costs and development time by embedding sensors directly into mechanical components and the structure of vehicles. Embedded sensors provide higher reliability and longer lifetime.

Power management, distribution, and charging systems for electric vehicles are a few examples of critical power electronics systems that can benefit from additive manufacturing. The adaptability of additive manufacturing processes allows designers to integrate complex components into simpler and lighter designs and print them as a single unit. This reduces material waste, decreases manufacturing time, and reduces the overall weight of the component. All of these are significant benefits for electric vehicles, helping reduce costs for consumers and improving fuel efficiency.

Additive manufacturing of Ti-45Al-4Nb-C by selective electron beam melting.

Selective electron beam melting (SEBM) is shown to be a viable production route for titanium aluminides components. Fully dense and crack free parts can be produced. The material properties were optimized by adjusting scanning strategy as well as heat treatment with particular consideration of the application to turbocharger wheels.

Basically, the measured deviation varies from +0.6 to –0.1 mm. Leading edge and trailing edge display deviations less than 0.3 mm. The transition zone between blade and hub shows a deviation in the range of +0.6 mm (Fig. 6.107). The observed errors of SEBM manufactured parts are larger than those of typical machined parts. First results of thermomechanical tests with additive manufactured turbocharger

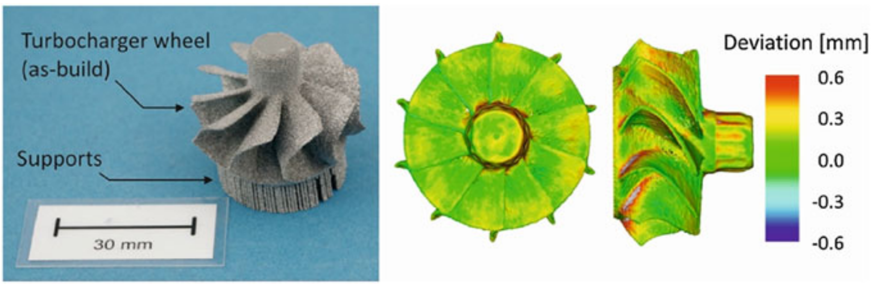


Fig. 6.107 As-built condition of turbocharger wheel (left) and resultant deviation from 3D-dataset (right). The back face is covered by supports and therefore not measured by fringe projection. The measured deviation of other sections varies from +0.6 to –0.1 mm [36]

wheels (surface roughness: as-built) display a reduced efficiency compared to standard turbocharger wheels. It is assumed, that the reduction in efficiency results from surface roughness and geometrical deviations.

Conclusions

Traditional manufacturing technologies like injection molding or casting, are very cost-effective for parts produced in high quantities of thousands and above. These methods include high initial investment and a very low cost of per-unit manufacturing. This financial model is not cost-effective for low volumes. On the other hand, AM in these cases is ideal, especially for highly complex parts. Just by eliminating the costs of initial investment or tooling, it can already save thousands of dollars, and lower the cost per part significantly.

AM promises to be a powerful complement to traditional manufacturing and the end-to-end supply chain. Mass customization will become less expensive, consumers will become micro-manufacturers, and customer demands will be met more quickly. In addition, the supply chain will become more local, globally connected, and more efficient. AM is going to change the way manufacturing will work in the future.

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Chapter 7
Development of Material and Processing Parameters for AM

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Abstract The development of parameters for a certain additive technology is the key to increase the number of materials that are processed as well as the applications. This chapter shows the details to take into account for the development of parameters for various technologies.

7.1 Development of Materials for Material Extrusion (MEX)

Material Extrusion (MEX) allows to use a wide range of thermoplastics that are commercially available in spools, satisfy nearly all the material requirements for numerous applications and are moderately priced compared to other AM techniques. Until the year 2012, the materials for MEX, especially those for low cost 3D-printers, were mainly limited to acrylonitrile butadiene styrene (ABS) and poly(lactic acid) (PLA), due to their ease of processing both in terms of filament production and MEX. Even nowadays, these two materials are still the top-sellers among the MEX material portfolio and the price of commercial filaments are around 20€/kg in a variety of colours. Recently, the material alternatives have increased considerably, leading to a variety of commercially available thermoplastics. Figure 7.1 summarises the availability of the most important polymer types as filaments for MEX; the information about the commercial availability is based on the materials advertised in numerous websites from different companies. Many polymer types (displayed in orange in Fig. 7.1) have already been commercialised, as both the industry aims to widen the material portfolio for MEX in order to expand the application of this AM technology. Besides PLA and ABS, polyethylene terephthalate (PET) and polycarbonate (PC)

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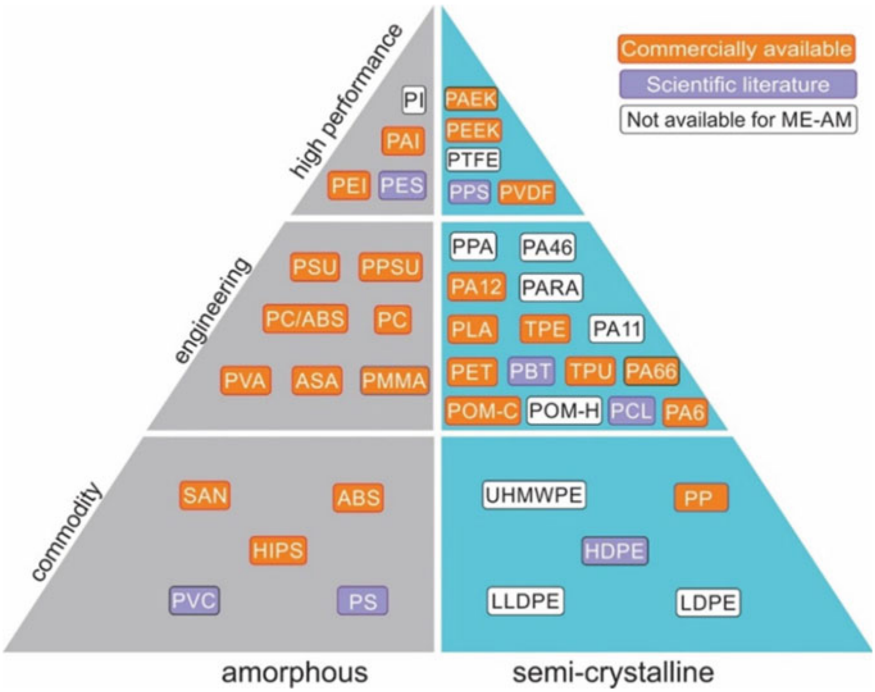


Fig. 7.1 Pyramid of polymeric materials as a function of the availability of the materials in the MEX market. For the commonly used polymer abbreviations refer to He et al. ([56]—licensed under CC BY)

can nowadays be already declared as standard MEX materials. However, most of the other materials, even those that are commercially available, cannot always be used trouble-free, thus they require plenty of hands-on experience and as such still need improvements, as has been shown for various investigated filament types.

The increase of scientific studies (displayed in purple in Fig. 7.1) on polystyrene (PS), polyether sulfone (PES), polybutyleneterephthalate (PBT), high-density-polyethylene (HDPE), polyvinyl chlorine (PVC), as well as polycaprolactone (PCL) shows the efforts to widen the material portfolio. The fact that even niche materials, such as silicone elastomers, recycled polymers, plant-based polymers, biopolymers, or highly-filled polymers for the indirect production of metals/ceramics have been under investigation for the use in extrusion-based AM confirms the versatility of MEX and reflects the wide spread use of MEX for many applications. Nevertheless, the usability of such novel materials for MEX as an everyday usable and reliable material such as PLA or ABS will be determined in the future.

By looking at Fig. 7.1, it can be seen that many amorphous polymers are available commercially. This is because amorphous materials have a low coefficient of thermal expansion, which facilitates their processability by MEX, especially in terms of shrinkage, warpage, and distortion. However, many of the amorphous polymers have low toughness, a narrow range of service temperature, and a weak resistance to chemicals. Figure 7.2 also shows a smaller proportion of semi-crystalline thermoplastics available for sale. Especially polymers with a high degree of crystallinity, such as the commodity semi-crystalline plastics, namely low-density-polyethylene (LDPE), linear low-density-polyethylene (LLDPE), ultra-high molecular weight polyethylene (UHWMPE), polyoxymethylene homopolymers (POM-H), polytetrafluoroethylene (PTFE) or certain polyamide (PA) types appear to be particularly challenging to be processed by means of MEX. Even though semi-crystalline thermoplastics possess outstanding and unique properties, their use in MEX has not yet been thoroughly studied.

In order to visualise the great potential of semi-crystalline thermoplastics, Fig. 7.2 shows the toughness/stiffness-balance of different commercially available filament types and selected experimental MEX materials from the open literature. Amorphous thermoplastics are easy to process, but they have a small toughness (elongation at break between 3 and 9%) and lower stiffness (Young's modulus between 1900 and 2400 MPa). Semi-crystalline thermoplastics, on the other hand, reveal a wider range of toughness and stiffness, with a Young's modulus between 800 and 4000 MPa and an elongation at break between 2.5% and 1600%. When fillers are added to

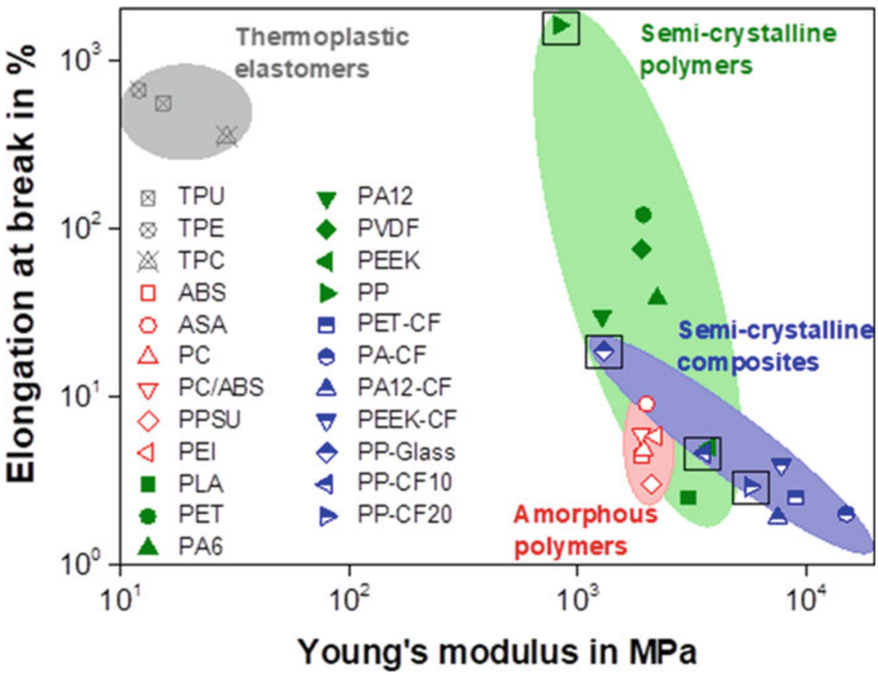


Fig. 7.2 Toughness/stiffness balance of MEX materials classified as thermoplastic elastomers, amorphous and semi-crystalline polymers, and semi-crystalline composites ([56]—licensed under CC BY)

semi-crystalline Thermoplastics (i.e. semi-crystalline composites in Fig. 7.2, their stiffness is enhanced drastically (e.g. up to 15,000 MPa for PA filled with carbon fibres (CF)), which is much higher than that of amorphous polymers, while their toughness remains in a similar range to that of the amorphous polymers. Hence, semi-crystalline polymers, especially semi-crystalline composites, have a great potential for the use as filaments in MEX. In order to prepare composite materials compounding is needed. How to compound materials is described in the following section.

7.1.1 Compounding of Special Materials for Material Extrusion AM

One way to change the properties of materials is to blend or mix them with other materials, which can be referred as compounding. Compounding has also been applied for thermoplastics used in MEX. One way to compound is to add different thermoplastics together in order to create blends, another way is to add solid fillers to prepare composites. As previously described, thermoplastic composites have better mechanical performance as their unfilled counterparts. A somehow unexpected change in the processability has also been observed particularly in semi-crystalline thermoplastics that tend to warp during MEX processing. It has been shown that the addition of fillers can prevent warpage and increase the geometrical accuracy of specimens printed with semi-crystalline thermoplastics, since the shrinkage after solidification is reduced, and the thermal conductivity as well as the viscosity of the molten material are increased. Therefore, it is important to learn the different ways used to prepare thermoplastic composites.

Thermoplastic composites may be produced mainly by three different methods: in situ polymerization, solution intercalation and melt processing. In situ polymerization consists on dispersing particles of different sizes in liquid monomers or monomer solutions. The resulting mixture is polymerized using standard polymerization methods. One advantage of this process is that there is the potential to graft the polymer onto the particle surface, which greatly increases the mechanical performance of the composite. When using in situ polymerization, particles may still require surface modification, because even though it is easier to disperse in a liquid than in a viscous melt, the settling process is also faster.

Solution intercalation is based on a two-step process, which is generally applied when the fillers are nano scale. First, the particles are initially dispersed in a solvent in which they are swellable, examples of a solvent include water, chloroform or toluene. In the second step, the swollen particles are mixed with a polymer solution. The polymer chains intercalate and displace the solvent within the interlayer of the filler particles. When the solvent is removed, the intercalated structure remains, resulting in a very well dispersed composite.

In situ polymerization and solution intercalation methods involve the use of solvents that are not environmentally friendly, flammable, health hazards and expensive. These two techniques require a solvent that is compatible with both the polymer and the filler particles, something that is not available all the time. Also, these two techniques are not compatible with common polymer processing equipment. As a consequence, melt processing has become the preferred method of producing thermoplastic-based composites. Melt processing utilizes conventional thermoplastic polymer processing techniques such as extrusion and internal mixing. Consequently, it would be easier for the polymer processing industry to adopt and integrate melt production of composites within their production lines.

Since melt processing is the simplest way to obtain thermoplastic-based composites, the following section will deal with the dispersion of filler particle in thermoplastics under melt processing. A good dispersion of filler particles inside the polymer matrix provides composites with better physical properties and better quality in the final 3D printed parts. When filler particles are well dispersed, there is an increase on the surface area that is available to interact with the polymer matrix. Therefore, better filler–polymer affinity improves the dispersion. The dispersion of particles not only depends on the affinity between the matrix and the filler, but also on the processing conditions used during melt compounding.

Compounding can be achieved in a continuous or a batch mode. For industrial production of compounds continuous production is most of the time preferred due to its higher productivity. Continuous compounders include co-rotating twin-screw extruders, Buss co-kneaders and Farrell continuous mixers. Batch compounders include high shear internal mixers, and roll mills.

The co-rotating intermeshing twin screw extruder is a high-speed machine used primarily in compounding applications. The intermeshing and low clearances between the screws creates a self-wiping feature that provides some advantages not available in other types of twin- screw machines, such as a complete elimination of any stagnant zone. They are usually made in a modular design, that is, the screw is made of a variety of elements that slide over a common shaft, and the barrel is assembled from several elements bolted together. This allows the geometry of the machine to be altered depending on the requirements of the specific process, resulting in a large degree of flexibility. Among the main screw elements used in co-rotating twin screw extruders are the conveying elements and the kneading disks. The kneading discs are the dominant elements in determining mixing efficiency. In general, co-rotating twin screw extruders are very efficient machines for dispersing particles in a viscous molten thermoplastic, therefore they are used in high volume productions. A photograph of a co-rotating twin screw extruder is shown in Fig. 7.3.

When developing new materials is generally preferred to use small amount of materials to avoid unnecessary waste; therefore for compounding small scales batches, two-rotor counter-rotating non-intermeshing internal mixers, also known as, kneaders are widely used in both academic and industrial research and development laboratories (Fig. 7.4). Kneaders measure and record the torque and the material temperature as functions of time and this allows studying the mixing process. When the material is fully melted the measured torque becomes directly proportional to

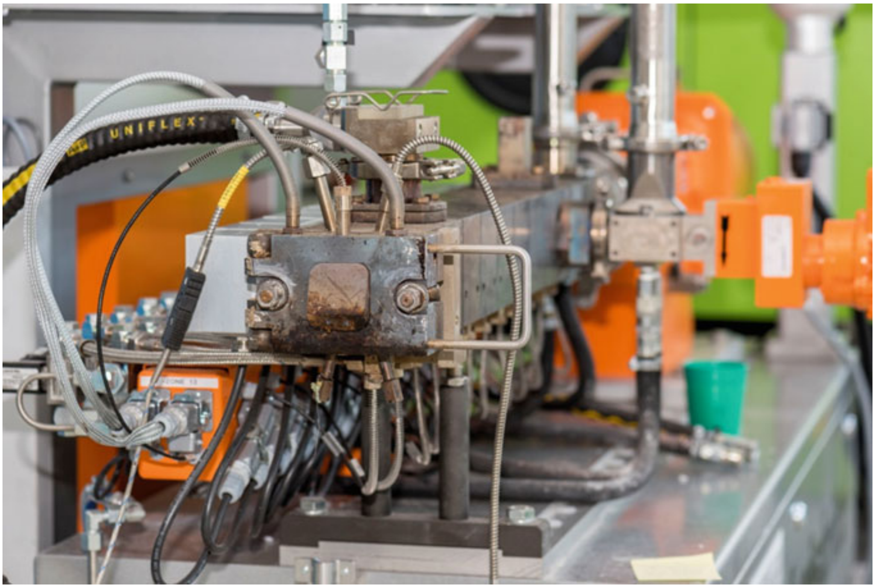


Fig. 7.3 Co-rotating twin screw extruder for continuous compounding (*Source* MUL facilities)

the viscosity of the melt and for this reason these devices are referred as torque rheometers.

New thermoplastic compounds for material extrusion additive manufacturing (MEX) can be prepared in a kneader, especially when the final formulation is still under development and the particular functionality needs to be tailored. For example, it might be desirable to increase the thermal conductivity or the tensile strength of a thermoplastic material to have applications where heat management and strength may be an issue. Fillers such as metal powders or carbon fibers can be added to thermoplastics to this effect.

The material that is extracted from a kneader is usually in large pieces that are not easy to process by other machines such as extruders in order to make filaments. In order to break the large pieces of the compounds obtained after kneading different size reduction machines can be used. One of these devices is a cutting mill such as the one shown in Fig. 7.5. Size reduction in cutting mills is performed by shearing and cutting. The material is introduced through a hopper into the grinding chamber where it is seized by the rotor and it is comminuted between the rotor blades and the stationary cutting bars inserted in the milling chamber. At the bottom of the milling chamber there is a sieve that determines the size of the particles to be obtained after the milling process. As soon as the particles are small enough to pass through the openings of the bottom sieve, they are discharged and collected in a receptacle.

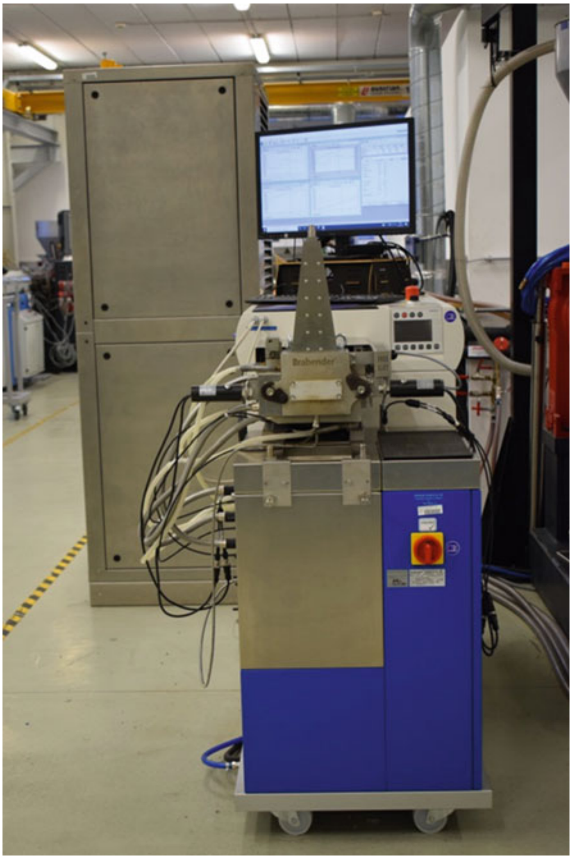


Fig. 7.4 Kneader for compounding at small scale (*Source* MUL facilities)

7.1.2 Differential Scanning Calorimetry of Polymeric Materials for MEX

When new materials are prepared is important to check their thermal properties, such as their melting and crystallization temperatures. In MEX, the filament is melted, and the unmolten material is used to extrude the melt through the nozzle; once the material is extruded it is deposited on the build platform or the previously deposited layer. Therefore, it is important to known at which temperature the material melts and solidifies in order to set up the printing equipment at the right extrusion temperature and build platform temperature. Please notice that for amorphous or glassy thermoplastics, such as the numerous used in MEX it is incorrect to refer to a melt transition, so the term melt refers to producing a liquid at the required processing temperature. One way to determine the transition temperatures of polymeric materials is to use differential scanning calorimetry.

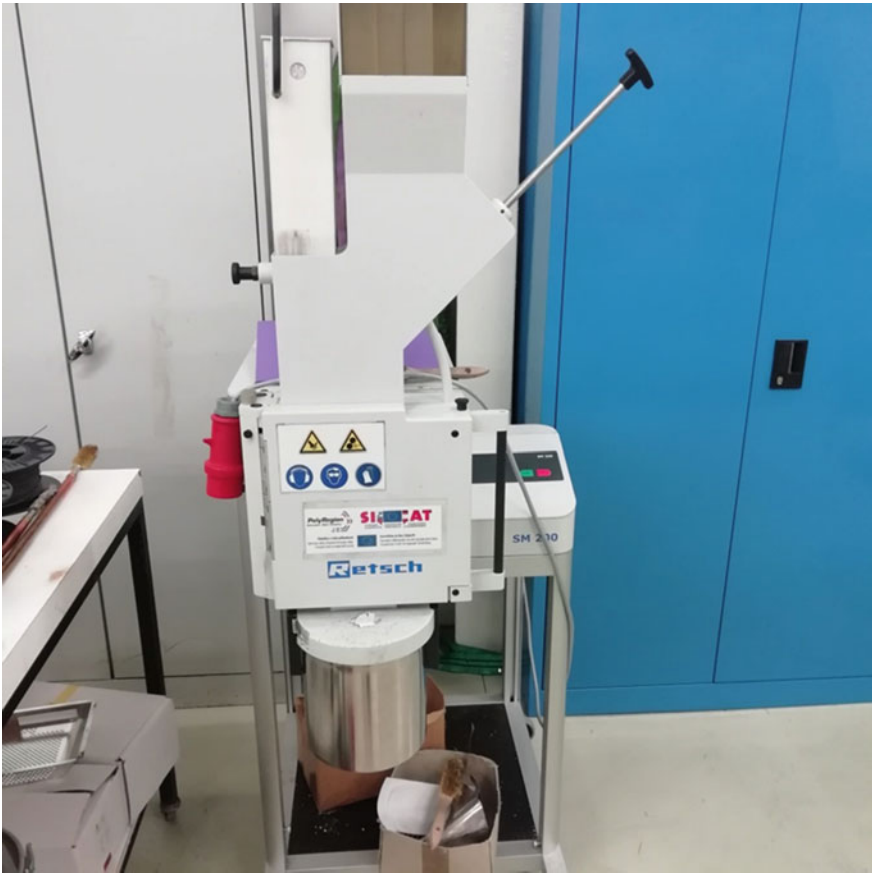


Fig. 7.5 Cutting mill for granulating the compounds prepared in the kneader (*Source* MUL facilities)

Differential Scanning Calorimetry (DSC) is a thermo-analytical measuring technique where the difference in heat flow rate between a sample and a reference is monitored as a function of time while the two samples are exposed to the same heating or cooling cycle. In other words, DSC is used to determine the amount of heat absorbed or released by a substance while undergoing a physical or a chemical change. Heat absorption or release occurring at any transition changes the total energy of the material, which is characterized in terms of enthalpy (H) when the pressure remains constant. The change of enthalpy between two states (δH) can be estimated as:

$$\delta H = \int c_p dT \tag{7.1}$$

where c_p is the heat capacity and T is the temperature.

Processes that increase enthalpy are called endothermic, some examples include the glass transition, melting and evaporation of polymers; while process that lower enthalpy are called exothermic and some examples include crystallization and decomposition of polymers. Therefore, using DSC, the transition temperatures of polymers for MEX can be measured and later on used to determine the processing temperatures at which to process materials in the AM process. The heat capacity of a polymeric material can also be measured using DSC devices. In order to measure the heat capacity, the heat flow ($\dot{Q}$), the heating or cooling rate (v_T), the sample mass (m) must be known. Once these parameters are known, the heat capacity c_p can be estimated using the following equation.

$$c_p = \frac{\dot{Q}}{m v_T} \tag{7.2}$$

As it can be seen in the previous equation the mass of the specimen (m) and the heating or cooling rate (v_T) can influence the measured values and thus comparative DSC measurements should be done using similar masses and at the same heating or cooling rates. In addition, Eq. 7.2 describes that the heat flow is directly proportional to the heat capacity, and therefore the glass transition temperature (T_g) can be determined by observing the change in the slope of the heat flow against temperature curve.

The T_g of an amorphous polymer material can be useful to know at which temperature the print bed of MEX machine should be set. It has been found that when the bed temperature is higher than T_g of the material to be printed the adhesion of than material increases and therefore the specimens can be fabricated without the risk of detachment from the build platform.

By increasing the temperature above T_g of semi-crystalline materials, such as many polymers used in MEX, it is observed that crystals begin to fall apart and chains come out of their ordered arrangement in what it is called melting. This endothermic transition is represented by a peak in the heat flow curve, where the top of the peak is referred as the melting temperature (T_m) and calculating the area below such peak, the latent heat (δH_m) can be estimated. Something similar can be done to estimate the crystallization temperature (T_c), when the temperature is lowered, and an exothermic transition is observed. These two temperatures are crucial during the process of MEX. The extrusion temperature should always be higher than T_m and the extrudate should be cooled down below T_c in order to have geometrical stability of the deposited layers. The extrusion temperature should be set up more than 10 degrees higher than T_m since the heat transfer from the heating block to the viscous polymer melt is quite low and the residence time is quite short. It is important to mention that the contact temperature at which the extruded material comes in contact with the solidified layer plays an important role in the interlayer cohesion and as such to the mechanical properties of the fabricated specimens.

Fig. 7.6 Differential scanning calorimetry device (*Source* MUL facilities)

An example of how to perform DSC measurements is shown here. The equipment shown in Fig. 7.6 is a DSC1 from Mettler-Toledo, Switzerland and this is the device used to measure the thermal properties of materials compounded for MEX.

7.1.3 High Pressure Capillary Rheometry of Polymeric Materials for MEX

A high-pressure capillary rheometer allows the routine analysis of the viscosity of polymer melts and composites at shear rates from 10 to 10^6 s^{-1}. The realizable shear rate range depends on the viscosity of the material to be tested, the selected temperature, and the used die geometry (e.g., round die or slit die). Capillary rheometers are well suited to measure viscosity values representative of the MEX process since they operate in steady shear flow modes and at shear rates that are relevant for material extrusion processes (10^2–10^3 s^{-1}).

The capillary rheometer is composed of a test barrel that is temperature controlled and an exchangeable die at its end. The die can have a variable geometry (e.g. round or slit). When all test parameters are defined and the system reaches the test temperature, the test barrel can be filled with polymer granulate. In order to fill it bubble free, the material should be filled in small portions and manually pressed with a tamper. The measurement is ready to begin when the test barrel is full. Then, the preheat time (or melting time) starts. At the end of the preheat time, the test starts automatically by the movement of the piston with the first preselected feed rate. And the melt inside the test barrel is extruded through the die by means of a piston. The melt pressure is measured by using mounted pressure transducers before the round die or along the slit length of the slit die. As soon as the pressure varies exactly within the tolerance limit, the speed of the piston is recorded. Therefrom, the apparent viscosity data are calculated immediately. At the same time, the piston speed is increased to the next value. In this way, the whole speed program is run step by step.

The two types of dies used for capillary rheometry are presented together with a discussion of important points one should be aware of when measuring viscosities with them.

Round Die

Capillary rheometers with round dies are widely used in polymer melt rheometry. Round dies exist in different lengths with the same diameter (L/D = 10, 20, and 30). The entrance angle of a round die is 180°. To measure the temperature near the die wall, thin thermocouples can be attached to the die. Using the dimensions of the die, the speed of the piston, and the related pressure drop, the so-called apparent viscosity is calculated. In order to obtain the correct viscosity of polymeric materials, two corrections are commonly applied to round dies data: the Bagley correction and the Weissenberg-Rabinowitsch correction. The Bagley correction takes care of viscoelastic effects at the entrance of the die. During the melt flow in the die inlet and outlet pressure losses are developed, and the Bagley correction can be used to correct these pressure losses. Therefore, several measurements with capillaries with the same diameter but with different lengths have to be done to apply this correction.

The plotted measured pressures (p_{meas}) of the die versus L/D ratio in general can be described by a linear function for each individual shear rate. The extrapolation of these straight lines to the L/D ratio = 0 provides the pressure correction value (p_{en}) mentioned in

$$\tau_r = \frac{(p_{\text{meas}} - p_{\text{en}}) \cdot R}{2 \cdot L} \tag{7.3}$$

where τ_r is true shear stress, p_{en} is entrance pressure loss, and R is die radius.

The apparent shear rate for round die $\dot{\gamma}_{a,r}$ is calculated by using

$$\dot{\gamma}_{a,r} = \frac{4 \cdot \dot{V}}{\pi \cdot R^3} \tag{7.4}$$

with $\dot{V}$ as the volumetric flow rate.

The Weissenberg-Rabinowitsch correction for the round die considers the fact that the shear rate mentioned in Eq. (7.4) is only valid for Newtonian fluids and provides the true shear rate at the capillary wall for them; therefore, Equation has to be used.

$$\dot{\gamma}_r = \frac{\dot{\gamma}_{a,r}}{4}\left(3 + \frac{dlog\dot{\gamma}_{a,r}}{dlog\tau_r}\right) \tag{7.5}$$

Finally, the true viscosity is calculated from

$$\eta = \frac{\tau_r}{\dot{\gamma}_r} \tag{7.6}$$

Slit Die

In the slit die, the pressure gradient, which is used to calculate the viscosity, is measured by using a series of pressure transducers along the length of the slit. The pressure profile along the slit die is measured by melt pressure transducers.

The temperature at the die wall is recorded by using thermocouples, which are fixed very near to the inner wall of the slit. The slit die has the rectangular channel of width (B) and height (H). The pressure drop Δp can be determined by taking the difference of two pressures measured along the flow length and the corresponding distance ΔL between the pressure transducers. Thus, no Bagley correction is necessary when the pressure drop is measured along the slit. However, a so-called shape factor F_p in Eq. (7.9) might be employed to account for the influence of the width in the rectangular flow channel. The true shear stress τ_s can be calculated from the measured pressures along the slit length and geometrical parameters of slit die, by using

$$\tau_s = \frac{\Delta p \cdot H}{2 \cdot \Delta L} \tag{7.7}$$

is applicable when the ratio B/H is greater than 40; in other cases, τ_s is given by Eq. 7.8:

$$\tau_s = \frac{\Delta p \cdot (B \cdot H)}{2 \cdot \Delta L \cdot (B + H)} \tag{7.8}$$

The apparent shear rate $\dot{\gamma}_{\text{app},s}$ given by

$$\dot{\gamma}_{\text{app},s} = \frac{6 \cdot \frac{\dot{V}}{F_p}}{B \cdot H^2} \tag{7.9}$$

The Weissenberg-Rabinowitsch correction adjusts the shear rate at the wall for non-Newtonian liquids, such as molten thermoplastics. The true shear rate at the wall for a slit die $(\dot{\gamma}_s)$ is calculated using Equation

$$\dot{\gamma}_s = \frac{\dot{\gamma}_{\text{app},s}}{3}\left(2 + \frac{dlog\dot{\gamma}_{\text{app},s}}{dlog\tau_s}\right) \tag{7.10}$$

Finally, the true shear viscosity is calculated using

$$\eta = \frac{\tau_s}{\dot{\gamma}_s} \tag{7.11}$$

An example of how to perform a capillary rheometry measurement is shown here. A picture of the Rheograph 2002 high pressure capillary rheometer (Göttfert Werkstoff-Prüfmaschinen GmbH, Buchen, Germany) is shown in Fig. 7.7.

Fig. 7.7 High pressure capillary rheometer for measuring viscosity at high shear rates (*Source* MUL facilities)

7.1.4 Rotational Rheometry of Polymeric Materials for MEX

In order to measure the viscosity at lower shear rates or lower frequencies a rotational rheometer is used. Also, when the viscosity is too low for a material that it drips out of the capillary without any force being applied by the piston, then the rotational rheometer is an option to measure the viscosity of those fluids. When the rheometer is used in oscillatory mode the viscoelastic response of materials can be measured and it is described by the values of the storage and loss moduli. These two moduli can give information regarding the structure of the polymer or the filled composites and can be used as a quality control measure for materials to be used in MEX.

Rotational rheometers generally have two rotational-symmetric components mounted on a common axis, with the fluid to be rheologically characterized between them. The shear rate results from the angular velocity at which the components rotate, while the shear stress comes from the torque that is applied to the sample. A rotational rheometer can be of two types, controlled stress or controlled rate. In a controlled stress rheometer, the shear stress is specified, and the velocity gradient is determined proportionally to the viscosity. In a controlled rate rheometer, the shear rate is specified, and the resulting shear stress is determined. The most common geometries used in rotational rheometry are plate-plate, cone-plate, and coaxial. Only the plate-plate rheometry will be discussed here since this is the most versatile geometry since it can be used with unfilled and filled molten thermoplastic polymers, which can be used in the MEX process.

Plate-plate rheometry is characterized by the use of two parallel plates with a radius R and separated by a distance H. In this configuration, the velocity gradient depends on R and H. Consequently, the shear rate can be modified by changing the distance H or the angular velocity ω. The shear rate in a plate-plate arrangement varies also along the radius of the plates and is maximum $\dot{\gamma}_{\mathrm{R}}$ at the external radius R, thus the maxim shear rate can be calculated with the following equation:

$$\dot{\gamma}_R = \frac{R \cdot \omega}{H} \tag{7.12}$$

The angular velocity can be calculated from the rotor speed N measured as the number of revolutions per minute with the following equation:

$$\omega = \frac{2\pi \cdot N}{60} \tag{7.13}$$

The shear stress τ is obtained from the applied torque M, the radius of the plate R and a correction factor n, known as the power law exponent from the Weissenberg correction since polymeric materials are non-Newtonian fluids, as described above:

$$\tau = M\frac{2}{R^3}\left(\frac{3+n}{4}\right) \tag{7.14}$$

When the applied shear stress or strain is sinusoidal in nature, the viscoelastic moduli can be measured. This kind of tests is called oscillatory dynamic tests. For rheological measurements done on a controlled rate rheometer, one can impose the deflection angle φ or the strain γ as a sinusoidal function of time t and angular velocity ω given as:

$$\varphi(t) = \varphi_A \sin\omega t \tag{7.15}$$

or

$$\gamma(t) = \gamma_A \sin\omega t \tag{7.16}$$

where index A is for the applied amplitude.

The torque Mor the shear stress τ can be measured and will also be sinusoidal functions shifted by a phase shift angle δ, given by the following equations:

$$M(t) = M_A \sin(\omega t + \delta) \tag{7.17}$$

or

$$\tau(t) = \tau_A \sin(\omega t + \delta) \tag{7.18}$$

The opposite will be true for a controlled stress rheometer. The torque or the stress is applied as a sinusoidal function and the angle of deflection or the strain is measured as sinusoidal functions shifted by a phase shift angle.

Once the shear stress, the shear strain and the phase shift angle are known, the elastic or storage modulus G', the viscous or loss modulus G'', as well as the complex viscosity η^* can be calculated using the following three equations:

$$G^{'} = \frac{\tau_A}{\gamma_A}\cos\delta \tag{7.19}$$

$$G^{''} = \frac{\tau_A}{\gamma_A}\sin\delta \tag{7.20}$$

and

$$\left|\eta^*\right| = \left|\frac{\tau_A}{\gamma_A}\right| \cdot \frac{1}{\omega} \tag{7.21}$$

Before measurements can be performed in the rotational rheometer, it is recommended to press small disks in order to minimize the amount of air trapped when melting granules directly at the rheometer. Trapped air can considerably affect the

Fig. 7.8 Vacuum press for sample preparation for rotational rheometry and thermal conductivity (*Source* MUL facilities)

measured values in a rotational rheometer. In order to produce dense disks of the material to be investigated a vacuum press is used like the one shown in Fig. 7.8.

Once the specimens for rotational rheometry are prepared then measurements can begin. A photograph of a rotational rheometer is shown in Fig. 7.9.

7.1.5 Thermal Conductivity of Polymeric Materials for MEX

The thermal conductivity of the materials to be processed by MEX affects how fast the material melts and solidifies after deposition. The rate at which the material solidifies affects the quality of specimens printed with an MEX machine. For example, it has been observed that for semi-crystalline polymers it is better that the polymers have a higher thermal conductivity in order to prevent warpage of the printed specimens during the MEX process.

The thermal conductivity of polymers can be measure with several methods; one of these methods is the modified transient plane source (MTPS) method. Because the

Fig. 7.9 Rotational rheometer for measuring viscosity at lower shear rates (*Source* MUL facilities)

MTPS method is fast, reliable, and non-destructive. A photo of the device to measure thermal conductivity is shown in Fig. 7.10.

The system is comprised of a sensor, control electronics and computer software. The sensor has a central heater/sensor element in the shape of a spiral surrounded by a guard ring. The guard ring generates heat in addition to the spiral heater, thus, approximating a one-dimensional heat flow from the sensor into the material under test in contact with the sensor. The voltage drop on the spiral heater is measured before and during the transient. The voltage data is then translated into the effusivity value of the tested material. The conductivity is calculated from the voltage data an iterative method.

The sensor used to measure the effusivity has a solid surface optimally engineered for the testing of fluids. When measuring solids, a contact agent is required as there is some contact resistance that may significantly affect the results if not addressed within the measurement protocol. The quality of contact and therefore the

Fig. 7.10 Thermal conductivity device that uses the modified transient plane source method (*Source* MUL facilities)

heat transfer depends on many parameters such as type of material, surface quality and wettability. The best contact agent available is water, since it has a relatively high thermal conductivity (~0.6 Wm^{-1} K^{-1}), low viscosity, and is easy to apply and clean. Water can be used in a limited temperature range though, from around 5 °C to around 70 °C. At temperatures lower than 5 °C and higher than 70 °C alternative contact agents are available. Calibrations of solids (except for foams) are all done with water.

In order to obtain better results, it is better to use flat discs that completely cover the sensor of the thermal conductivity device. For that reason, specimens were prepared in the vacuum press following the procedure describe in the rotational rheometry section. Examples of the discs prepared with the copper compounds are shown in Fig. 7.11.

7.1.6 Filament Production for MEX

Extrusion to produce filaments to be used in MEX is an important step in order to ensure good quality in the parts produced by MEX. The filament must have a round cross-section so it can be easily fed to the liquefier in the extrusion head. The measure of how round a filament is known as ovality and for a perfectly round filament its ovality is equal to zero. The filament should also have a very narrow distribution of diameter as close as possible to the target diameter of 1.75 mm. Filaments with good quality are produced when the extrusion rate, the haul-off rate and the winding unit are all stable and adjusted accordingly.

Fig. 7.11 Samples for thermal conductivity measurements prepared in the vacuum press (*Source* MUL facilities)

The MEX process based on filaments, deposits material through the liquefier based on the constant displacement of the 1.75 mm diameter filaments. The filament displacement rate and the feeding roller speeds are calculated according on the specified build conditions and assuming the diameter of the filament is constant. It can be inferred that if the filament diameter is less than the assumed diameter of 1.75 mm, the flow rate of the material being extruded is less than the expected rate. Variations of the diameter result in underflow that can result in insufficient contact between adjacent deposited strands, creating a weak point or severe underflow there may not exists any contact between the deposited strands resulting in voids between the strands, which in turn make the parts weaker in term of their mechanical performance. Filaments with too large diameter can lead to overflow and to the accumulation of material around the nozzle or on certain parts of the printed specimen, which eventually lead to geometrical inaccuracies. Increase in the ovality in the other hand, can lead to slippage of the filament between the rollers, which in turn can lead to less than optimum flow and thus similar effects as a varying diameter. For these reasons, it is important to produce filaments with the diameter as close as possible to the specified dimension, usually 1.75 or 2.85 mm and with an ovality as close as possible to zero.

Filaments can be produced in the capillary rheometer like the one shown in Fig. 7.12, but instead of dropping the extrudate into the lower platform, the extrudate is collected and transported on a conveyor belt away from the die. This is shown in Fig. 7.12. This method does not give filaments with high quality, but it is preferred when the amount of material available is little, which is the case during the material development process.

The better way to produce filaments in a continuous fashion is to use a single screw extruded fitted with a round die. The extrudate is also collected on a water bath or a conveyor belt that transports it to the haul off unit and finally to the winding unit. This method is preferred when the amount of material is larger then one liter, since a higher amount of material needs to be wasted before the extrusion process is

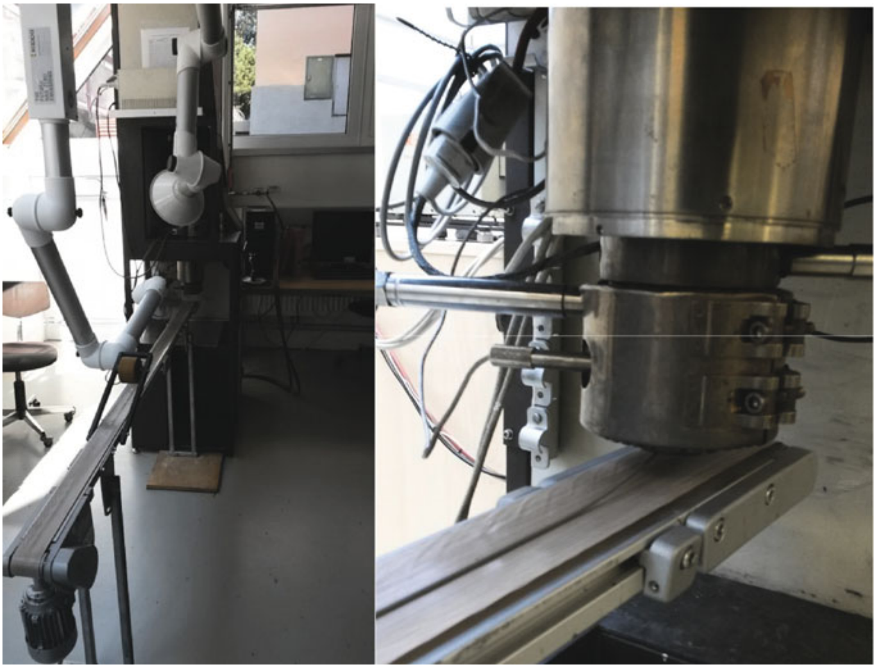


Fig. 7.12 Filament production set up for small amounts (*Source* MUL facilities)

stable. A schematic representation and a photograph of a filament extrusion line is shown in Fig. 7.13.

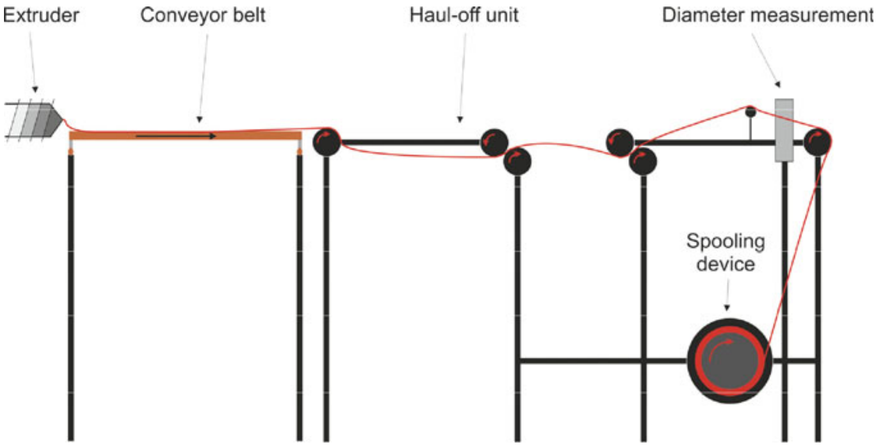
7.2 Development of Materials for PBF Technologies

7.2.1 Metallic Materials

The use of metal powders in the Additive Manufacturing industry is increasing in different sectors since it became a suitable process to produce complex metal net shape parts, and not only prototypes as before.

On one hand, metallic materials play a very important role in additive manufacturing concerning: (i) making parts from powders, (ii) powder manufacturing, (iii) families of metallic powders for AM, (iv) powder characteristics, and (v) influence of powder characteristics on the powder behaviour.

On the other side, efforts on research and development of advanced materials need to be concentrated in the challenge of reaching full or near full density without compromising microstructure while keeping good dimensional stability and tight



a)

b)

Fig. 7.13 Filament extrusion line for large amounts: **a** shematic (courtesy of Damir Ciglar), **b** real line (*Source* MUL facilities)

tolerances as well as tailoring special properties bymeans of advanced microstructure control (Fig. 7.14).

Among the benefits of **making parts from powders** by using metal additive manufacturing technologies it can be found:

- Increased design freedom compared to conventional casting and machining.

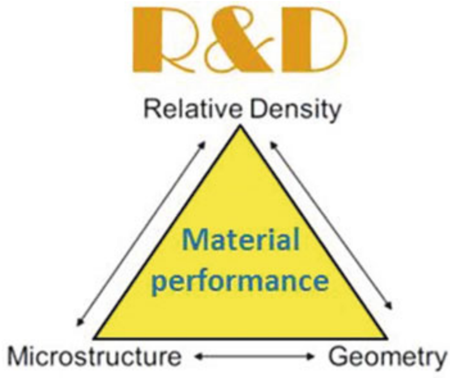


Fig. 7.14 Relationship between density, microstructure and geometry for creating an advanced material (*Source* AIDIMME)

- Net shape process with less raw material consumption which is really important in the case of expensive or difficult to machine alloys. This net shape process means reducing the number of assembly operations such as welding or brazing.
- Short production cycle time to process complex parts layer by layer in a few hours. Then, total cycle time including post processing usually takes a few days or weeks which generally is much shorter than conventional metallurgy processes with production cycles of several months.

However, some limitations need to be considered:

- Material choice because many alloys are available, but some of them are not suitable for AM such as non weldable metals or difficult-to-weld alloys which can require specific approaches.
- Material properties since it has been known that some parts made from AM tend to show anisotropy in the build direction (Z axis).
- Densities of 99.9% can be reached, but some residual internal porosity may remain.
- Mechanical properties are usually superior to cast parts but in general inferior to wrought parts.
- AM technology is not only used for prototyping but also for metal part production.
- Increasing the metal powder production for AM might reduce powder costs too.

7.2.2 Powder Manufacture and Metal Powders for Additive Manufacturing (AM)

There are many ways in which metals might be produced in powder form. One of the key points in **powder manufacturing** is the different powder shapes (Fig. 7.15) that can be achieved depending on the powder production method.

The most important powder production methods are:

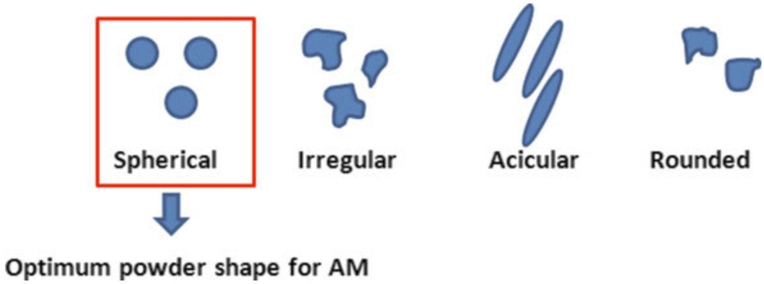


Fig. 7.15 Example of powder shapes (*Source* AIDIMME)

- Mechanical methods by disintegration without phase change: machining and mechanical communition (milling).
- Physical methods by disintegration with phase change: atomization techniques than can be gas atomization or water atomization.
- Chemical reduction methods by ore reduction, thermal decomposition, hydrometallurgy.
- Electrolytic reduction methods by precipitation from aqueous solutions or melt electrolysis.

Metal Powders for Additive Manufacturing are usually produced using the gas atomization processing. In this manufacturing process, a molten metal is broken up into small droplets and quickly solidified before they come into the contact with each other or with a solid surface. The main way is to disintegrate a thin stream of molten metal by subjecting it to the impact of high energy jets of gas or liquid. The main difference relies on the particle shape obtained; powders produced by gas atomization present spherical shape while powders produced by water atomization show irregular shape.

Gas atomization is the usual powder manufacture method for additive manufacturing due to the following characteristics:

- Powder particles present the same chemical composition since the starting constitutent metals are fully alloyed in the molten state.
- Spherical shape is positive for powder flowability, powder density and size distribution.
- A wide range of alloys are currently able to be processed by gas atomization.

There is a specific gas atomization process known as VIM *Vacuum Induction Melting* gas atomization where the melting process takes place in a vacuum chamber. This is highly recommended for atomizing reactive elements like titanium (Ti), copper (Cu), aluminium (Al) and also superalloys to avoid the drawback of oxygen pick-up. Figure 7.16 shows TiAl powder particles produced by VIM gas atomization.

Other particular metallic materials like molybdenum (Mo) and tungsten (W) (refractory metals) are produced by plasma atomization which generally results in more spherical particles with less amount of finest particles. Figure 7.17 exhibits two

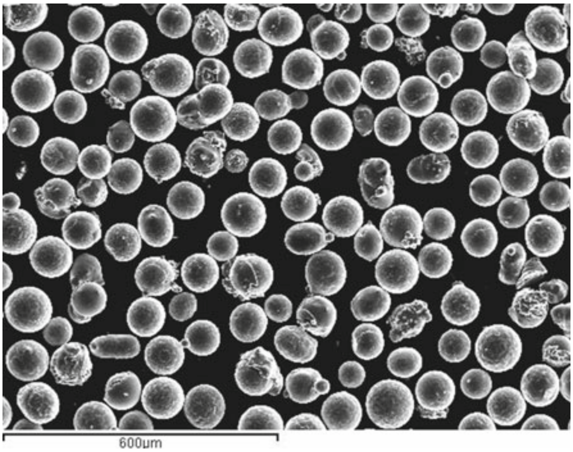


Fig. 7.16 TiAl powder particles produced by VIM (*Source* AIDIMME)

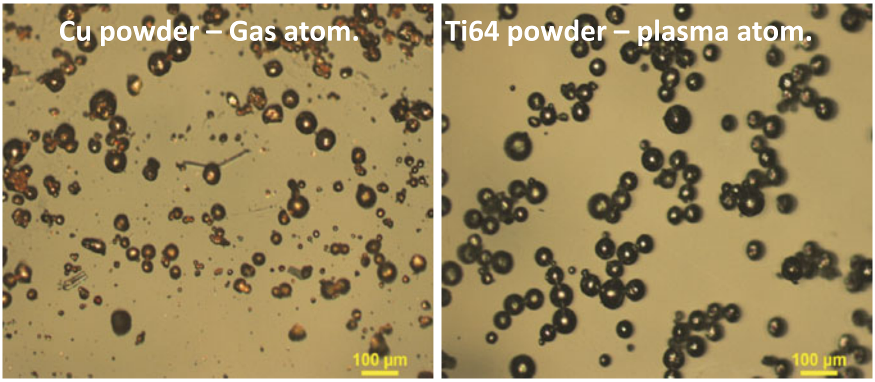


Fig. 7.17 Copper (on the left) and Ti6Al4V (on the right) powder particles produced by gas and plasma atomization, respectively (*Source* AIDIMME)

different metals, pure copper on the left and Ti6Al4V alloy on the right produced by gas and plasma atomization, respectively. It can be seen how the gas atomization technique gives both finest and less spherical particles compared to plasma technique.

The spectrum of powder manufacture methods together with the disruption of the additive manufacturing technologies has made possible a wide range of alloys in powder form:

- Steels
- Commercially pure (CP)-titanium and titanium alloys
- Aluminium alloys
- Nickel base superalloys
- Cobalt base superalloys
- Pure copper and copper alloys

- Magnesium alloys
- Precious metals: gold, silver and platinum
- Refractory metals: molybdenum and tungsten
- Metal matrix composites.

The quality of metal powders is extremely important since many other aspects from the AM process will be influeced by the powder quality: (i) build-to-build consistency, and thus, the production of defect-free components, (ii) mechanical properties, (iii) process qualification and, (iv) reproducibility between AM systems.

As it has been mentioned in Sect. 4 *Additive Manufacturing Processes Classification*, metallic materials are mainly processed by PBF-EB/M or PBF-LB/M technologies. Depending on the material and the technology selected, the main features of metal powders usually are:

- Metal powders for PBF-EB/M: less expensive and with a Particle Size Distribution (PSD) between 45 and 105 μm.
- Metal powders for PBF-LB/M: more expensive and with a PSD between 20 and 50 μm.

This particular difference on size will influence mainly in: (i) surface roughness of the final part, and (ii) ability to flow and spread:

- Metal powders for PBF-EB/M: this wide range and big size of particles results in a final part with rougher surface as well as in a powder with better ability to flow and spred.
- Metal powders for PBF-L/M: in this case, finer particles give smoother surfaces of the final part but it is detrimental for the flowability which can provoke that the powder does not flow and this can result in lack of fusion and defects on the final part.

The further processing and results achieved in the final AM part are highly influenced by the powder characteristics. Figure 7.18 exhibits the main **powder characteristics** that should be characterized for the proper understanding of metal powders behaviour.

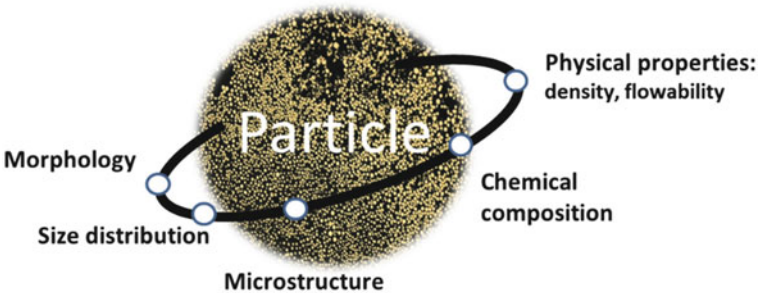


Fig. 7.18 Powder characteristics (*Source* AIDIMME)

Morphology, size distribution, microstructure, chemical composition and physical properties such as density and flowability are the powders characteristics that will define the behaviour of a metal powder and the ability to be processed by AM technologies. The way in which these five properties are correlated to each one is summarized in Table 7.1.

Additionally, each metal powder should be considered as unique and thus, specific aspects need to be analyzed:

- Health, safety and environmental issues.
  - i.e., in nanomodified powders, the presence of nanoparticles should be to take into account for specific Personal Protective Equipment.
  - i.e., in metallic powders, the Minimum Ignition Energy (MIE) Test should be analyzed in order to determine the minimum energy of an electrical spark that will result in ignition of a dust cloud under specified test conditions. This value is extremely important during handling reactive or fine powders and during processing and post-processes in AM technologies out of protective atmospheres.
- Powder reusability.
  - i.e., definition of conditions for re-using fresh powders after AM cycles.
- Powder storage, handling and aging.
  - i.e., protective gas, control of humedity and temperature is strongly recommended for almost all alloys.

Introduction to Powder Characterization for AM

A high-quality AM production is related to the starting material (also known raw material or feedstock). It should be paid attention to the powder and its properties Fig. 7.19.

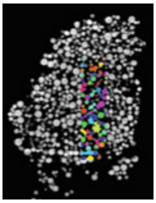
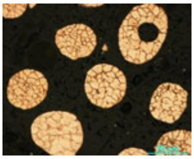
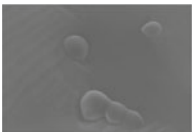
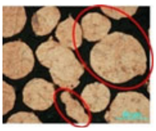
Additive Manufacturing providers are the responsible to define powder properties requirements for a particular additive manufacturing technology. Generally, the AM provider is the powder provider too but, in some cases, it is possible to process powder provide by a third supplier. So, who is going to process the material has to assure that the powder properties meet the defined powder requirements.

In addition to the metal powder requirements defined by the supplier, it is important to know if there is any specific standard for this material. Recently, a set of Additive Manufacturing Standards have been developed.

Regarding AM powder characterization for powder bed fusion technologies, two main standards for Ti6Al4V are found:

- F2924-14 standard specification for additive manufacturing titanium-6 aluminum-4 vanadium with powder bed fusion

Table 7.1 Relationship between powder characteristics and powder behaviour

Particle characteristic	Defects		Influence on powder behaviour
Morphology	Irregularity of the powder grain		• Decreases the apparent density • Increases the reduction in volume • Increases the green strength of the compact • Better sintering behaviour
Size distribution	Fine particle sizes tend to leave smaller pores closed during sintering		• High amount of fine particles reduces flow properties • Powder particles below 10–20 μm are detrimental to powder flowability • Influence on: ability to spread, powder density, melting energy and final surface roughness
Microstructure	Microstructure should be analysed to control: gas porosity, damaged particles, microstructure evolution, grain boundaries…		• Detec adversed phenomena such us oxidation, pick up of humidity, etc
Chemical composition	Purity of powders is critically important (i.e. interstitials elements such as O, N, C, S). for material properties		Particularly, influence on: • Melting temperature • Mechanical properties • Weldability • Thermal properties (thermal conductivity, heat capacity etc.)
Physical properties: density	Apparent density is a function of both particles shape and porosity	 	Strongly influence on the strength of the compact obtained

(continued)

Table 7.1 (continued)

Particle characteristic	Defects		Influence on powder behaviour
Physical properties: flowability	Related to the processing conditions during handling and mixing		Highly dependant on the physical properties of the material itself

Source AIDIMME

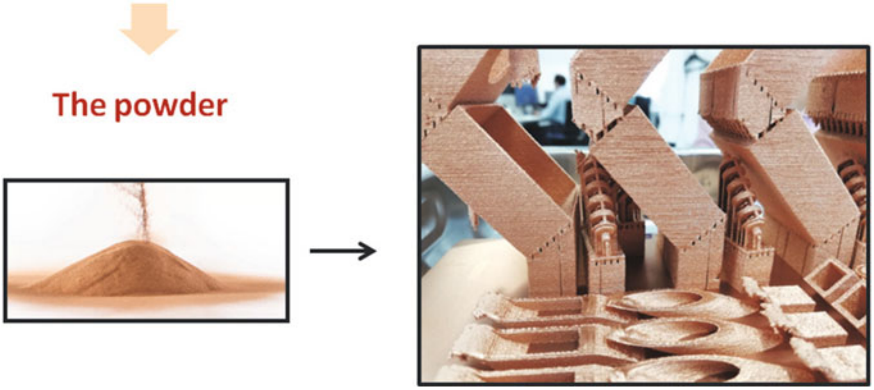


Fig. 7.19 Quality of AM parts is directly dependant on the raw material or feedstock (*Source* AIDIMME)

This specification covers additively manufactured titanium-6aluminum-4vanadium (Ti-6Al-4V) components using full-melt powder bed fusion such as electron beam melting and laser melting. It indicates the classifications of the components, the feedstock used to manufacture Class 1, 2, and 3 components, as well as the microstructure of the components. This specification also identifies the mechanical properties, chemical composition, and minimum tensile properties of the components. (This abstract is a brief summary of the referenced standard. It is informational only and not an official part of the standard; the full text of the standard itself must be referred to for its use and application).

In addition to this material standard, ASTM F3049-14 must be included to control the feedstock.

- ASTM F3049-14 standard guide for characterizing properties of metal powders used for additive manufacturing processes

This specification determines the properties of the feedstock powder used in these processes is a necessary condition for industry's confidence in powder selection and ability to produce consistent components with known and predictable properties. The intention of this guide is to provide purchasers, vendors, or producers of metal powder to be used in additive manufacturing processes with a reference for existing standards or variations of existing standards that may be used to characterize properties of metal powders used for additive manufacturing processes. It will serve as a starting point for the future development of a suite of specific standard test methods that will address each individual property or property type that is important to the performance of metal-based additive manufacturing systems and the components produced by them. While the focus of this standard is on metal powder, some of the referenced methods may also be appropriate for non-metal powders.

7.2.3 Tests for AM Powder Characterization

As introduced in section before, there is a strong relationship between powder properties and the powder behaviour. An overview of tests for the AM powder characterization is shown in Fig. 7.20.

- **Particle Size Distribution analysis**: The aim of this analysis is to ensure that every powder lot is sized for the application, meeting the additive technology requirements. Particle size distribution by laser diffraction method follows standard procedure according to ASTM B822-10.

  In Powder Bed Fusion technologies the most common range of particle size is:

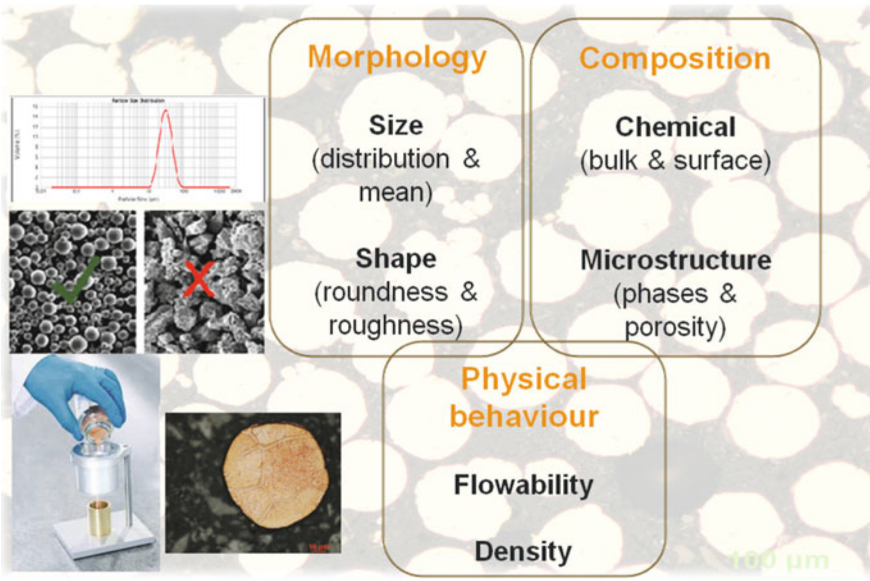


Fig. 7.20 Overview of tests for AM powder characterization (*Source* AIDIMME)

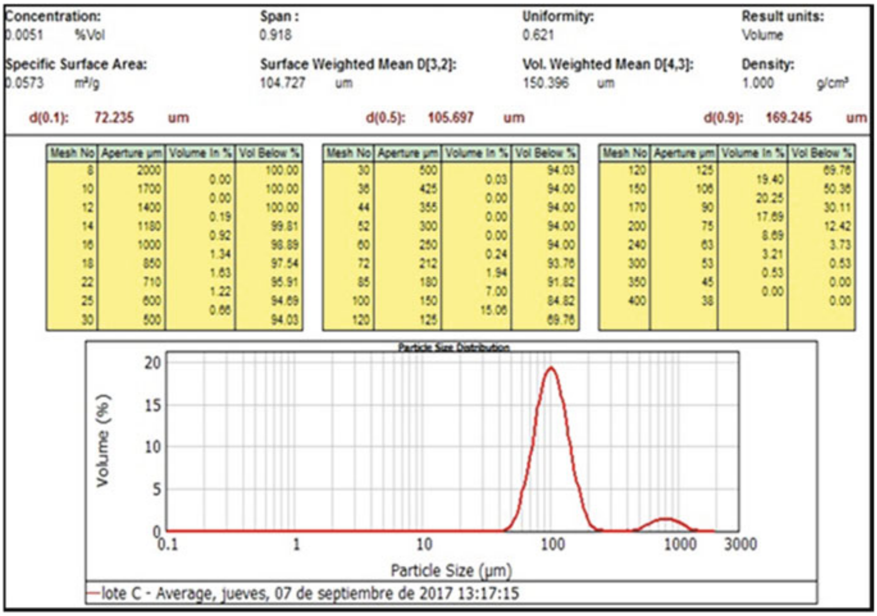


Fig. 7.21 Example of a PSD report (*Source* AIDIMME)

– PBF-LB/M: Particle size distribution between 20 and 63 microns
– PBF-EB/M: Particle size distribution between 45 and 105 microns. No presence of particles smaller than 10 microns. The presence of particles smaller than 10 micros could be dangerous if the AM peripheral devices does not work under inert gas conditions or controlled atmosphere.

An example of PSD report is shown in Fig. 7.21.

- **Full chemistry analysis**: The aim of this analysis is to ensure that the chemical composition of the powder meets the requirements before and after its additive manufacturing processing. Chemical content of the alloy requirements are included in the reference standard of the material. For instance, ASTM F2924-14 and ASTM F3001-14. Different chemical analysis techniques are employed:

– Surface analysis:

X-Ray photoelectron Spectroscopy.
Augen Slectron Spectroscopy.
Secondary Ion Mass Spectroscopy.

– AM processed material analysis:

Inductively Coupled Plasma.
Atomic Absorption Spectrometry.
Optical emission (High T combustion).

Fig. 7.22 Equipment for chemical analysis characterisation at AIDIMME: **a** Ultima2 (ICP-OES), **b** Leco CS230 and **c** ONH-2000(IGF) (*Source* AIDIMME facilities)

Infra-red.
X-ray Fluoresence.
X-ray powder diffraction.

– Microanalysis

Scanning Electron Microscopy.
Energy Dispersive X-ray Spectroscopy.
Nanoprobe.

For impurities and inclusions detection:
– Chemical analysis
– Microscopy techniques.
In case of Ti6Al4V powder, two main kinds of analysis are found:
– Composition via ICP—established ICP analytical routine: Ti, Al, V, Fe, Cr, Mo, Nb, W, Cu, Ni, Co, Fe, Mn, Sn, Si, P, Ta, B, Y.
– Other elements—C, N, O, S, H via LECO combustion analysis (Fig. 7.22).

In order to analyze aluminum, vanadium and iron content, it has been used high performance ICP-OES (inductively coupled plasma optical emission spectrometry). In order to analyze carbon content, it has been used the Leco, due to difficulties in getting Carbon and Sulphur into solution, these elements are not readily measured by ICP Spectroscopy and an alternative technique is combustion analyzer for the measurement in metals, ceramic and other inorganic materials. Oxygen, Hydrogen and Nitrogen content is determined by inert gas fusion (IGF).

Chemical analysis explained before follows the standard procedures according to ASTM E1941 for Carbon, for Hydrogen, ASTM E1409 for Oxygen and Nitrogen, and for other elements.

- **Microstructure analysis**: The aim of this analysis is to ensure no internal gas in the powder particles and evaluation of the powder morphology according to ASTM E3-11. Standard guide for preparation of metallographic specimens. Powder requirements are defined by the additive manufacturing provider.

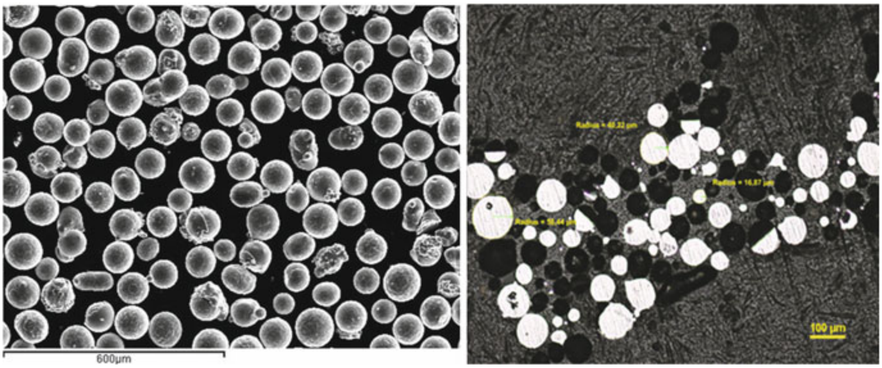


Fig. 7.23 Spherical particle shape with presence of satellites (left) and powder internal porosity (right) (*Source* AIDIMME)

For instance, PBF-EB/M powder particles shall be spherical, with minimum are/volume ration and no presence of internal porosity (Fig. 7.23).

- **Flow analysis**: This analysis ensures batch consistency and optimal flowability for AM process according to additive manufacturing technology provider. The flowability characteristic of a powder is directly related to both the physical properties of the material itself, as well as the specific processing conditions in the handling system. The flowability is tested using Hall flowmeter (Fig. 7.24), according the ASTM B213.

Fig. 7.24 Hall flow rate equipment (*Source* AIDIMME)

Usually, a Hall funnel (2.54 mm orifice) is employed. In case the powder does not flow freely through this, a Carney funnel (5.08 mm orifice) is employed. For PBF-EB/M technology the flow rate (Hall-ASTM B213) shall be lower than 30 seconds/50 g. In case of Ti6Al4V alloy for PBF-EB/M, flow rate is around 20-22 seconds/50g.

- **Apparent density analysis**: This analysis ensures low porosity powder to obtain an optimal part performance. The apparent density is the ratio of the mass to a given volume of powder. This is determined by means of Hall flowmeter funnel as described in ASTM B212. In case the powder does not flow, standard ASTM B417 with Carney funnel is followed. For PBF-EB/M technology the apparent density must be higher than 50% of solid material density. In case of Ti6Al4V powder for PBF-EB/M, the apparent density is around 2.5 g/cm^3.

7.2.4 Processing Parameters Determination for PBF-EB/M

As explained previously, PBF-EB/M machines are partially open-software so that users can modify and adjust the process parameters either for standar materials or for new powders. In some occasions process parameters can be adjusted in order to improve the process perfomance, for instance, the thicker the layer thickness is, the higher the build ratios will be, but simply changes like layer thickness will require a completely new setup of process parameters in order to melt the powder properly. Not only build ratio can be optimized, but also the behaviour of the melted material.

Therefore, it can be distinguished two different workpaths:

- Process parameter adjustment for standard materials: Improve somehow any of the features of the process when working with standard materials. This will imply from slight variations to very complex process adjustments in order to enhace the machine performance.
- Process parameter determination for nonstandard powders; this approach requires apparently much more efforts since there is not a first processing parameter setup. In this case different parameters must be tested so that consolidated material is analyzed afterwards in order to define the optimal energy to be deposited. The challenge to be faced within this approach is to find a processing window where material is flawlesly melted.

Standard Parameters Adjusted During Parameter Development:

- Scanning speed: (mm/seg) defines the velocity of the beam while melting the powder in different stages as contours, hatch or waffer. Increased velocity will lead to a reduction in the energy deposition.
- Focus offset: defines how focused or defocused the beam is. Depending on the build phase, defocused beams are required or not. Very sharp beams will increase the accuracy of the scanning path but on the other hand will increase the energy density.

- Line offset: (mm) distance between scanning lines. Every layer is made up of consecutive lines that increase the heat acumulation in the processed part. Low line offset values will lead to lack of fusion whereas very close lines will lead to part overheating.
- Beam current: (mA) current applied in each phase to heat or melt the powder.
- Process temperature (C): value measured beneath the build plate. Process temperature needed to partialy sinter the powder deposited each layer.
- Layer thickness (mm): powder bed height.

In addition, PBF-EB/M technologies use complex functions in order to regulate the energy deposition bearing in mind the part geometry. The aim of these functions is to prevent process issues like heat accumulation and so on.

- Thickness function: this function explores previous layers and analyze the areas that were melted so as to adjust the power and scanning speed. Energy density is reduced in low conductivity areas (non melted material) in order to prevet overheating. This function is normally triggered when overhanging.
- Speed function: measures the line path length and adjust both the beam current and the scanning speed in order to homogenize the temperatures no matter the geometry that is being melted.
- Turning point: Although melting path can be modified, it normaly presents a snake shape where at the end of a line there is a corner where energy can be accumulated. Turning point function aims to reduce the beam speed in this area so as to maintain constant temperatures (Fig. 7.25).

Processing Window

Process parameter development for new materials is an iterative process where the material density and properties after consolidation are improved. The goal is to achieve what is better known as "processing window" (Fig. 7.26) which is basically a certain area where parameters allow us to obtain processed material in a proper manner.

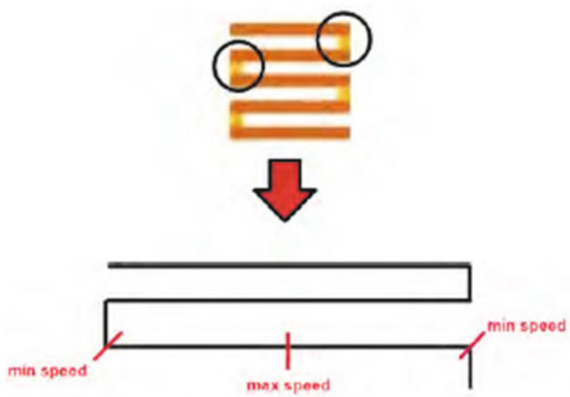


Fig. 7.25 Turning point scheme (*Source* AIDIMME)

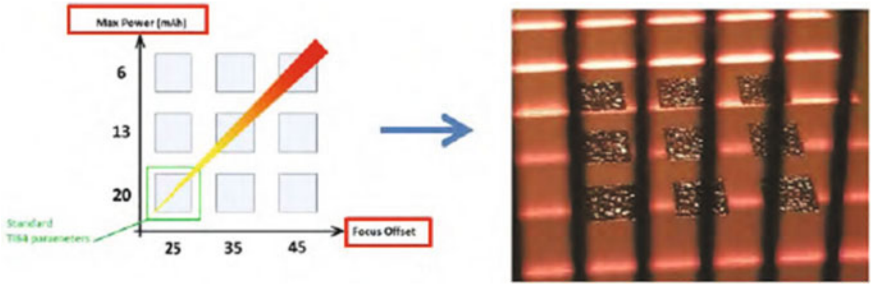
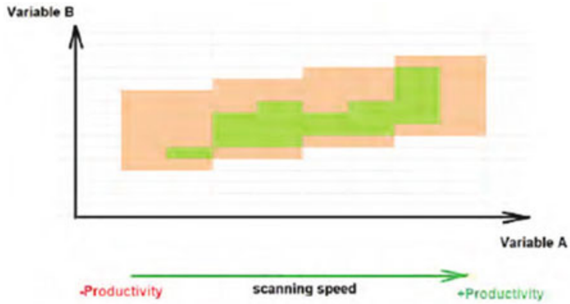


Fig. 7.26 Processing window gathering (*Source* AIDIMME)

Fig. 7.27 Processing window of a certain material (*Source* AIDIMME)



This process implies huge efforts, material and partially dedicated machines. It is normaly required to carry out consecutive builds varying some of the parameters pointed out previously, rejecting the ones where consolidated material presents lack of fusion or building issues and approving the ones where consolidated material presents good qualities.

As a summary, what it is obtained from this process parameter development is a window where some parameters define the processing boundaries of a certain material. Although only two variables are represented in the table below it is normaly required to adjust the whole setup of process parameter but only two specific variables are mapped within the window.

Green highlighted areas correspond to suitable process conditions whereas orange areas determine the processing boundaries or limits from which material is not properly processed (Fig. 7.27).

7.2.5 *Qualification of the PBF-EB/M Production*

Qualification is defined as a method to ensure that an AM process (combination of technology and material) is controlled and the result of it meets required specifications

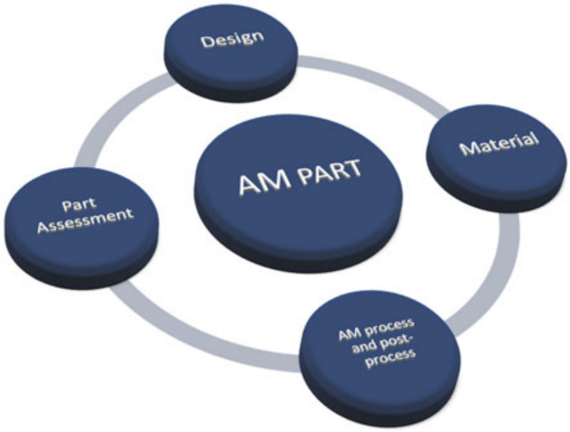


Fig. 7.28 Overview of all steps to obtain and AM part (*Source* RepAir project, AIDIMME)

in a repeatability manner. **Reproducibility** and **Repeatability** are the key values to include AM technologies as a production technology.

AM Challenges for Manufacturing Metallic Components for Critical Markets

Looking an overview of all steps required to obtain an AM part, it is necessary to evaluate all challenges of each step in order to control all possible variables and ensure that results meets all requirements of each step (Fig. 7.28).

For each step, there are some challenges that it is essential to consider its influence in the whole process in order to include an AM technology as a manufacturing option in critical sectors like aircraft or medical.

In terms of materials, it is important to consider:

– Powder properties differences from different powder suppliers. There are some powder manufacturing processes (gas atomization, plasma atomization, etc.) and results regarding powder properties are different.
– Differences in raw material from different batches, because AM technologies allow the use of blended powder, so the properties of the feedstock differ from virgin powder.
– Powder properties variation due to the reusability of it.
– Possible impurities due to non-dedicated machines.

Regarding Additive Manufacturing processes and post-processes:

– The complexity of the deposition process: energy source type and deposition feed raw material delivery and build chamber conditions.
– The physical phenomena related with AM are complex and dependent on multiple factors: Process variables vs mechanical properties and distortions.
– The need of post-processes for finishing parts, including machining critical areas to meet dimensional tolerances, grinding and blasting to reduce surface roughness.

Regarding Design and Part assessment:

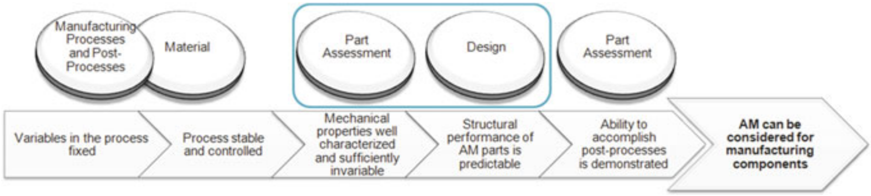


Fig. 7.29 Qualification process overview (*Source* RepAir project, AIDIMME)

– AM is not sufficiently understood nor characterized.
– Mechanical properties datasets are not available. It should be very interesting to have mechanical properties of a combination of material/machine in order to know the material properties in simulation software for designing process.
– Neither a correlation between product and process specifications is available.
– Nowadays, there are a lot of standard under development. New standards will bring these technologies closer to the industry.

As a summary, it is important to highlight that the process qualification is a method by which the parts processed as it has been specified are examined to ascertain if they meet the required specifications (qualifying criteria) in a repeatedly manner to be identified as qualified on Fig. 7.29.

The aim of the qualification procedure is to identify the variables of the process and its allowance range in order to know their influence in the part performance and process reproducibility. Thereby, this qualification process provides a correlation between product and process specifications to ensure adequate and consistent performance of parts; the procurement procedures; and assessment procedures for part acceptance.

How AM Could Be Introduced in an Affordable Way to Critical Markets Like Aircraft, Automotive, Medical?

Some industrial sectors are very restricted related to design modifications, such as an aircraft sector. In order to introduce in an affordable way AM in the industry is better to start testing and checking an AM part similar to its conventional part. For this reason, for some sector these are the steps for its introduction in some sectors:

1. AM of well-known geometry or small modifications for no critical parts.
2. New design geometry adapted to AM for no critical parts.
3. New design geometry adapted to AM for critical parts.

An overview of a strategy for AM implementation is presented in Fig. 7.30.

REPAIR Project: Future RepAIR and Maintenance for Aerospace Industry (2013–2016)

RepAIR Project performed a research on future repair and maintenance for the Aerospace industry. Therefore, the onsite maintenance and repair of aircraft by integrated direct digital manufacturing was in the focus of this project. REPAIR project

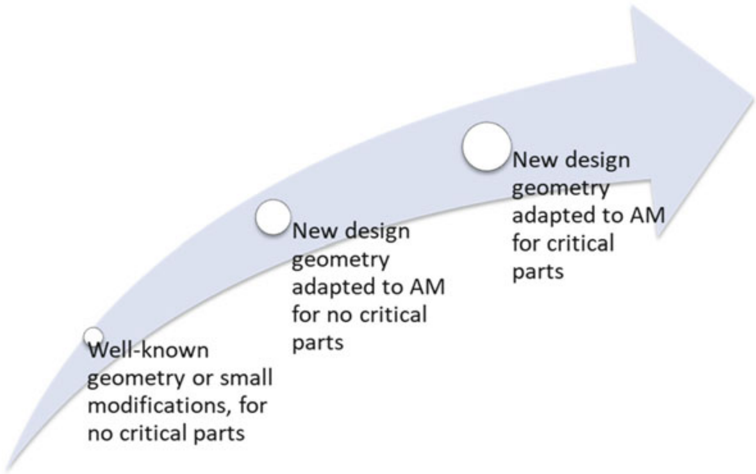


Fig. 7.30 Overview of an AM implementation strategy (*Source* RepAir project, AIDIMME)

was funded by European Commission FP7 Program. The main objective of RepAIR project was to shift the "make" or "buy" decision towards the "make" decision by cost reduction in the remake and rework of spare parts and therefore improve cost efficiency for maintenance repair in aeronautics and air transport.

A crucial advantage of this technology was the flexible availableness (even at the gate) allowing on-time maintenance. Through a higher level of automation und fewer stages of production, less personal costs are necessary which therefore reduce the MRO costs. These operations require a higher qualification and promote the preservation and expansion of highly qualified workplaces in Europe. Moreover, the storage costs will be significantly reduced.

The partners that participated in the project were APR, AIMME, ATOS, AVANTYS engineering, The Boeing Company, Cranfield University, Danish Aerotech, Danish Techn. Institute, Lufthansa Technik, O'Gayar Consulting, SLM Solutions, University of Paderborn. More information about this project can be found in.

Development of the Process Qualification in RepAIR Project

A process qualification procedure is the method used for the assessment of all the variables/factors suitable to influence in both technical requirements of the final part and process reproducibility compliance as well. This method should be developed based on the expertise and knowledge of all the processes considered in the supply chain and considering potential dependencies between variables coming from different processes such as post-melting processes.

The process qualification procedure requires the assessment and control of key raw materials/feedstock, consumables, and process parameters; the development of a fixed practice for each AM component; the verification of each fixed practice via NDI and destructive testing; and part-specific acceptance testing (both NDI and destructive testing) to ensure the integrity of parts.

Once the specification is generated and the supply chain defined, development of design data must be accomplished using material produced to the requirements of the specification. If the products of the AM process are confirmed to be robust by exhibiting nearly isotropic and uniform behaviour throughout the entire component and having low variability from part to part when parts are produced within the limits of the specification, a single design database for a given alloy is feasible. Once design data are available, an assessment of the predictability of structural performance must be conducted.

As result of the execution of the process qualification, it derives a knowledge about which should be the variables/factors with more impact in the part performance –key factors-, the allowance range for the key factors and the characterisation data for predicting structural behaviour among design.

Therefore, in the production of AM components, quality procedures and quality control should be developed and implemented in a quality management system for monitoring the key factors and verifying if they are inside of the allowance range. Finally, the verification of each fixed practice via NDI and destructive testing; and part-specific acceptance testing (both NDI and destructive testing) to ensure the integrity of parts (Fig. 7.31).

The general approach for the **process qualification procedure** could be divided in four steps:

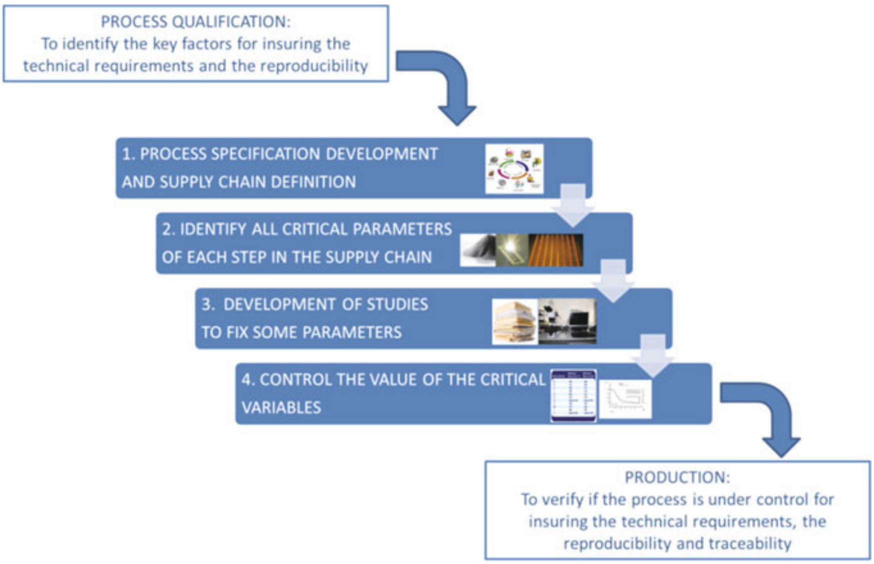


Fig. 7.31 General approach for the process qualification procedure and its application in the production (*Source* RepAir project, AIDIMME)

1. *Process specification development and supply chain definition.*

On this step, a process specification should be developed for AM manufacturing component. As part of the process specification, the AM process and post processes should be established based on some sensible technical requirements from the component such as:

- Material(s) specification(s): it is required to provide information related to the material such as material standard reference. The material standard establishes the chemical and mechanical behaviour of the material and some conditions for purchasing, storing, handling or processing. In some cases, other standard references would be considered for further information required such as testing methods for properties assessment. In this topic, special attention should be paid to the standards published from the ASTM F-42 and ISO TC-261 standardisation group and other known and accepted by component sector. Other material requirements not considered in the corresponding standards should be provided in addition.
- Geometry: it is required to provide the geometry in a 3D solid model format; the dimensional, geometrical and surface tolerances required through the corresponding drawing. If it is required a redesign of the part with the aim to reduce the weight of the part, the 3D model of the redesigned part should be provided. If some post processes are required in order to meet the technical requirements such as machining the definition of all 3D solid models required per process including the allowance material in the critical areas of the part should be provided as well.
- Use conditions: it is required to provide information related to the use of the part such as its function; the load conditions; the part environment conditions –chemical, temperature range, pressures range, humidity range; the configuration of the part within the system to which it belongs; the interactions with other parts or systems.
- Possible failure modes: it is required to provide information about the possible failure modes such as type of failure mode; frequency of the failure mode; failure location on part; mean time to repair/replace the part. The assessment tests should be considered in the process qualification procedure depending on the possible failure modes.
- Economic measures: it is required to provide information related to economical issues such as the economic goal; the description of the current manufacturing processes; the current part costs; the production targets; the batch size for primary equipment; the batch size of parts; the average technical delay; the average logistic delay; the average administrative delay and other issue relevant for taking economical decisions related to the process specification.
- Traceability: it is required to provide information/documentation about how a part is identified by itself and in relation with the subsystems or systems it

is included; about the raw material; about the process specified for manufacturing the part; about the providers considered into the supply-chain, about the assessment tests for validating the part.

Therefore, the process specification for manufacturing a component should be established based on all the information previously gathered considering the prior aspects. The process specification should include issues such as:

- All the manufacturing techniques used for achieving the final part: the specification of the AM technologies and the corresponding heat and surface treatments required after melting the parts. A workflow of all the steps required should be developed.
- The raw material processed or feedstock by the manufacturing techniques: the specification of the powder, the use conditions, the recyclability of the powder, the ageing allowed of the powder, the performance variance among the process and the powder blend procedure.
- The geometries required among the process: it is required to distinguish between the initial part model and the redesigned part model. Even, other additional geometries required in intermediate steps should be specified such as the geometry related to the supports for the AM technique and the geometry for machining process with the corresponding overmass to be removed afterwards.
- The AM process plan. It is required to establish the geometries to be built per cycle. The cycle refers to an individual build platform for the AM process. Depending on the process specification for qualifying the process, it could be required to build per cycle not only the parts if not also some witness specimens for assessment purpose. In addition, some other considerations should be considered such as the location of the parts in relation with the powder bed –build platform-, the build orientation, the properties variance along the chamber volume. To qualify the AM process plan specified some other conditions should be fixed among the cycles such as the system; the process settings –process parameters-; the operators knowledge; the maintenance agreements; the execution of the calibration process and the operational instructions to operate properly.
- The post-processing plan: it is required to provide information about the post-processes required to meet the technical requirements such as heat and surface treatments. This information would include the geometries required in each post process; the fixtures developed for machining and the strategy to obtain a surface quality part; the heat treatment settings for stress relief and/or improving the microstructure and the HIP settings for reducing the porosity and for improving the structural performance of the part.
- The assessment plan: it is required to establish the definition of a set of studies to be carried out through NDT and destructive tests to characterise all the process specified. In these studies the raw material, the AM processed material and the part should be characterised following the assessment developed. The characterisation studies proposed should consider the standards as reference for establishing the

qualification process. A prior selection of standards required should be established from the beginning.

- The process reproducibility: the number of cycles required in order to assess the reproducibility of the process specified. A comparison between the results from the characterisation of the different cycles should be considered to determine potential variance between the results.

2. *To identify all critical variables—parameters- among the process specification of each step in the supply chain: key factors.*

Among the process specified for manufacturing a part, many variables—parameters are involved. All these variables have a cross-linked relation between them due to the nature of the AM technologies. Therefore, it is required to know about the potential dependencies between them.

It refers to critical variables, to the set of variables with more influence in the quality of the resultant part. The quality of the resultant part deals with the compliance with the technical requirements required and if the process specified becomes stable and repeatable. *These critical variables should be considered as key factors to be monitored among the process specified*.

Of all manufacturing techniques considered in the process specification, the newest and less known are the AM, in particular metal AM processes. So, efforts have concentrated in the definition of the parameters of the AM process and its dependencies with other conventional processes. To do this task, a list of the parameters among the process specification should be considered and classified in the next groups:

- Plant
- Raw material
- AM processed material
- Post processes
- Part.

In the process qualification, some of the parameters are not variable along the cycles or batches usually. On that case, we consider in the studies those as fixed parameters. Figure 7.32 shows a preliminary set of parameters.

3. *Development of studies to fix some parameter and to analyse the influence of all of them.*

After considering a list of parameters classified in groups, some studies should be considered for analysing the influence in the quality of the part of each parameter by itself and in relation with others.

The studies look for evaluating the dependencies between, the raw material in a specific powder batch; the reusability of the powder; the AM processed material properties depending on the bed location (along X–Y axis and Z axis) and the build direction (X, Y and Z axis); the influence of the HIP and the surface roughness in the fatigue behaviour.

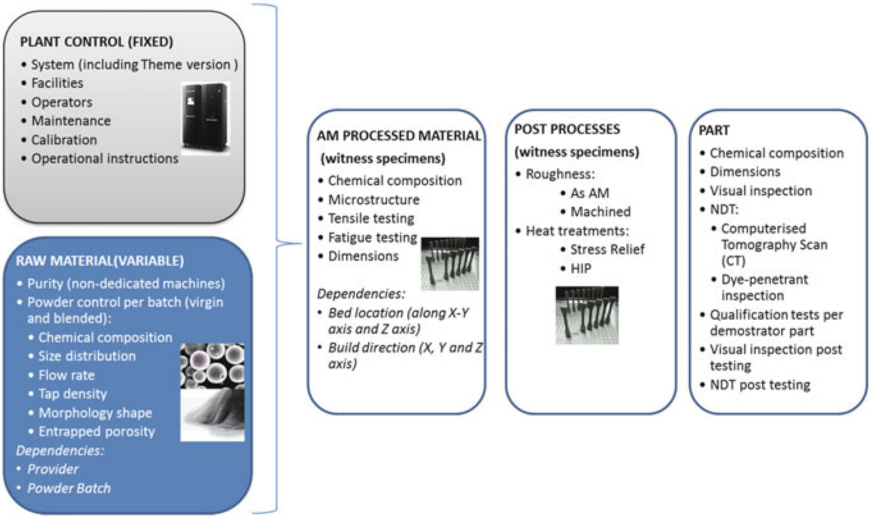


Fig. 7.32 Preliminary definition of AM process parameters classified in groups (*Source* RepAir project, AIDIMME)

Before to carry out these studies, it is crucial to review all scientific publications and internal studies developed by the technology provider or AM experts in order to delimit the extent of the studies to carry out. The conclusions and the knowledge acquired in these reports shall be documented.

4. *Control the value of the critical variables or key factors.*

Finally, after searching relevant publications or carrying the studies proposed before, as result the key factors would be identified and also it would be possible to know about which is the allowance range for each of them. The term "allowance range" means the lower and upper value of each parameter considered as boundaries. If the value of one key factor is inside of this allowance range, it is possible to say that the part quality is in compliance concerning this parameter.

The aim to setup the allowance range of the key factors is that in production, it is possible to monitor its values and if they are inside of the established boundaries or not. The assessment of the key factors should be implemented in the quality management procedures as quality control points.

A Guide for Additive Manufacturing Qualification Procedure Implementation

Based on the qualification process qualification procedure developed in the project a guide for AM Qualification Procedure was defined, this guide covers additively manufactured Ti6Al4V components using full-melt powder bed fusion such as electron beam melting and laser melting,

This method is based on the requirements specified in the standard ASTM F2924-14 and the expertise from experts with complementary background. The method proposed for AM Qualification considers the following steps for AM manufacturing process (Fig. 7.33).

(1) **Component requirements specification**. This contains a specific register of a set of requirements to be acquired for the component considered. The requirements specification will drive the qualification method, herewith even, the component design, and the manufacturing plan. Once the design of the part and the manufacturing plan are implemented, verification of the component will be carried out against the requirements specified in this specification.

(2) **Manufacturing plan for qualification**. Once the component requirements have been specified a manufacturing plan for qualification can be specified. This plan requires several build cycles in which different witness specimens are assessed in accordance with the corresponding chapters of the ASTM F2924-14. The specimens considered are for chemical composition from powder lots and melt material as well, microstructure and mechanical property—tensile and fatigue-. Different location, orientation on the build platform, number of test specimens for each build cycle are considered for establishing the relationships between these process variables and the results. Moreover, the assessment of the results reproducibility among build cycles is driven in the manufacturing plan. Prior to proceed with the manufacturing plan execution it is convenient to ensure issues related with the control of the AM facilities (AM machine, auxiliary equipment, software version) and AM personnel qualification.

(3) **Feedstock (powder)**. In this se. ction it is described the studies to be considered for specifying the feedstock –metal powder- in the process qualification method. Special attention will be required to the following facts:

- There are some causes, which may affect to the presence of inclusions and impurities in the chemical composition of the powder, even in the melt material, such that the final material chemistry will be not in accordance with Table 1 from ASTM F2924-14. The use of a non-dedicated machine for one specific metal, which requires changing the powder alloy and in consequence, it is one of the most relevant causes of the powder contamination.
- High chamber temperature—case of PBF-EB/M—during building derives in a variation in chemical composition regarding virgin powder due to evaporation of some elements. During handling, some alloys may suffer significant oxygen pick-up, even due to humidity inside the build chamber, which may not be completely eliminated. Oxygen pick-up may increase material fragility. The chemical composition of the metal powder shall be

Fig. 7.33 AM manufacturing process steps (*Source* RepAir project, AIDIMME)

adequate to yield, and after processing, the final material chemistry shall be in accordance with the Table 1 of the ASTM F2924-14.

- The use of the used powder is allowed, but additionally to the effects of variance in the chemical composition described above, modifications in other powder properties such as size distribution, particle shape, apparent density and flow rate may produce also bad fusion results.
- Powder blends are allowed unless otherwise specified between the component supplier and the component purchaser, as long as all powder used to create the powder blend meet the requirements listed in Table 1 from ASTM F2924-14 and lot numbers are documented maintained.

Therefore, it is convenient to consider in the process qualification method the following studies related to the feedstock control:

- Assessment of the amount of inclusions and impurities present in the chemical composition of the feedstock. The assessment of the chemical composition in the melt material will serve to ascertain if the final material chemistry is in accordance with Table 1 from the ASTM F2924-14. However, the assessment of the chemical composition in the powder prevents non-conformities for build cycles before processing.
- Assessment of the feedstock properties variation along several build cycles. This study considers the assessment of the property variations in both, powder and melted material as well, when the same powder lot is processed several times in different build cycles in a machine. Powder properties assessed shall be chemical composition, size distribution, particle shape, apparent density and flow rate. Meanwhile AM processed material assessed shall be chemical composition. This study provides information about the most limiting element in the chemistry, hereafter referred as "critical element" and a correlation of the percentages by weight of this element between the melt material and powder. This information shall drive the procedure for blending the powder and shall provide the maximum number of times used powder can be used.

(4) **AM and post-processed material characterization**. As part of the manufacturing plan for qualification it is included the specification of the post-processing sequence of operations. Post-processing operations may be used to achieve the desired shape, size, surface finish, or other component properties.

According to the component requirements specified, a structural performance of the AM processed material shall be characterised in the process qualification method. Therefore, once the feedstock studies described in the prior section have been conducted, the critical element has been identified and the powder blending has been specified, the processed material shall be characterised using as feedstock, several samples with a percentage by weight of the critical element into the minimum and maximum values specified in Table 1 from ASTM F2924-14. That means, the structural properties of the AM processed material shall be predictable if it is processed from any feedstock with a percentage by weight of the critical element into these values.

(5) **Manufactured component**. The component properties depend on the position and location of they are processed on the build platform.

The design of the support structures may influence in the result of the component processed by AM. Support structures act as not only for supporting the weight of the material when it is melted if not also as heat conductor between the melt point and the build platform. Distortion during and after this process is mainly due to thermal gradients and local strains caused by phase changes. It cannot be avoided, but the support structure can be designed in such a way that distortion is minimised.

Post-processing operations may be used to achieve the desired shape, size, surface finish, or other component properties.

On that case, it is required finally an assessment of the component properties in order to qualify if the process for manufacturing the component as it is specified in the manufacturing plan shall comply the component requirement specifications.

Depending on the market sector, during the AM component manufacturing, a set of samples shall be built together with the component in order o guarantee the correct manufacture of the component, ensuring the chemical composition and mechanical properties of the AM processed material. This guide could be considered as reference for other metal alloys using full melt powder bed fusion such as electron beam melting and laser melting.

RepAIR Project Study Case:

According to the qualification process guide described, the following case study has been considered for its implementation following the standard reference ASTM F2924-14:

(1) Component requirements specification. The selected case study is a non-structural load-bearing bracket. The material for this part is Ti6Al4V. The dimensions are about 180 × 110 × 40 mm. Its modes of failure can be an overload, a fatigue failure or a creep distortion. A drawing with dimensions, tolerances and references has been provided by the OEM.
(2) Manufacturing plan for qualification. For manufacturing the bracket, both PBF-LB/M and PBF-EB/M has been considered. This study case only shows the implantation of PBF-EB/M in the manufacturing plan. The part after AM processed should be machined and HIP treated for acquiring the dimensions, surface roughness and fatigue behavior required. The location, orientation of the part in the build platform is specified according technical and economic feasibility. Thereby, the minimum support structures are considered for avoiding machining operations but preventing distortions and manufacturing failures.

The qualification platform was designed taking into account all previous considerations. It was built three times, for the assessment of process robustness and results reproducibility. This platform includes the following samples (Fig. 7.34).

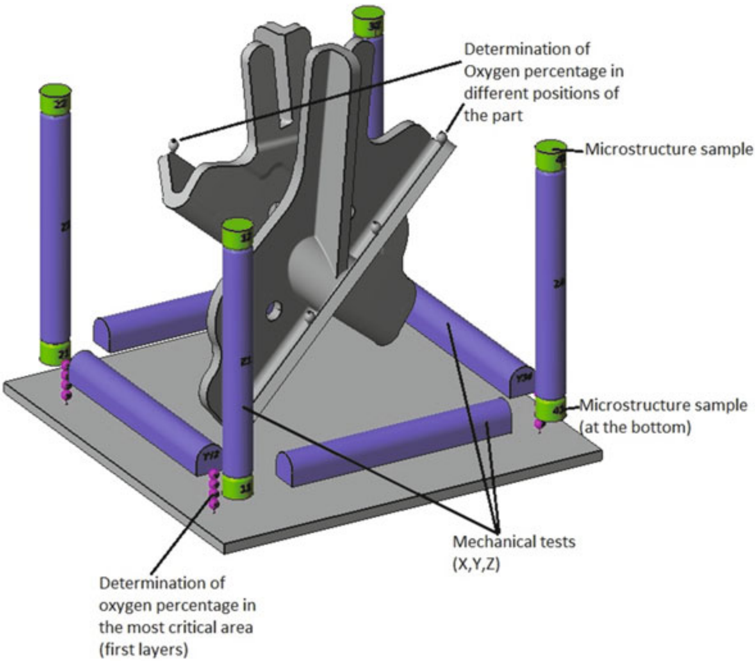


Fig. 7.34 Manufacturing platform definition for qualification (*Source* RepAir project, AIDIMME)

Considered samples are:

– Witness specimens for chemical composition analysis of the AM processed material:

- Sphere coupons of 5 mm diameter for characterizing the Oxygen content by weight. Four of these spheres are linked between them for ascertaining the Oxygen content variation along z-axis. The linked spheres are built in every corner of the platform for ascertaining the Oxygen content variation along x and y-axis. These samples are built directly over the platform.
- Support structures have been used for other element characterization present in the alloy; and for the assessment of inclusions and impurities.
- Sphere coupons of 5 mm diameter for characterizing the Oxygen content by weight linked to the part. There are considered 3 items per part.

– Witness specimens for tensile test of the AM processed material:

- The geometry of the specimen considered is according the standard reference.
- The number of specimens considered for tensile test was 8 per build cycle.
- The position of these specimens on the build platform was the following, all of them were separated over the build platform 15 mm at least and positioned close to each of its corners and its borders; they were oriented as follows, 4 in z

axis direction, 2 in x axis direction and 2 in y axis direction. Thus, it is possible to know about the property variations related to build position and orientation.

– Witness specimens for microstructure and porosity test of the AM processed material:

  - The geometry of the specimen considered is a cylinder coupon of 14 mm diameter and 10 mm length.
  - These specimens are linked to the vertical tensile bars, at each of its ends. Such that, 4 of them are separated over the build platform 15 mm at least. Thus, it is possible to know about the propery variations related to build position in x, y and z-axis.
  - The number of specimens considered for microstructure was 8 per build cycle.

– Components:

  - Two brackets are considered with the orientation more feasible from technical and economic point of view. This orientation prevents failures along manufacturing. The support structure design is conceived for reducing distortions phenomena and for minimizing the machining operations after AM process.

(3) Feedstock. For the characterisation of the feedstock the following assessment has been done in accordance with the standards listed into Table 7.2:

  – The assessment of the amount of inclusions and impurities based on the materials prior processed in the system.
  – The assessment of the feedstock properties variation along 3 build cycles using the same powder lot, after characterizing the starting powder.

(4) AM and post-processed material characterization. For the characterisation of the feedstock the following assessment has been done in accordance with the standards listed into Table 7.2:

  – The chemistry of the AM processed material.
  – The tensile properties of the melt material with and without HIP treatment.
  – The microstructure and porosity of the melt material with and without HIP treatment.

(5) Manufactured component. For the characterisation of the manufactured component the following assessment has been done:

  – Dimensional and surface measurement after machining and HIP treatment.
  – Two different fixtures and process parameters for machining operation has been considered from different suppliers.

Figures 7.35 and 7.36 show the witness specimens and parts manufactured by PBF-EB/M (Fig. 7.37).

Table 7.2 Standards for tests

Test required	Test standard
Chemical analysis	ASTM E2371. Test Method for Analysis of Titanium and Titanium Alloys by Direct Current Plasma and Inductively Coupled Plasma Atomic Emission Spectrometry (Performance-Based Test Methodology) ASTM E539. Test Method for Analysis of Titanium Alloys by X-Ray Fluorescence Spectrometry ASTM E1409. Test method for determination of oxygen and Nitrogen in titanium and titanium alloys by Inert gas fusion ASTM E1447. Test method for determination of Hydrogen in titanium and titanium alloys by inert gas Fusion thermal conductivity/infrared detection method ASTM E1941. Test method for determination of Carbon in Refractory and reactive metals and their alloys by combustion analysis ASTM E2371. Test method for analysis of Titanium and Titanium alloys by direct current plasma and inductively coupled Plasma atomic emission spectrometry EN 3976. Aerospace series. Titanium and titanium alloys. Test method. Chemical analysis for the determination of hydrogen content ASTM F2924-14. Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion ISO 17025. General requirements for the competence of testing and calibration laboratories

(continued)

Table 7.2 (continued)

Test required	Test standard
Powder morphology properties: tap density, flow rate, particle shape, and particle size distribution	ASTM B212. Test Method for Apparent Density of Free-Flowing Metal Powders Using the Hall Flowmeter Funnel ASTM B213. Test method for flow rate of metal powders using the hall flowmeter funnel ASTM B214. Test Method for Sieve Analysis of Metal Powders ASTM B243. Standard Terminology of Powder Metallurgy ASTM B822. Test Method for Particle Size Distribution of Metal Powders ASTM E3. Guide for Preparation of Metallographic Specimens ASTM E11. Specification for Woven Wire Test Sieve Cloth and Test Sieves ASTM E407. Practice for Microetching Metals and Alloys ASTM F2924-14. Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion, Sects. 7 and 9 ISO 9044. Industrial Woven Wire Cloth – Technical Requirements and Testing. Related Compounds by Light Scattering ISO 17025. General requirements for the competence of testing and calibration laboratories
Microstructure—sample preparation, alpha case, porosity, grain size and surface contamination	ASTM E3. Guide for Preparation of Metallographic Specimens ASTM E112. Test Methods for Determining Grain Size ASTM E407. Practice for Microetching Metals and Alloys ASTM F2924-14. Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion EN2003-4. Aerospace series- Test methods- Titanium and titanium alloys- Part 009: Determination of surface contamination ISO 17025. General requirements for the competence of testing and calibration laboratories

(continued)

Table 7.2 (continued)

Test required	Test standard
Tensile sample preparation and test	ASTM E8M. Test Methods for Tension Testing of Metallic Materials ISO 6892. Metallic materials - Tensile testing - Part 1: Method of test at room temperature ASTM F2924-14. Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion ISO 17025. General requirements for the competence of testing and calibration laboratories

Source RepAir project, AIDIMME

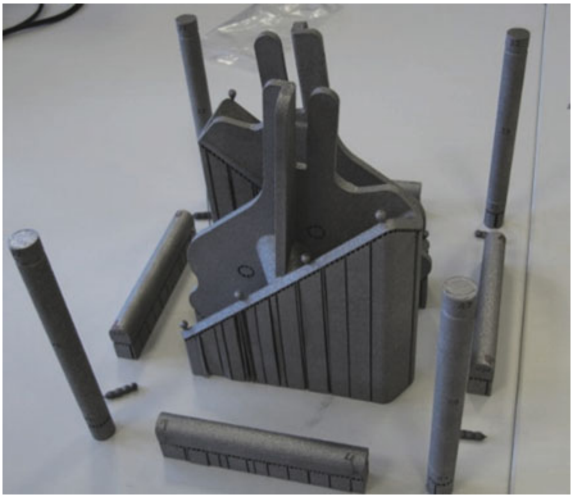


Fig. 7.35 Build cycle manufactured (*Source* RepAir project, AIDIMME)

Fig. 7.36 Tensile bars together with samples for microstructure and porosity testing (*Source* RepAir project, AIDIMME)

– Feedstock. There is not relevant variation of the powder characteristics along the three build cycles. There is not presence of impurities or inclusions after following the powder handling procedures established by the technology developer, even in a non-dedicated system for a given alloy.
– AM processed material:
  - The chemistry of the AM processed part is according to the Table 1 specified in ASTM F2924-14, even in the case of Oxygen as critical element in this alloy (Table 7.3). The values shown in the graph correspond to the average of the % Oxygen of all specimens per build cycle (Figs. 7.38, 7.39).

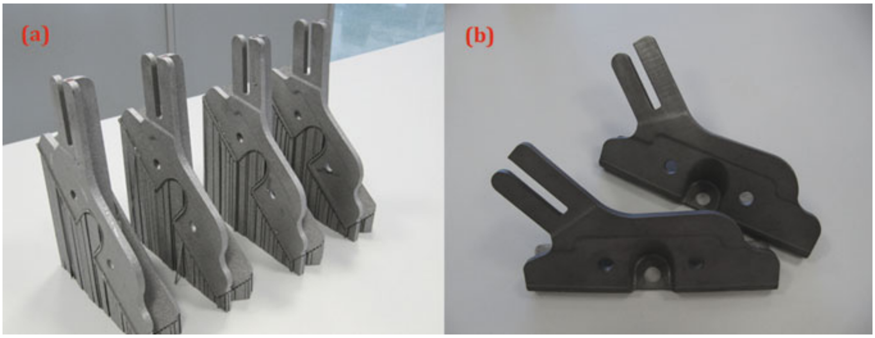


Fig. 7.37 Manufactured parts with (**a**) and without support (**b**) (*Source* RepAir project, AIDIMME)

Table 7.3 Evolution of % Oxygen content (average of all specimens) in AM processed material along the build cycles

Build cycle	Oxygen content (%) by weight
Build cycle 1	0.1446
Build cycle 2	0.1505
Build cycle 3	0.1541
Maximum oxygen allowed according to ASTM F2924	0.20

Source RepAir project, AIDIMME

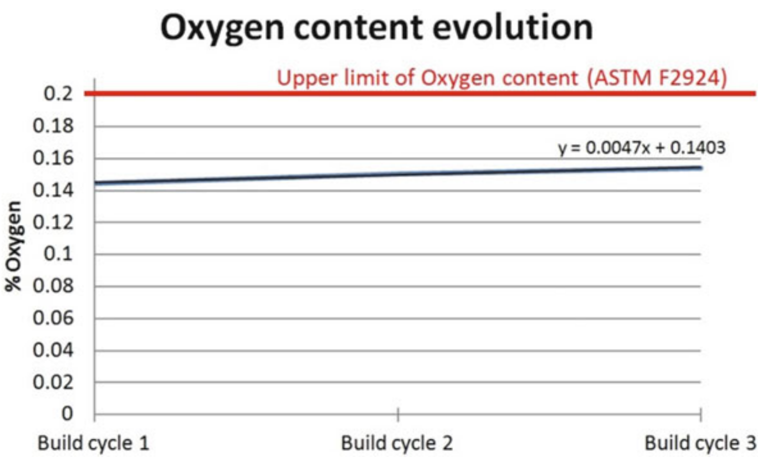


Fig. 7.38 Oxygen evolution in AM processed material (*Source* RepAir project, AIDIMME)

– Concerning the tensile tests of the specimens with and without HIP treatment, all of them are according with the ASTM F2924. Table 7.4 shows the results per build cycle considering the build orientation (horizontal vs. vertical). Figure 7.40 shows

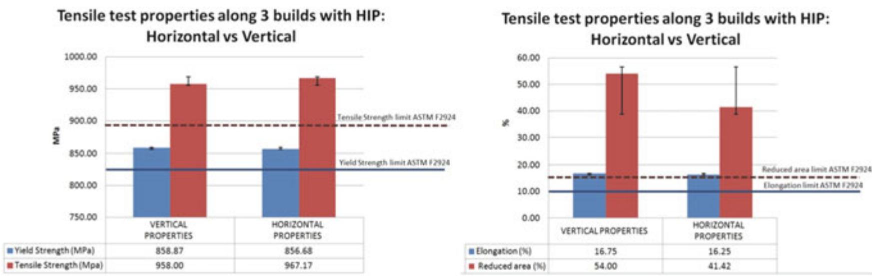


Fig. 7.39 Tensile properties variation considering build orientation for the specimens HIP treated (*Source* RepAir project, AIDIMME)

the tensile properties comparing the average values of all specimens without and with HIP treatment.

– It is important to highlight the repeatability of the mechanical properties: repeatability trend curve (Fig. 7.41), and the curves stress vs. strain from all the specimens with HIP treatment (Fig. 7.42). The build cycle, the location and the orientation of the specimens are considered in the legend of the graph.

– For Ti6Al4V grade 5, HIP process reduces or eliminates internal porosity that contains parts processed by AM (Table 7.5; Fig. 7.43), and this phenomenon improves the fatigue behaviour of the material. HIP process increases the columnar grain size in both, width and length and also it increases the thickness of the α-plates along the build direction (Fig. 7.43). In general, the size of α-platelets colony is very small and in the majority of cases they are present in singular forms. Therefore, HIP treatment modifies the microstructure and reduces slightly the static mechanical properties of the material (Fig. 7.40).

7.2.6 Powder Recycling for PBF-EB/M

Feedstock control in an AM technology is highly important to obtain good and reproducible results in an AM production. In case of Powder Bed Fusion technologies, it is necessary to guarantee that the properties of the powder as feedstock are suitable for this technology as it was mentioned at the beginning of the chapter.

In chapter 7 of the ASTM F2924-14 it is highlight:

- **The use of the used powder is allowed**. The proportion of virgin powder to used powder shall be recorded and reported for each production run. The maximum number of times used powder can be used as well as the number of times any portion of a powder lot can be processed in the build chamber should be agreed upon between component supplier and purchaser.

Table 7.4 Results of tensile test of the specimens with and without HIP treatment

Build cycle and specimen build orientation	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduced area (%)
BP0-vertical (Z-axis) no HIP treated	922.38	1012.05	15.00	40.00
BP0-horizontal (XY-axis) NO HIP treated	917.75	1018.69	15.50	43.50
Average of Specimens no HIP treated	920.07	1015.37	15.25	41.75
BP1-vertical (Z-axis) HIP treated	849.70	948.96	16.63	54.25
BP1-horizontal (X–Y axis) HIP treated	837.46	953.13	14.25	39.50
BP2-vertical (Z-axis) HIP treated	857.62	956.55	16.88	54.25
BP2-horizontal (X–Y axis) HIP treated	861.77	968.85	17.25	44.75
BP3-vertical (Z-axis) HIP treated	869.30	968.49	16.75	53.50
BP3-horizontal (X–Y axis) HIP treated	870.82	979.53	17.25	40.00
average of specimens HIP treated	857.78	962.58	16.50	47.71
Minimum tensile properties (according to ASTM F2924)	825	895	10	15

Source RepAir project, AIDIMME

- **Powder blends are allowed**, unless otherwise specified between the component supplier and the component purchaser, as long as all powder used to create the powder blend meet the requirements listed in the corresponding standards and lot numbers are documented maintained.

ASTM F2924 allows the use of used powder and blended powder, but how many times is it possible to re-use it? Which is the procedure for blending the powder?

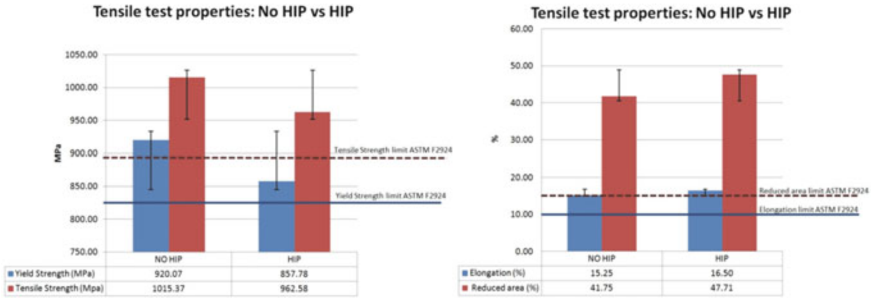


Fig. 7.40 Tensile test properties with and without HIP treatment (*Source* RepAir project, AIDIMME)

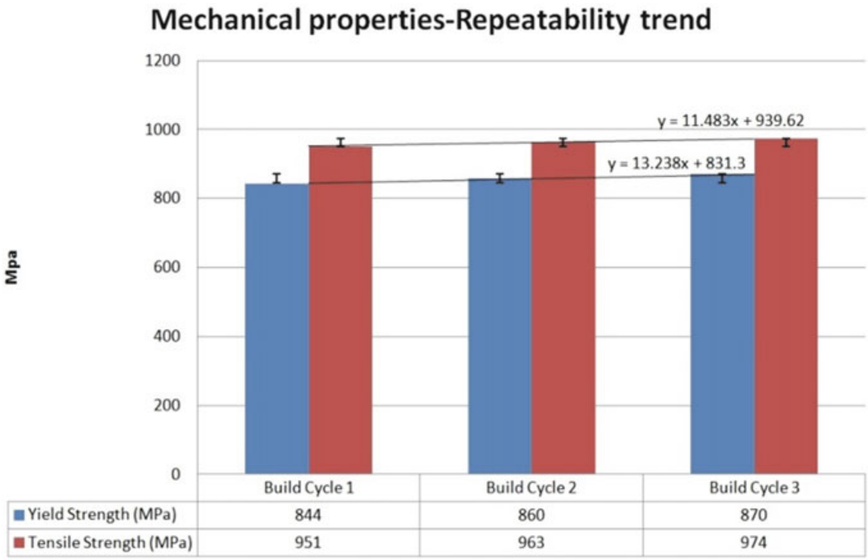


Fig. 7.41 Repeatability of the mechanical properties (*Source* RepAir project, AIDIMME)

The following information on feedstock control in PBF-EB/M technology is extracted from to two research projects: (i) AEROBEAM [1], and (ii) MANSYS [37].

- **AEROBEAM**: Direct Manufacturing of stator vanes through electron beam melting (2012–2013). Evaluation and comparison of mechanical properties between fresh and recycled powder.

Aimed at investigating the mechanical properties of aeronautical Ti6Al4V stator vanes elaborated by Electron Beam Melting, tensile and fatigue tests were performed on both fresh and recycled powder to assess the mechanical properties of Ti6Al4V

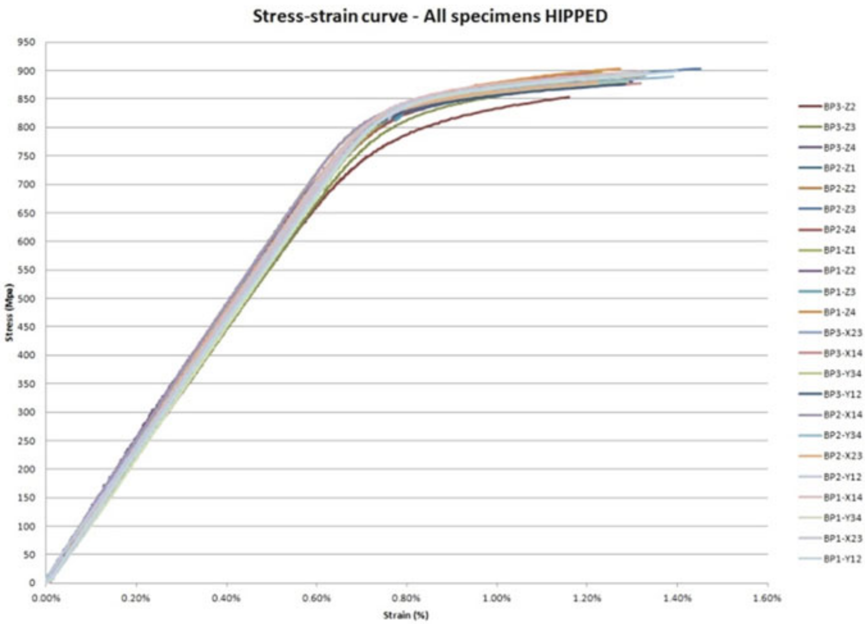


Fig. 7.42 Stress versus strain curves from all the specimens with HIP treatment (*Source* RepAir project, AIDIMME)

Table 7.5 Average values of porosity and melted material with and without HIP treatment

	Porosity (%)	Melted material (%)
As built material without HIP treatment (XY Plane) build cycle 0 (BP0)	0.0754	99.9246
As built material without HIP treatment (XZ Plane) build cycle 0 (BP0)	0.3267	99.6733
As built material with HIP treatment (XY Plane) build cycle 1 (BP1)	0	100
As built material with HIP treatment (XZ Plane) build cycle 1 (BP1)	0	100
As built material with HIP treatment (XY Plane) build cycle 2 (BP2)	0.0028	99.9972
As built material with HIP treatment (XZ Plane) build cycle 2 (BP2)	0.0045	99.9955
As built material with HIP treatment (XY Plane) build cycle 3 (BP3)	0	100
As built material with HIP treatment (XZ Plane) build cycle 3 (BP3)	0	100

Source RepAir project, AIDIMME

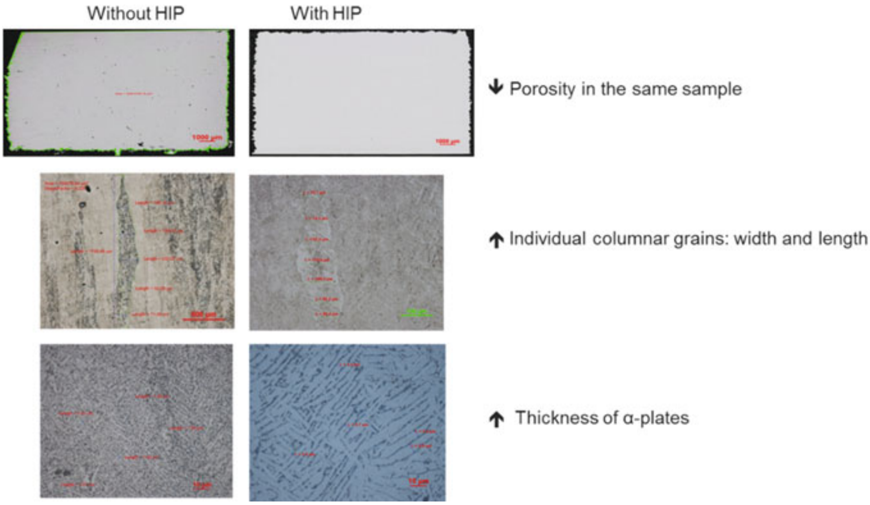


Fig. 7.43 Microstructure evaluation and comparison between with and without HIP (*Source* RepAir project, AIDIMME)

material elaborated by EB-PBF. Limit of use of the recycled Ti6Al4V atomized powder associated with the PBF-EB/M process will be determined.

Partners: AIMME, CEIT. Topic Manager: SAFRAN Snecma.

Funded by: European Commission FP7 Program. Cleansky JTI-CS-2012-01-ECO-01-049

- **MANSYS**: Manufacturing decision and supply chain management SYStem for additive manufacturing (2013–2016).

ManSYS aims to develop and demonstrate a set of e-supply chain tools to enable the mass adoption of Additive Manufacturing. "A complete decision making system and robust supply chain management system for metal additive manufacturing; enabling the production and delivery of quality assured, highly customized products and services".

Partners: AIMME, BCT GmbH, Berenschot, GE Marmara Technology Center (GE MTC), LPW, Materialise, Poly-Shape, Smith & Nephew, TNO, TWI, Twocare, Wisildent.

Funded by: European Commission FP7 Program. FoF.NMP.2013-9 (Advanced concepts for technology-based business approaches addressing product-services and their manufacturing in globalised markets).

There are some particularities related to the Powder Bed Fusion technologies that influence in the status of the powder.

- The use of non-dedicated machines for one specific metal, which requires changing the powder alloy periodically; it is one of the most relevant cause of the powder contamination and finally the built material is contaminated too. It is no possible to work in specific area of medical sector, such as AM implants.

- In the case of PBF-EB/M—High chamber temperature during building derives in a variation in chemical composition regarding virgin powder due to evaporation of some elements. During handling, some alloys may suffer significant oxygen pick-up, even due to humidity inside the build chamber, which may not be completely eliminated. Oxygen pick-up, may increase material fragility, but also affects powder fluidity, avoiding proper powder distribution in layers and may produce bad fusion between them.

Due to the described particularities some studies were done in order to control the PBF-EB/M feedstock:

- Assessment of the amount of inclusions and impurities present in the chemical composition of the feedstock for PBF-EB/M. The assessment of the chemical composition in the material as built serve to ascertain if the final material chemistry is in accordance with the Table 1 of the ASTM F2924-14. However, the assessment of the chemical composition in the powder prevents non-conformities for build cycles before processing.

  The ARCAM A2 machine for this example is a non dedicated machine, for this reason an exhaustive cleaning process was performed when a new material shall be processed.

  A list of the metal alloys previously processed in the machine shall be specified; in this case the metal alloys were CoCr ASTM 75, Nickel alloy and pure Copper powder.

  The chemical composition analysis was assessed in different samples, from powder lot and as built material as well. Table 1 from ASTM F 2924 shows the small percentage of impurities that are allowed for this kind of material.

  Results from different builds show that the clean procedure followed before proceed with new powder batch is correct and it is possible to process Ti6Al4V with guarantee that there is not presence of impurities according to ASTM F2924-14 or ASTM F3001-14.
- Assessment of the feedstock properties variation along several build cycles. This study considers the assessment of the property variations in both, powder and as built material as well, when the same powder lot is processed several times in different build cycles in a machine. Powder properties assessed shall be chemical composition, size distribution, particle shape, apparent density and flow rate. As built material property assessed shall be chemical composition.

  – The **identification of the critical elements** in the chemical composition
  – Identification the **Maximum number for re-using the same powder**

The study was performed on Arcam A2 machine, using Ti-6Al-4V powder provided by Arcam AB. Builds were manufactured consecutively with the same recycled powder. After each build, all the powder—the blasted, the vacuum-cleaned and the one remaining in the hoppers—was sieved and mixed together. Then, a sample of approximately 20 g of powder is taken for powder analysis. Once the powder samples were taken, the powder hoppers are reloaded with the sifted powder from the bucket and the next build is prepared. The builds were performed in the room with controlled temperature (21–23 °C) and controlled humidity (35-40%).

The powder analysis strategy was established in the following manner: the powder was analyzed build after build until reaching the build in which one or more elements are out of range.

After evaluation of all chemical analysis results, it was established that the maximum level of recyclability in this study is 12. This value depends strongly on oxygen content which is the only one that in this analysis showed clear tendency of increase. It must be underlined that the recyclability level will always depend on the initial oxygen content in the fresh powder (in this case it was 0.14%). All other alloying elements are more or less constant and way under the allowed limit. It is of much importance to highlight that this study was performed under the most critical scenario, since no fresh powder was added at any point. The common procedure in EB-PBF manufacturing is to keep the same powder quantity by adding new powder as it is spent. In other words, the mixture of fresh and recycled powder will leave us always on the safe side in comparison to these results.

It is possible to conclude that the used if Ti6Al4V is allowed, it is required to monitor the content by weight of the Oxygen in the material in order to avoid risks. This parameter should be considered as critical element in the chemistry of this alloy and therefore, it is shall be specified as one item to be controlled in a Quality process.

7.2.7 Parts Characterizing and Qualification

Introduction to Technologies for Part Qualification

After an Additive Manufacturing process of a set of parts in a build plate, a part qualification or testing procedure shall be followed in order to assure that parts meet customer requirements (specially for critical parts). A tentative procedure could be:

1. Visual inspection (surface porosity, defects, etc.).
2. Evaluation of log files and AM reports, in order to detect possible fails like vacuum, temperature, electron gun problems, etc. Variables depend on the AM technology.
3. Chemical analysis (with a tester that is built in the same build cycle than the critical part).
4. Dimensional tolerances (with the dimensional tester).
5. Dimensional tolerances of the part (depending on the shape of the part it is necessary specific equipment like Scanner 3D).
6. Mechanical behaviour (with tensile test specimens or product test, but they are destructive tests).
7. Non-Destructive Testing (NDT) to control what happen inside the part (Dye-penetrant inspection, Ultrasonic inspection and CT scan).
8. Other tests depending on the application of the final part.

Figure 7.44 exhibits an example of visual inspection defects.

One of the most widespread applications of metal Additive Manufacturing is the manufacture of unique parts; therefore Non-Destructive Tests are needed for evaluation. There are two kinds of defects:

– External defects, such as surface defects, surface porosity, distortion, surface inclusion, textures.
– Internal defects, such as internal porosity, inclusion and lack of fusion.

Some of the NDT are suitable for detecting external defect, such as Visual test or Fluorescent Penetrant Inspection (FPI) and for internal defects are suitable techniques like X-Ray and Computer Tomography Scan (CT Scan). Computer Tomography (CT scan) may be selected as the most suitable non-destructive test for the inspection of an AM part. All kind of defects (internal and external) are detected by this testing method.

Computer Tomography Scan Inspection for Qualifying AM Parts

CT scan or computed tomography (formerly computerized axial tomography scan or CAT scan) is a non-destructive materials test which makes use of computer-processed combinations of many X-ray measurements taken from different angles to produce cross-sectional (tomographic) images (virtual "slices") of specific areas of a scanned object, allowing the user to see inside the object without cutting.

Good results are observed in parts processed by Additive manufacturing Technologies for three main reasons:

– Defects detection

- Internal pores.
- Cracks.
- Inclusions.
- Non melted material inside channels (trapped powder).
- Cleaning parts deficiency.

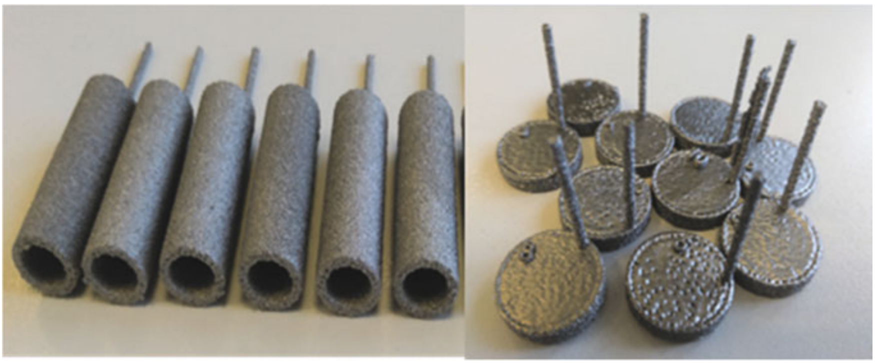


Fig. 7.44 Example of visual inspection defects (*Source* AIDIMME)

– During process parameters development process, detection of internal pores and cracks in a specific location (hatch or contour) allow modifying specific parameters depending on this defect and the detected location.

CT scan measurement principle is the measurement of the attenuation of the X-Ray radiation due to the component geometry and the density of the material used.

There are some parameters to take into account before CT scanning of a part, because b it determines the power of the equipment to be used and if it is possible to make the measurement:

– Volume of the part.
– The material.
– The thickness of the part that depends on the density of the material and the equipment technical characteristics.
– The shape of the part.

These parameters determine the measurement of a part as well as whether it is possible to scan more than one part at the same time.

There are different companies around Europe that offer CT scan services. Following examples were developed by AIDIMME with the collaboration of Carl Zeiss Iberia Company that belongs to Zeiss Group and it is located in Barcelona.

AM defects detection:

Example 1 Tensile test inspection (Fig. 7.45).

One of the tensile test specimens exhibited poor elongation during tensile testing (Fig. 7.46).

CT scan was performed in a tensile specimen belonging to the same group of the failed one. Lack of fusion was detected (Fig. 7.47).

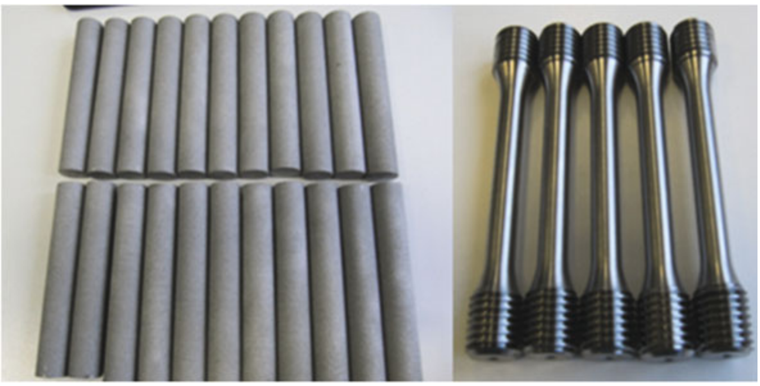


Fig. 7.45 PBF-EB/M bars and tensile test samples after machining by AIDIMME (*Source* Fractal project)

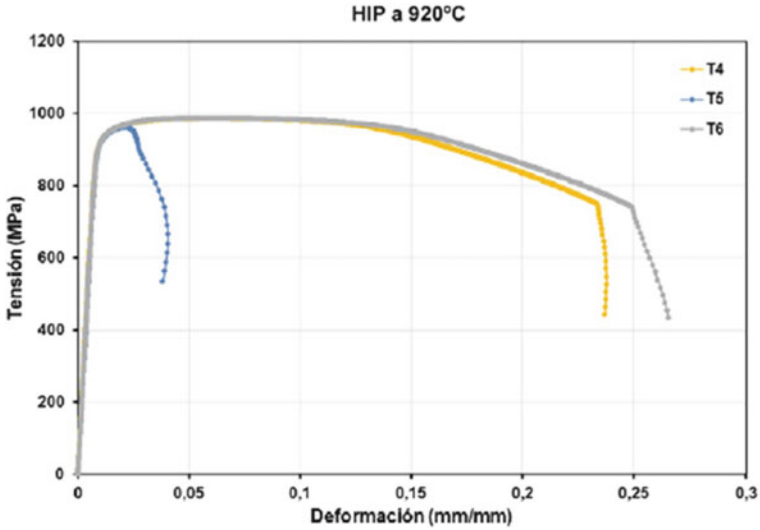


Fig. 7.46 Tensile test results (developed by CEIT) (*Source* Fractal project)

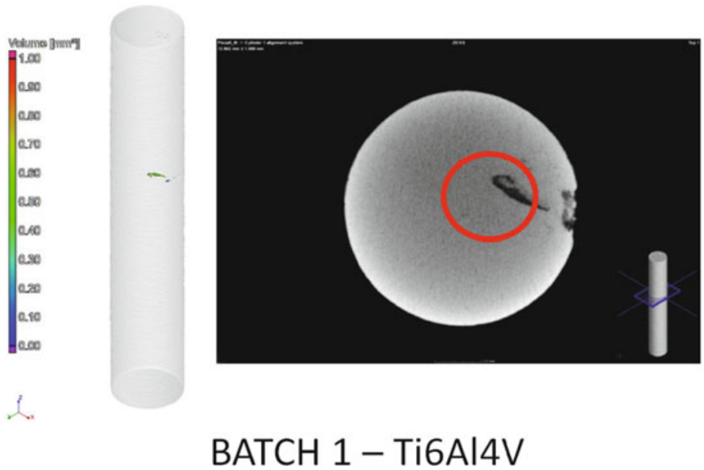


Fig. 7.47 Lack of fusion detection (*Source* Fractal project)

Example 2 Inner channels with unmelted powder (Fig. 7.48).

Example 3 Porosity detection (Fig. 7.49).

Example 4 Detailed evaluation of powder particles.

Differences in porosity, volume, morphology or irregularities can be analized in powder particles through CT-scan (Fig. 7.50).

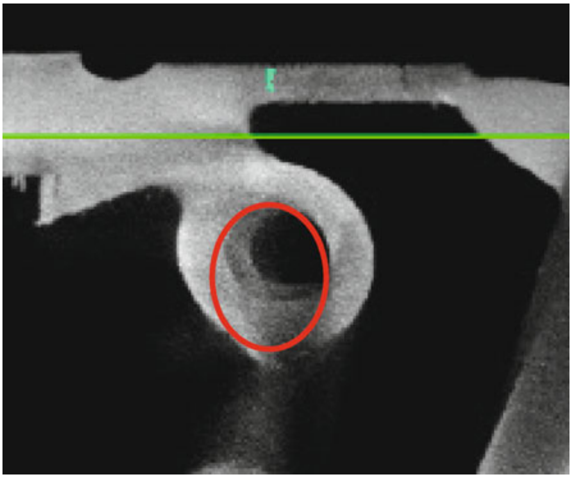


Fig. 7.48 PBF-EB/M cleaning process deficiency (*Source* Fractal project)

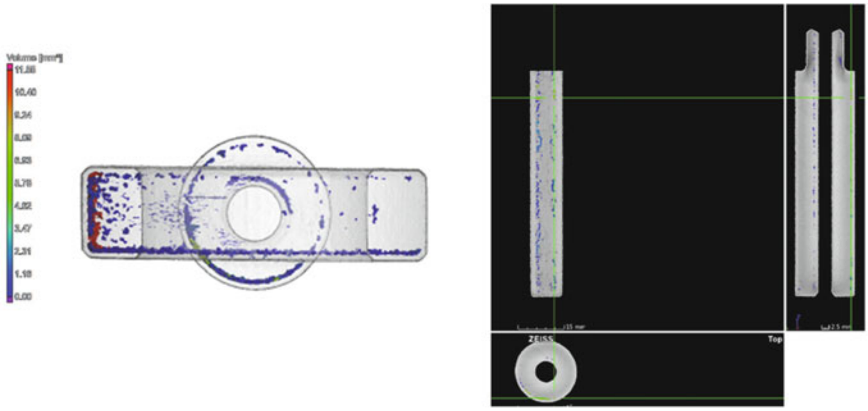


Fig. 7.49 Porosity detection in the borderline between contour and hatch due to wrong adjustment of overlapp parameter (*Source* Fractal project)

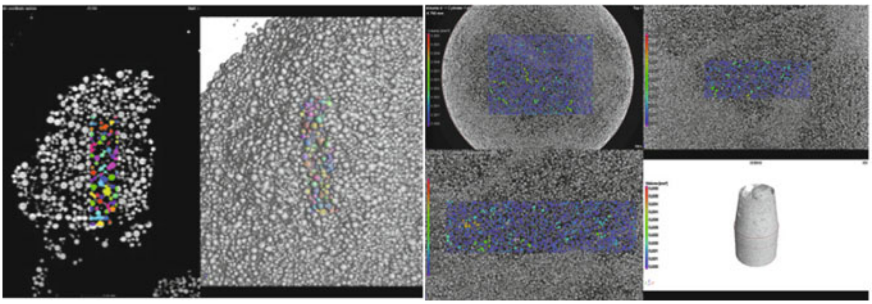


Fig. 7.50 Detailed evaluation of powder particles (*Source* AIDIMME)

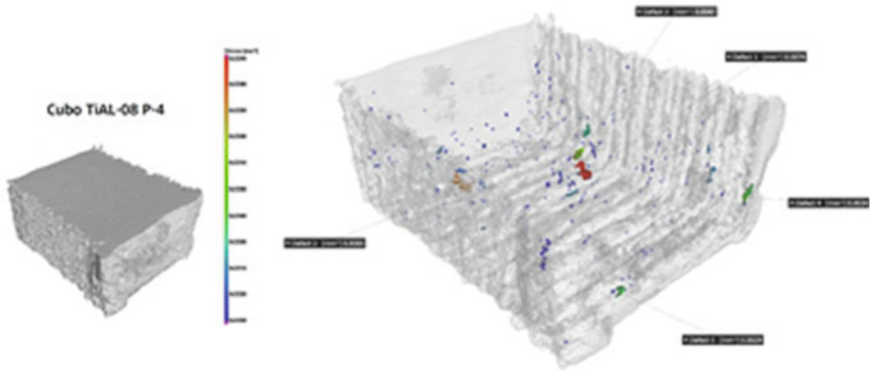


Fig. 7.51 Detailed inspection of PBF-EB/M processed material (*Source* AIDIMME)

Example 5 Porosity inspection, lack of fusion and powder acumulation in PBF-EB/M processed material (Fig. 7.51).

Example 6 Selection of the best process parameters for specific alloys.

The processed material might be evaluated in both XY and Z build directions (Fig. 7.52).

Quality of the processed material can be examined by using ct-scan to observe any difference between different combinations of process parameters (Fig. 7.53).

Example of 3D Scanner for Qualification.

First, the build plate containing all parts including testers should be scanned. Second, parts from plate should be removed and finally, testers and critical parts should be scanned (Fig. 7.54).

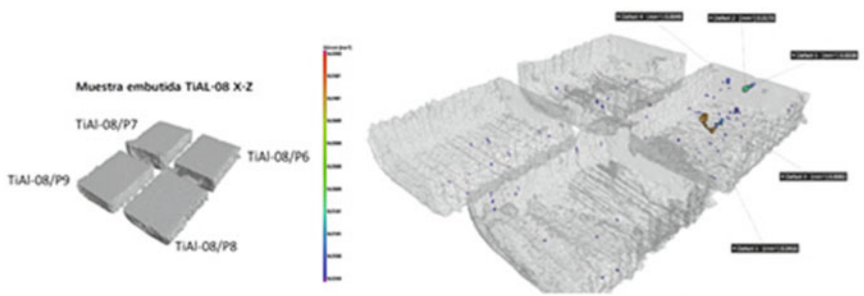


Fig. 7.52 Detailed evaluation in Z build direction (*Source* AIDIMME)

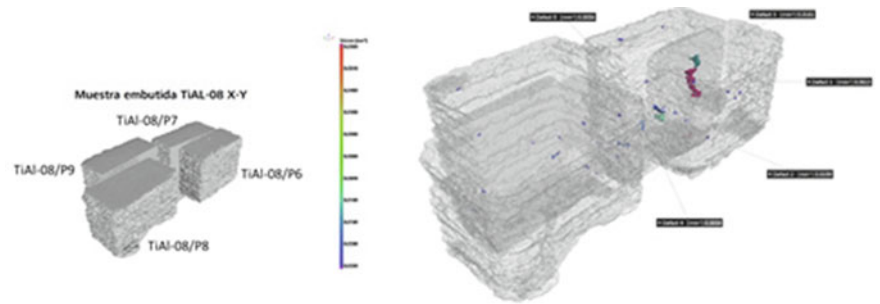


Fig. 7.53 Detailed evaluation in X–Y build direction. Evaluation of different combination of process parameters (*Source* AIDIMME)

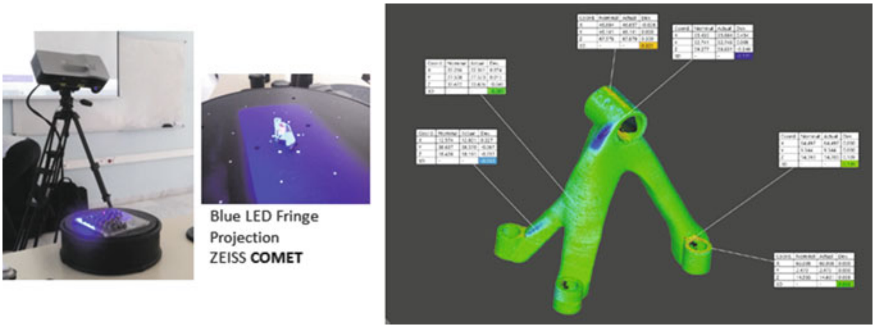


Fig. 7.54 Example of 3D scan for qualification (*Source* Skin project, AIDIMME)

7.3 Development of Materials for PBF-LB/P

7.3.1 Processing Parameters Determination for PBF-LB/P

As in the PBF-EB/M technologies, most part of the PBF-LB/P equipments are partially open so that users can modify the processing parameters in order to improve the results obtained in standard materials or to gather new processing parameters for nonstandard materials.

Therefore, two different approaches can be followed:

– Process parameter adjustment for standard materials: by modifying certain parameters or process features we can improve the surface roughness or the build ratios of PBF-LB/M parts.
– Process parameter determination for nonstandard materials; this approach requires apparently much more efforts since there is not a first processing parameter setup. In this case different parameters must be tested so that sintered powder is assessed afterwards in order to determine the optimal energy to be deposited. The challenge

to be faced within this approach is to find a processing window where material is flawlesly sintered.

Standard parameters adjusted during parameter development/process improvement:

- Line offset (mm): distance between scanning lines. Every layer is made up of consecutive lines that increase the heat acumulation in the processed part. Low line offset values will lead to lack of fusion whereas very close lines will lead to part overheating.
- Laser power (W): determines the energy aported by the laser source, depending on the material nature this value will vary. In addition, CO_2 lasers require periodical recharges thus laser power will vary during the life cycle of the laser.
- Part location and part orientation are detrimental for the part quality obtained. As gathered in the following lines, this input will be curzial in the surface roughness and dimensional accuracy of parts produced by PBF-LB/P.
- Process temperature (°C): as a remainder, PBF-LB/P process work under a preheated environment which is at 12–16 °C below the sintering /melting point of the material. Temperature should be adjusted depending on the material nature.
- Layer thickness (mm): powder bed height.

Processing parameter influence in PBF-LB/P parts are collected from results achieved in SKIN project carried out by AIDIMME. The aim of the project was to improve the surface quality of additive manufacturing parts in order to improve their mechanical performance, both in metal parts processed with PBF-EB/M technology and in polymer parts processed with PBF-LB/P technology.

As a clear result of how parameters affect the part surface finish, a deep study was carried out by AIDIMME within an internal project called SKIN. In this project, different strategies where applied while sintering parts in PBF-LB/P so as to cuantify surface finish improvements in polyamide-12 parts manufactured in a 3D systems SINTERSTATION 2500 Laser sintering equipment. Results are represented in lines below.

- Influence of different part orientation.
- Influence of different line offset values.

Part Orientation

When it comes to part positioning, the way the part is located inside the build envelopment will determine how accurate the part is reproduced. In this sense, a surface which is facing the upper part of the build volume is not reproduced as smooth a surface that is facing down. Measuring in different directions it is demonstrated that critical surfaces which are important must be placed facing down (Fig. 7.55).

In addition, not only this phenomenon affects the surface roughness of laser sintered parts but also the part position in reference to the X–Y-Z axis. Samples allocated in different ways inside the production envelopment were measured.

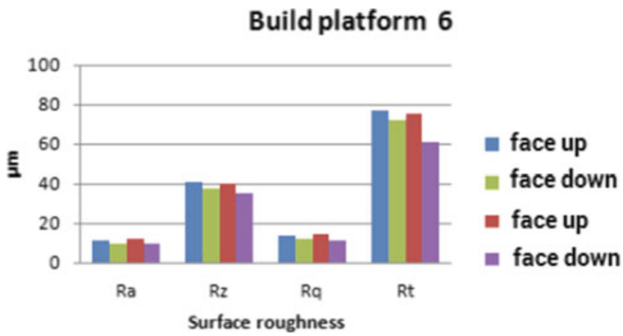


Fig. 7.55 Assessment of surface roughness in PBF-LB/P parts (*Source* Skin project, AIDIMME)

– Parts facing X and Y reference axis came out smoother that samples facing the Z axis (Fig. 7.56).
– On the other hand, when testing gradual angled Z samples, like represented in the figure below. Sample positioned completely parallel to the Z axis obtained the best results (Fig. 7.57).

Line Offset

As previously pointed out, very closed scanning lines could lead to a part overheating producing dramatic results in laser sintered parts, whereas wider line ofset values can lead to weak parts. Within skin project different values were tested obtaining the smoothest surfaces for a line offset of 0.11 mm (Fig. 7.58). However, it was demonstrated that wider values as 0.13 mm can improve the build ratios barely affecting the surface roughness. Therefore, 0.13 mm of line offset was considered a good balance between part quality and build ratio.

As in any process parameter development, the behaviour of each material will be different and therefore will require specific processing parameters. Hence the

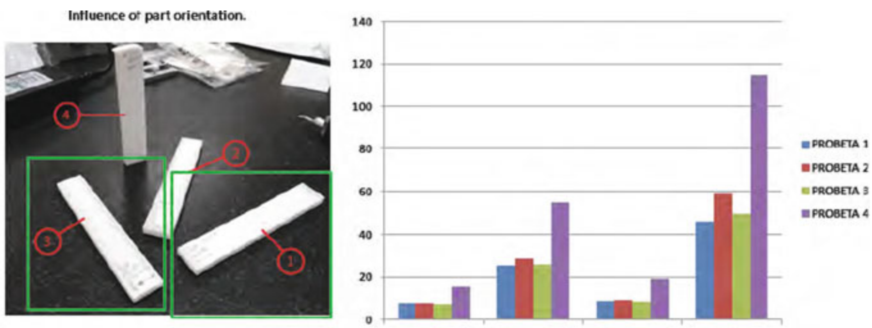


Fig. 7.56 Surface roughness in LS parts positioned in different reference axis (*Source* Skin project, AIDIMME)

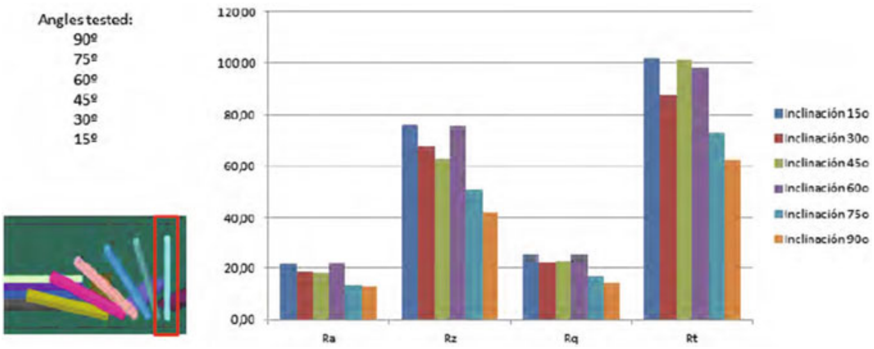


Fig. 7.57 Angled parts respect the Z axis. Surface roughness measurements (*Source* Skin project, AIDIMME)

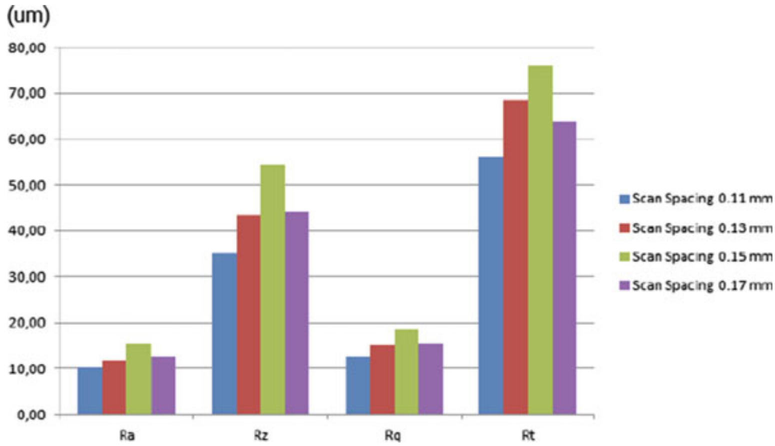


Fig. 7.58 Line offset samples—surface roughness (*Source* Skin project, AIDIMME)

processing window must be gathered. This is an iterative process where different parameters are tested and gradually adjusted in order to improve the material processability.

Values represented in this section correspond to tests manufacted by a sinterstation 2500 equipment from 3D systems.

7.3.2 *Qualification of the PBF-LB/P Production*

One of the key factors in PBF-LB/P technology is temperature stability. Slight variations in the temperature whithin the process will lead to part distortions, curling and

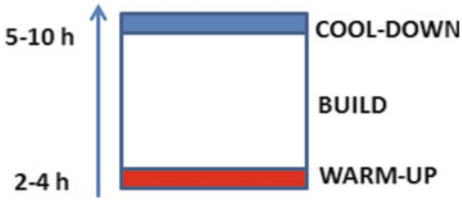


Fig. 7.59 Process timing depending on area (*Source* AIDIMME)

Fig. 7.60 Example of high grade of packaging (*Source* AIDIMME)

other typical issues of additive manufacturing. Figure 7.59 shows process timing in a build cake depending on area.

Other important issue may be taking advantage of a support free technology by means of nesting softwares as Magics. This can help the technician with the parts allocation by improving the build density as much as possible. The more parts fit in the build envelopment the cheaper the unitary costs will be.

- **Example** 1. **Sinterstation DTM 2500**. The smaller the parts are the better the packaging will be. Mean value of 6.044 cc (Fig. 7.60).
- **Example** 2. **Sinterstation DTM 2500**. Qualification of the build production by controlling X-Y scale at different heights and Z scale in the corners Fig. 7.61.
- **Example** 3. Laser power test to detect possible laser failure (Fig. 7.62).

It should be also highlighted the important role of powder handling and mixing in qualification of PBF-LB/P production. This is explained in detail in the following section: Powder blending and recycling for PBF-LB/P.

7.3.3 Powder Blending and Recycling for PBF-LB/P

Powder blending and recycling in PBF-LB/P is highly important due to most part of the production costs come from the feedstock itself. This means that a wrong powder reusability methodology can lead to a higly affected powder batch that does

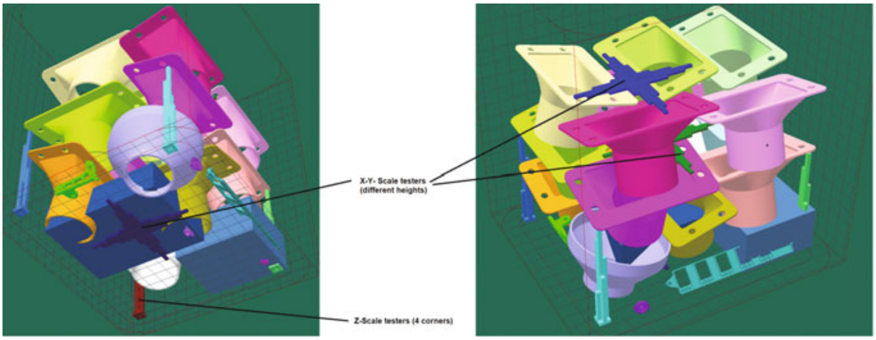


Fig. 7.61 Example of X–Y-Z testers (*Source* AIDIMME)

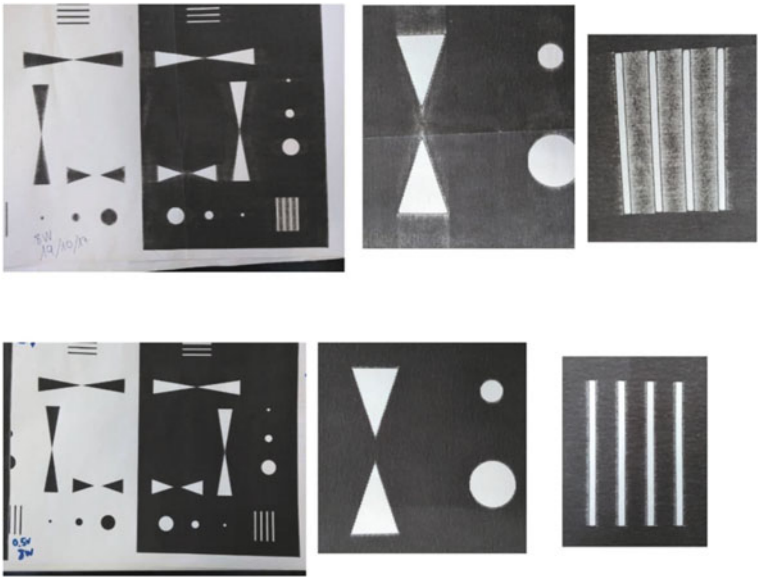


Fig. 7.62 Example of laser failure (*Source* AIDIMME)

not allow us obtaining high quality parts due to the phenomenon known as "orange peel" (Fig. 7.63). Some drawbacks like poor mechanical properties of the final part or difficulties in process parameters are originated by this adverse phenomenon.

LS powders will be deteriorated, thus must be refreshed with new material for further usages. Should the refreshing powder not be enough, sintered parts will show orage peel and poor quality.

It can be found in bibliography some methods like the Melt Flow Rate Test (MFRT) where we can quantify how affected the powder is. This method measures the time while a certain amount of powder is melted through an extruder at a specific

Fig. 7.63 Example of orange peel (*Source* AIDIMME)

temperature. Depending on this value already used feedstock must be refreshed in a controlled manner improving the reusability yields.

Based on the recommendations of machine suppliers, all the un-sintered powder collected from a build must be mixed with fresh powder in a constant ratio either manually or automatically. Based on experience and literature, it can be recommended not to use constant ratios. Powder should be mixed in order to keep the Melt Flow Rate between 24 and 26 g/10 min.

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Chapter 8
Development of FGM and FGAM

Eujin Pei and Israt Kabir

8.1 Functionally Graded Material (FGM)

FGM is a special class of composite material that was first developed in Japan around 1984 for the propulsion system and airframe of space planes. The challenge was to create a thermal barrier that would be capable of withstanding a temperature of 1000 °C over a cross-section of 10 mm. A sharp interface between the matrix and the reinforcement in a traditional composite material would cause cracking in high temperatures. The cracks occur due to the generation of interfacial stress induced by the mismatch of thermal expansion between two different materials. FGM introduces a smooth gradual transition at the interface of two different materials, thereby avoiding sharp interfaces. They are characterised by spatially varying the composition or micro-structures across the volume of a material, contributing to corresponding changes in material properties in line with its functional performance. For example, a metal-ceramic reinforced FGM can withstand high temperature environments by combining the best properties of both materials. The thermal stress at the critical locations can be controlled.

Composites Versus FGM

Traditional composite materials are a homogeneous mixture of two different materials. The final properties of the composites are derived from the properties of the separate materials. However, the two materials experience sharp changes as evident in the coated or laminated composites. Whereas in FGM, the actual properties of different materials can be retained and the change in properties is gradual at the gradient zones or interface, as illustrated in Fig. 8.1.

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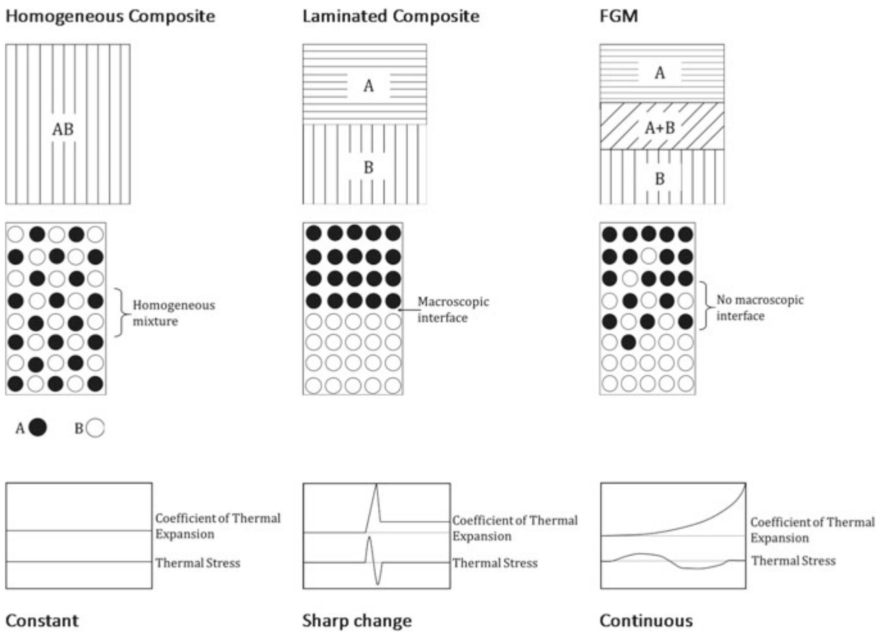

Fig. 8.1 Difference among traditional composites and two component FGM (Reproduced from Loh et al. [2])

8.1.1 Benefits of FGM

The use of FGM is significant as it combines multiple properties in a single part, eliminating sharp interfaces among gradient zones, thus increasing the interfacial strength. This also provides capabilities for part integration and increasing the part lifetime. The use of FGM can also lead to improved material properties and efficiency compared to alloys and metals. The use of FGM parts allows properties such as weight, modulus of elasticity, fracture toughness, wear resistant and hardness of materials within a component to be precisely controlled. As a result, various combinations of incompatible substances can be joined to create new materials for applications. Such materials can also be selectively reinforced in regions that require special properties.

8.1.2 Classifications of FGM

There are generally two categories of FGM, comprising of homogeneous and heterogeneous FGM as presented in Fig. 8.2. Homogeneous FGM are made up of a single material. Heterogeneous FGM are composed of two or more materials. The

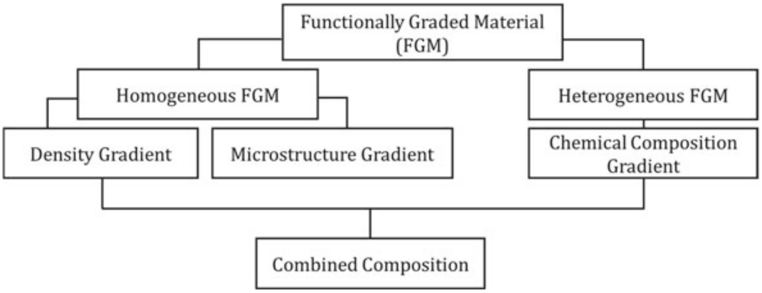

Fig. 8.2 Categories of FGMs (*Source* UBRUN)

components can be either graded with varying chemical compositions, densities or microstructures, or as a combined form. In homogeneous FGM, variable functionality is mainly achieved through the density gradient or by changing the microstructure. Both homogeneous and heterogenous FGM are explained in the following sections.

Homogeneous Composition

Density gradient

In homogeneous FGM, the density gradient is achieved based on the degree of porosity that is spatially distributed across the material. There are two ways of altering the density gradient in the FGM material, which is by changing either the pore size and/or the pore density. The shape and size of the pores can be designed and varied, according to the required properties of the component. Figure 8.3 illustrates both pore size and pore density gradation of a homogeneous FGM material.

The gradation of pore size can be achieved by varying the powder particle sizes during the gradation process or by optimising the processing and sintering parameters. The density of the porosity can be altered by varying the number of porosities distributed throughout the structure as shown in Fig. 8.4. Density variation in a monolithic structure helps to reduce the overall weight and the density of the part. As a result, this may influence the tensile strength and Young's modulus of the material.

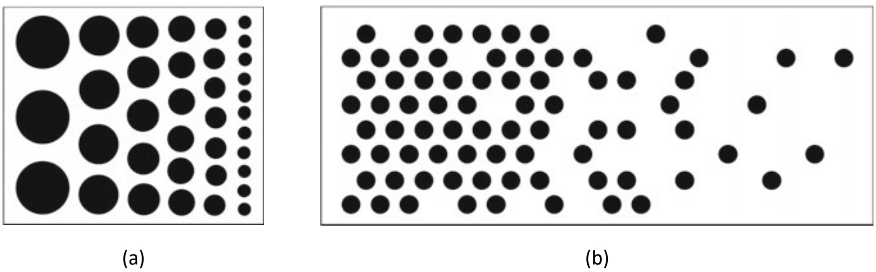

Fig. 8.3 Two types of density gradient, by regulating the **a** pore size and **b** pore density (*Source* UBRUN)

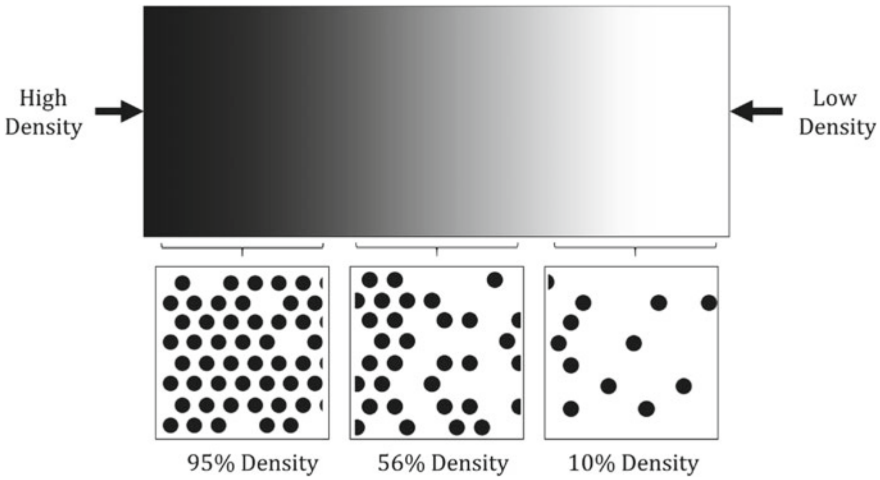

Fig. 8.4 Density variation is achieved by controlling the percentage of porosity distribution (Reprinted from Additive Manufacturing, Volume 23, 2018, [2], Copyright 2021, with permission from Elsevier)

Microstructure gradient

In a microstructure graded FGM, the microstructure is tailored for a gradual change of the material properties. This can be achieved during the solidification process, whereby the surface of the material is quenched. The core of the material cools down slowly, which further produces a different microstructure from those on the surface of the part.

Heterogeneous Composition

In heterogeneous FGM, two or more materials are present. As the composition of multi-materials is varied from one material into the other, it results in different phases with different compositions. The different phases are dependent on the compositional quantity and manufacturing conditions of the reinforcing material. For example, a binary heterogeneous FGM system contains two components A and B. The concentration of A varies along the length from 100 to 0% leading to the formation of different phases in the material. Theoretically, there are three zones with different phases. In the first zone, the concentration of A is more than B. In the second zone, the concentration of B is more than A. Lastly, the mixed zone has a combined composition of A and B in which the gradual transition of microstructure and composition is present.

Combined Composition

Another class of FGM that brings together both homogeneous and heterogeneous categories is known as combined composition. This is where a combination of variable density, chemical composition and microstructure exists within the FGM.

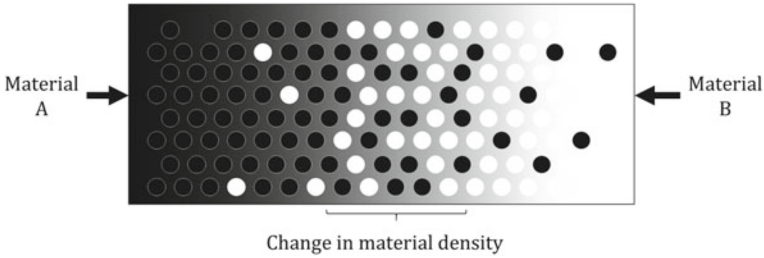

Fig. 8.5 Combined composition heterogenous FGM with two material components (Reprinted from Additive Manufacturing, Volume 23, 2018, [2], Copyright 2021, with permission from Elsevier)

Figure 8.5 shows a heterogeneous FGM with both variable density and chemical compositions, known as combined composition FGM.

8.1.3 Manufacturing Methods for FGM

Different fabrication methods of FGM are available for thin or bulk types of products. Thin-film FGM is used in some applications that require different surface properties as opposed to bulk materials. Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) processes are principal methods used to produce FGM coatings. In some applications, bulk FGM is required where the material is exposed to extreme working environments. The FGM manufacturing techniques are divided into 3 groups: gas, liquid, and solid phase processes. The common fabrication methods in a gaseous phase include PVD and CVD. Liquid phase methods include Centrifugal Casting and Tape Casting. Solid phase methods include the use of Powder Metallurgy. In addition, Additive Manufacturing (AM) techniques can be used for both liquid and solid phases, in which this process is known as Functionally Graded Additive Manufacturing (FGAM). The following sections describe the manufacturing methods for FGM in detail.

Gas-Assisted FGM Production by Physical Vapour Deposition (PVD)

PVD is a vaporisation-based vacuum deposition method in which the solid material is evaporated and deposited as a thin film through means of condensation. PVD is used for high melting point and low vapour pressure materials. High temperature is also required to vaporise the material in which specific techniques include sputtering, evaporation, and plasma-spray. The thickness of the thin film on the surface ranges from nanometers to micrometers. Parts produced by PVD is often used in mechanical, optical, chemical, or electronic applications, especially for automotive, aerospace, biomedical, defence, die and moulding industries.

Gas-Assisted FGM Production by Chemical Vapour Deposition (CVD)

CVD is a process where a gaseous precursor reacts to form a solid coating on a heated substrate. The reactions of by-products are removed from the chamber with unused precursor gases. The process is carried out in hot-wall reactors and cold-wall reactors.

Liquid-Assisted FGM Production by Centrifugal Casting

To produce FGM by centrifugal casting, a molten material containing another reinforcing material is poured into a rotating mould. A centrifugal force is created that helps to draw the molten material towards the mould and create a separation in the suspended solid powder material. The graded distribution of the FGM formed by centrifugal casting method is influenced by the processing parameters such as the density variation between the reinforcing and the molten material, the particle size, particle distribution, viscosity of the molten material and the solidification time.

Liquid-Assisted FGM Production by Tape Casting

Tape casting is achieved by spreading a slurry mixture onto a moving belt and passing the belt under the blade edge to shape the slurry into a tape form of a constant thickness. Thin sheets of ceramic are cast as a flexible tape with a thickness of several μm to mm. The slurry consists of suspended ceramic particles and organic liquid that contains binder and plasticiser materials. Stepped gradients of FGM are produced by stacking those tapes made from different compositions.

Solid-State FGM Production by Powder Metallurgy

The Powder Metallurgy (PM) process is an old manufacturing technique for producing engineering components. The steps involved in the production of FGM using this method include preparation of the powder material, processing of the powder, the forming operation, and sintering or other pressure-assisted hot consolidation processes.

Table 8.1 presents an overview of common FGM manufacturing methods. Different applications may utilise one approach over another. However, when creating extremely complex end-use products that contain lattice structures, none of these manufacturing technologies are suitable. The use of Functionally Graded Additive Manufacturing (FGAM) is one such method to construct complex geometries and being able to achieve combined FGM compositions.

8.2 Functionally Graded Additive Manufacturing (FGAM)

FGAM is a layer-by-layer fabrication process that involves gradationally varying the material organisation within a component to achieve an intended function. FGAM can produce engineered freeform structures with customisable site-specific properties, tailored at small sections or at a strategic location that would be impossible

Table 8.1 Overview of conventional processing methods for FGM (Reprinted from Materials Science and Engineering: A, Volume 362, Issues 1–2, 2003, [1], Copyright 2021, with permission from Elsevier)

Process	Layer thickness[a]	Type of FGM	Versatility in phase content	Versatility in component geometry
PVD	C	Coating	Very good	Moderate
CVD	C	Coating	Very good	Moderate
Centrifugal casting	C	Bulk	Very good	Poor
Tape casting	M	Bulk[b]	Very good	Poor
Powder metallurgy	M, L	Bulk	Very good	Moderate

[a] L: large (>1 mm); M: medium (100–1000 μm); C: continuous
[b]Maximum thickness is limited

using traditional production methods. The advancement of AM technologies makes it possible to strategically control the density and directionality of material deposition within a complex 3D distribution. The amount, volume, shape and location of the reinforcement in the material matrix can be precisely controlled to achieve the desired properties for a specific application. The merits of FGAM stem from the use of Additive Manufacturing (AM) technologies to enable design freedom, for custom-made production, increasing the speed to cost ratio, providing easy accessibility with a single-step manufacturing process, reducing risks and addressing sustainability.

8.2.1 The FGAM Process Chain

A typical FGAM process chain is presented in Fig. 8.6 which presents the five steps involved in the manufacturing workflow of FGAM which are described as follows.

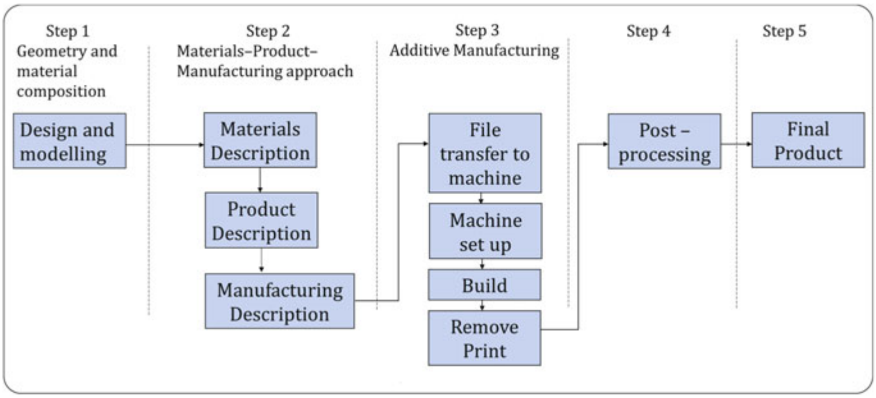

Fig. 8.6 The FGAM process flow from design to manufacturing (Adapted from Muller et al. [3])

1. Geometry and Material Composition: This first step involves the design and modelling process that consists of the development of the product using Computer-Aided-Design (CAD) for manufacturing, simulation, topology or infill optimisation. The mechanical function of the part is defined by describing the fundamental attributes before developing a modelling scheme. The factors considered at this stage include part geometry, material composition, optimisation, gradient vector dimension, geometry or surfaces attributed to the composition, property, material characteristics or other mechanical parameters.

2. Materials-Product-Manufacturing: There are three aspects considered in this step. In the materials description stage, it includes the material selection and microstructure allocation, defining the optimal material properties, the gradient and analysis of the void density. The data that concerns the chemical composition and characteristics of the part is modelled and analysed. Digital simulation is used to represent the materials, so as to formulate a matching epistemology for the material selection, gradient discretisation, volume of support, residual stresses, etc. Next, in the product description stage, the geometry and material composition with mathematical data is used to identify an appropriate manufacturing strategy and process control. Finally, in the manufacturing description stage, the build orientation of the part is determined, and the geometry is sliced. The manufacturing strategy is determined according to a triptych approach of material-product-manufacturing process. The mathematical data from product and material description is used to define the slicing orientation, categorised as either planar or complex slices.

3. Additive Manufacturing: The process consists of file transfer to the machine, the machine set-up, and the build process. While transferring the CAD file to the machine, the machine toolpath is defined and evaluated. Numerical Control (NC) programming is involved in the generation of paths and modification of process parameters using but not limited to G-code programming. The G-code or an appropriate data file is sent to the AM machine for the production sequence to commence.

4. Post-Processing: Post-processing ensures that the quality aspects such as surface characteristics, geometric accuracy, aesthetics and mechanical properties of the printed part meet its operating requirements or build specifications. AM post-processing methods include, but are not limited to tumbling, machining, hand-finishing, micromachining, chemical post-processing, electroplating and laser micromachining.

5. Final Product: After post-processing treatment, the final product is sent for quality assurance and validation. Experimental analysis such as non-destructive testing, stress analysis or microscopic imaging is carried out to validate the final product and its desired properties.

8.2.2 Design and Modelling of FGAM Parts

The design phase for FGAM is a critical and crucial step to ensure that accurate and high-quality parts are achieved. The design software for FGAM requires features that are able to model and simulate multi-materials and the composition for each material. The CAD software should be able to define the graded material in the 3D CAD file and using Computer-Aided-Engineering (CAE) for Finite Element Analysis (FEA) and calculations. Some CAD tools adopt a voxel-based approach to design FGAM models. The material values are assigned across a pixel grid on each geometry slice before converting them as a toolpath for manufacturing. These voxels are made up of different materials. The composition for hybrid materials has multiple elements with a weighted percentage. VoxCAD is an open source voxel-based digital materials simulator. This software can design FGM parts using voxel modelling and integrated with FEA features. It can perform 3D static and dynamic analysis including large deformations, collision detection and non-linear material models such as plastic deformation. It also supports parts with multi-materials, and with variable properties to simulate FGM characteristics.

Most AM software export the data in a mesh-based STL file format that is insufficient to retain the information for FGM parts. Design for FGAM requires file formats that can feature external and internal information, material specifications, mixed and graded materials and substructures, characteristics for materials and porous structures. Some potentially suitable file formats for FGAM include AMF (Additive Manufacturing Format), FAV (Fabricable Voxel) and 3MF (3D Manufacturing Format). AMF is an Extensible Markup Language (XML) file format capable of storing colours, materials, lattices, duplicates, and constellations of the volumes that make up the object. The AMF file format is supported by SolidWorks, Inventor, Rhino and Mesh Mixer CAD software. The file can contain functional representations, 3D texturing or volume texturing and voxel representation. FAV a voxel-based data format proposed by Fuji Xerox in collaboration with Keio University, Japan. Each voxel can be expressed with various attributes values, including colour (RGB, CMYK, etc.) and material information. The file format allows the user to design (CAD), analyse (CAE) and inspect 3D model data using Computed Tomography in an integrated process without having to convert the data. 3MF is another XML-based open format developed by the 3D Consortium that allows AM design applications to send “full-fidelity” 3D models to a mix of other applications, platforms, services and printers.

8.2.3 FGAM Technologies

There are six types of AM technologies used to produce FGAM parts. This includes Material Extrusion (MEX), Vat Photopolymerisation (VPP), Powder Bed Fusion

(PBF), Material Jetting (MJT), Sheet Lamination (SHL) and Directed Energy Deposition (DED).

Material Extrusion (MEX)

This process builds FGM parts layer-by-layer through computer-based controlled extrusion and deposition. This method has the potential to produce parts with locally-controlled properties by changing the deposition density and the deposition orientation, resulting in anisotropy in the properties along the horizontal axis. Li et al. found out that deposition directions in layers and gap sizes between the filaments are the most important parameters to control the mechanical properties. Other ME based methods use the mixing of paste or slurries such as ceramic slurries and metal pastes. In this process, it is important to control the paste mixing sequence and the extrusion parameters to achieve correct gradation in density.

Vat Photopolymerization (VPP)

Vat Photopolymerization (VP) can be used as an FGAM technique. A variant known as Direct Light Processing (DLP) is a mask-image projection method that was developed to overcome the shortcomings of a single-vat VP technique. The system comprises of switchable resin vats and micro-mirror devices. Instead of a laser heat source, it uses a Digital Micromirror Device (DMD) in which the sliced CAD models are converted into a 2D mask image. DLP systems project the mask images layer-by-layer to build a multi-material component systematically through a single build process. It is faster than conventional VP systems as it can form the whole layer simultaneously.

Powder Bed Fusion (PBF)

PBF involves the spreading and sintering of typically 0.1 mm thick of powder material layer-by-layer with a roller between the layers, then selectively fusing or melting either by laser or electron beam. The PBF technique can be classified into several types depending on the heat source and fusion process. Table 8.2 lists the PBF categories and the materials that have been successfully used to manufacture FGAM parts.

PBF-LB/P (SLS) can produce complex components of polymers with spatially varying mechanical properties using suitable means of powder delivery. It can fuse

Table 8.2 Different kinds of PBF technique used for FGAM

PBF techniques	Materials
Selective Laser Sintering (PBF-LB/P-SLS)	Nylon
Direct Metal Laser Sintering (DMLS) Selective Laser Melting (PBF-LB/M-SLM) Selective Mask Sintering (SMS)	Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel
Electron Beam Melting (PBF-EB/M-EBM)	Stainless Steel, Titanium, Aluminium, Cobalt Chrome, Steel, Copper

thin sections from 0.02 mm to 0.06 mm together and create very complex geometries. Chung and Das studied the production of FGAM polymer nanocomposites of Nylon-11 and silica with various volume fractions of 15 nm glass beads (0–30%). On the contrary, PBF-LB/M (SLM), DMLS and PBF-EM/M (EBM) are generally used to process metallic FGAM parts. PBF-LB/M can produce metallic FGAM where metal powders are deposited co-axially with a high-power laser beam. Two or more multiple feeders of powder are used to continuously modify the composition of the deposited metal. In previous studies, PBF-LB/M was used to produce FGM metallic parts and a periodic lattice structure of Al-Si10-Mg composite.

Material Jetting (MJT)

MJT, which is also known as PolyJet trademarked by Stratasys, can achieve the widest range of digital materials with varying physical properties in a single print using the Objet Studio and Polyjet Studio software. FGAM parts produced by MJT can have up to 82 different material properties including shore hardness, transparency, colour, unique properties, biocompatibility, etc. An example is a chair called the Gemini Acoustic Chaise designed by Neri Oxman from MIT. The chaise was designed to study vocal vibrations and the relationships between sounds and human physiology. The inner lining was printed using 44 composite materials with the Polyjet system.

Sheet Lamination (SHL)

SHL including Ultrasonic Consolidation (UC), can be used to produce FGM components. Examples of parts have been produced by joining 3 different metallic foils made up of stainless steel, aluminium, and copper together through ultrasonic welding using a UC machine that mechanically vibrates the welding head (the sonotrode) at 20 kHz. FGAM could be produced by adopting this machining strategy or by using an intermediate glue layer.

Directed Energy Deposition (DED)

DED systems consist of a nozzle mounted on a multi-axis arm, which deposits molten material in either wire or powder form onto a specified surface at an angle. Energy from laser, electron beam or plasma arc is used to create beads, tracks and layers of solid materials upon solidification of the melt pool on the substrate. The metallic powder is located coaxially with the energy source and delivered into the melt pool. Laser Metal Deposition (LMD) is a laser-based DED process which can fabricate metallic parts with a graded composition by adjusting the volume of metallic powders delivered to the melt pool. LMD has been used to produce FGM parts using 304L Stainless Steel and Inconel 625 with a 910 W Yttrium Aluminium Garnet (YAG) laser and hatch angle of 60°. Thermodynamic computational modelling is often used for optimising the process parameters to produce FGAM parts.

Table 8.3 The potential engineering applications of FGAM parts

FGAM parts	Applications
Rocket engine components, heat exchange panels, reflectors, turbine wheels, turbine blades, nose caps, etc	Aerospace sector
Dental implants, Skeletal implants, etc	Biomedical sector
Engine cylinder liners, leaf springs, spark plugs, driveshafts, car body parts, racing car brakes, etc	Automotive sector
Inner wall of nuclear reactors, solar cells, piezo-electric ultrasonic transducers, flywheels, etc	Energy sector
Bullet-proof vests, armoured components, etc	Defence sector
Cutting tools, blades, etc	Other sectors

8.2.4 FGAM Applications

FGAM technologies show huge potential for novel and existing applications. Table 8.3 presents a list of major FGAM applications including aerospace, biomedical, automobiles, and other industries.

8.3 Conclusion

The use of FGM as well as FGAM have a great potential to revolutionise the manufacturing world. Considerable progress has been made since the earliest discovery of FGM. Some of the major challenges in the use of FGAM include having a better understanding of materials, CAD tools and AM technologies. In terms of our knowledge of materials, current applications lack a broad understanding of the "processing-structure–property" relationship of FGAM components, especially for heterogeneous FGAM parts. Therefore, the behaviour of the manufactured part may deviate from the predicted properties. In addition, the availability of suitable materials for FGAM is still limited and variability in material interaction may occur at different operating conditions. Material data such as chemical composition, manufacturing constraints and build parameters are required. Suitable measurement and characterisation techniques to modify the microstructure, material arrangement, compatibility, mixing range, property distribution, etc. need to be established. A "function-behaviour-structure" ontology could be applied to model, calculate and predict the behaviour of a FGAM component. There is also lack of advanced CAD software to describe and translate the material properties and behaviours to design FGAM parts. The limited number of the voxel-based modelling engine and available features can sometimes lead to poor representation and managing of data. There is a need to develop new CAD/CAE software to specify, model and manage the material information for Local Composition Control (LCC). Furthermore, new AM slicing software is required to slice, analyse and prepare parts for FGAM fabrication. Lastly, conventional AM technologies still operate dominantly on isotropic materials, focusing on surface modelling. Most AM processes are also limited to in-situ mixing. Industrial-grade materials cannot be reliably blended or graded to form novel materials with the desired composition ratio. FGAM components are still prone to internal and external defects. Therefore, FGAM processes require a very high level of precise deposition with a reliable and predictable outcome. These are the current challenges facing the use of FGAM in which over time with more research and knowledge being generated, newer applications will emerge.

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Conclusion

A Guide to Additive Manufacturing book presents an overview of the current research status and expertise of the INEX-ADAM project consortium partners in the field of AM. Special attention was paid to the specific fields of AM. The book presents classification of the most commonly used AM technologies and their general workflow, from obtaining CAD data to the final product.

Standardisation generally has a great impact on the quality of products and services, so it is very important for emerging AM technologies and their applications. Therefore, a special chapter was dedicated to the standardisation in AM.

Although AM technologies have much less restrictions in production of complex parts compared to the traditional technologies, in order to be able to use all AM potentials and benefits, in design phase some specific rules have to be followed (DfAM). Therefore, the central book chapters contain basic rules of DfAM for most common used AM technologies and economic impact of DfAM approach, as well as simulation application in AM products optimisation (e.g. topology optimisation).

In a special chapter, the book presents three specific fields of AM application: toolmaking, medical and transportation application with specific demands on AM parts as well as benefits of AM application in those fields.

Further development of AM technologies and opening of new application areas greatly depends on development of new materials for AM, as well as on their properties. Therefore, a special chapter of the book is dedicated to AM materials development and their characterisation, as well as to the Functionally Graded Additive Manufacturing with Functionally Graded Materials.

Appendix A—List of AM Standards

List of Published AM Standards

1. ISO 17296–2:2015—Additive manufacturing—General principles—Part 2: Overview of process categories and feedstock

D. Godec et al. (eds.), *A Guide to Additive Manufacturing*, Springer Tracts in Additive Manufacturing, https://doi.org/10.1007/978-3-031-05863-9

2. ISO 17296–3:2014—Additive manufacturing—General principles—Part 3: Main characteristics and corresponding test methods
3. ISO 17296–4:2014—Additive manufacturing—General principles—Part 4: Overview of data processing
4. ISO 27547–1:2010—Plastics—Preparation of test specimens of thermoplastic materials using mouldless technologies—Part 1: General principles, and laser sintering of test specimens
5. ISO/ASTM 52,900:2015—Additive manufacturing—General principles—Terminology
6. ISO/ASTM 52,901:2017—Additive manufacturing—General principles—Requirements for purchased AM parts
7. ISO/ASTM 52,902:2019—Additive manufacturing—Test artifacts—Geometric capability assessment of additive manufacturing systems
8. ISO/ASTM 52,904:2019—Additive manufacturing—Process characteristics and performance—Practice for metal powder bed fusion process to meet critical applications
9. ISO/ASTM 52,907:2019—Additive manufacturing—Feedstock materials—Methods to characterize metal powders
10. ISO/ASTM 52,910:2018—Additive manufacturing—Design—Requirements, guidelines and recommendations
11. ISO/ASTM 52,911–1:2019—Additive manufacturing—Design—Part 1: Laser-based powder bed fusion of metals
12. ISO/ASTM 52,911–2:2019—Additive manufacturing—Design—Part 2: Laser-based powder bed fusion of polymers
13. ISO/ASTM 52,915:2020—Specification for additive manufacturing file format (AMF) Version 1.2
14. ISO/ASTM 52,921:2013—Standard terminology for additive manufacturing—Coordinate systems and test methodologies.

List of AM Standards Under Development

1. ISO/ASTM DIS 52900—Additive manufacturing—General principles—Fundamentals and vocabulary
2. ISO/ASTM FDIS 52902—Additive manufacturing—Test artefacts—Geometric capability assessment of additive manufacturing systems
3. ISO/ASTM FDIS 52903–1—Additive manufacturing—Standard specification for material extrusion based additive manufacturing of plastic materials—Part 1: Feedstock materials
4. ISO/ASTM DIS 52903–2—Additive manufacturing—Standard specification for material extrusion based additive manufacturing of plastic materials—Part 2: Process – Equipment
5. ISO/ASTM DTR 52,905—Additive manufacturing—General principles—Non-destructive testing of additive manufactured products

6. ISO/ASTM CD TR 52,906—Additive manufacturing—Non-destructive testing and evaluation—Standard guideline for intentionally seeding flaws in additively manufactured (AM) parts
7. ISO/ASTM AWI 52,908—Additive manufacturing—Post-processing methods—Standard specification for quality assurance and post processing of powder bed fusion metallic parts
8. ISO/ASTM AWI 52,909—Additive manufacturing—Finished part properties—Orientation and location dependence of mechanical properties for metal powder bed fusion
9. ISO/ASTM DTR 52,912—Additive manufacturing—Design—Functionally graded additive manufacturing
10. ISO/ASTM WD 52,916—Additive manufacturing—Data formats—Standard specification for optimized medical image data
11. ISO/ASTM WD 52,917—Additive manufacturing—Round Robin Testing—Guidance for conducting Round Robin studies
12. ISO/ASTM CD TR 52,918—Additive manufacturing—Data formats—File format support, ecosystem and evolutions
13. ISO/ASTM WD 52,919–1—Additive manufacturing—Test method of sand mold for metalcasting—Part 1: Mechanical properties
14. ISO/ASTM WD 52,919–2—Additive manufacturing—Test method of sand mold for metalcasting—Part 2: Physical properties
15. ISO/ASTM WD 52,920–2—Additive manufacturing—Qualification principles—Part 2: Requirements for industrial additive manufacturing sites
16. ISO/ASTM DIS 52921—Additive manufacturing—General principles—Standard practice for part positioning, coordinates and orientation
17. ISO/ASTM DIS 52924—Additive manufacturing—Qualification principles—Classification of part properties for additive manufacturing of polymer parts
18. ISO/ASTM DIS 52925—Additive manufacturing processes—Laser sintering of polymer parts/laser-based powder bed fusion of polymer parts—Qualification of materials
19. ISO/ASTM WD 52,926–1—Additive manufacturing—Qualification principles—Part 1: Qualification of machine operators for metallic parts production
20. ISO/ASTM WD 52,926–2—Additive manufacturing—Qualification principles—Part 2: Qualification of machine operators for metallic parts production for PBF-LB
21. ISO/ASTM WD 52,926–3—Additive manufacturing—Qualification principles—Part 3: Qualification of machine operators for metallic parts production for PBF-EB
22. ISO/ASTM WD 52,926–4—Additive manufacturing—Qualification principles—Part 4: Qualification of machine operators for metallic parts production for DED-LB
23. ISO/ASTM WD 52,926–5—Additive manufacturing—Qualification principles—Part 5: Qualification of machine operators for metallic parts production for DED-Ar

24. ISO/ASTM AWI 52,931—Additive manufacturing—Environmental health and safety—Standard guideline for use of metallic materials
25. ISO/ASTM WD 52,932—Additive manufacturing—Environmental health and safety—Standard test method for determination of particle emission rates from desktop 3D printers using material extrusion
26. ISO/ASTM WD 52,933—Additive manufacturing—Environment, health and safety—Consideration for the reduction of hazardous substances emitted during the operation of the non-industrial ME type 3D printer in workplaces, and corresponding test method
27. ISO/ASTM WD 52,936–1—Additive manufacturing—Qualification principles—Laser-based powder bed fusion of polymers – Part 1: General principles, preparation of test specimens
28. ISO/ASTM DIS 52941—Additive manufacturing—System performance and reliability—Standard test method for acceptance of powder-bed fusion machines for metallic materials for aerospace application
29. ISO/ASTM DIS 52942—Additive manufacturing—Qualification principles—Qualifying machine operators of metal powder bed fusion machines and equipment used in aerospace applications
30. ISO/ASTM CD 52,950—Additive manufacturing—General principles—Overview of data processing.