Strategy for knowledge transfer in AM as a hybrid process chain towards a transition from prototyping to commercialisation

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Abstract
Additive Manufacturing (AM) has gained considerable footprint as one of the key components in making the 4th industrial revolution a reality. Unlike traditional subtractive manufacturing processes which account for ~ 95% waste of material, AM provides almost unchallenged and sustainable manufacturing capabilities to drastically improve manufacturing efficiency due to its nature of adding material as opposed to removing it. Thereby, reducing life-cycle material mass and energy consumed. The ability to produce functional 3D parts with customized and complex geometries directly from CAD model data is particularly attractive. While metal AM processes such as laser powder bed fusion (L-PBF) are already producing customized metal parts in applications such as dental implants, the full benefits of the technology have not been fully realized. This necessitates a global drive to learn best practices in AM towards new avenues for impact in teaching and learning, and in accelerated lab-to-market transition. The key to this is understanding inputs and outputs of fundamental AM process parameters. This knowledge will help designers and potential end-users of the technology to quickly identify parameters which are most influential to structural integrity of parts produced. Considering that very little research has been performed on knowledge transfer among AM researchers, business and higher education, this paper is aimed at capacity building in AM technology by helping inexperienced users in higher education understand the technology better. Thereby, contributing to the inclusive global drive for an accelerated transition from prototyping to commercialization. The method used involves a standard systematic triangulation of the literature to categorise and describe fundamental process parameters which influence structural integrity of parts produced by the L-PBF. The findings of this work yield new knowledge in three domains. Firstly, the influential input parameters of L-PBF are identified as powder-specific, laser-specific and machine specific parameters. Secondly, various post-processing solutions which are often used address the drawbacks associated with the technology are mapped out as thermodynamic, mechanical, and chemical post-processing treatments. Thirdly, the L-PBF is conceptualized into a framework which can help reshape the role of designers by identifying AM as a hybrid process and knowing what to look for when looking to make functional parts using technology. In this way, the paper contributes a novel skillset and attitude required to convert digital capabilities such as AM into valuable tools and methods.

Keywords
Additive manufacturing; Laser powder bed fusion; post-processing solutions; hybrid manufacturing.

Introduction
Broadly, additive manufacturing (AM) is defined as a canopy term of manufacturing technologies used to join material layer by layer to make three-dimensional (3D) products from computer aided design (CAD) models (Gibson et al., 2015; Sreenivasan et al., 2010; Wohlers & Gornet, 2014). The technologies were previously known as Rapid Prototyping or Rapid Manufacturing technologies (Atzeni & Salmi, 2012; D. L. D. Bourell et al., 2009; Doubrovski et al., 2011), because they were historically limited to production of prototypes and casting inserts. However, a more recent definition for AM according to the ASTM F2792 is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM International, 2013). In this way, the AM techniques remove traditional manufacturing constraints by enabling a range of benefits without the need for part-specific tooling to make customized parts with complex geometries in one piece. Thereby, providing almost unchallenged and sustainable manufacturing capabilities to drastically improve manufacturing efficiency.

The interest to optimise AM technologies has been growing exponentially over the past couple of decades. In particular, there is a growing interest in the potential of metal additive manufacturing (MAM) technologies such as laser powder bed fusion (L-PBF) (Costa et al., 2006; Rombouts et al., 2006). Hence, the focus of this work is on L-PBF. A typical L-PBF process starts with pre-processing at the control centre where a 3D CAD model of a part to be printed is well-defined, then sliced by a computer program into layers (20-100 μm thick), with a 2D image generated for each layer. The digital information is used to drive the movement of the laser inside the machine chamber with controlled atmosphere of inert gas, where the actual building takes place. In the chamber, the building process is cyclical and consists of three steps which are repeated until the end of the construction process. Firstly, a re-coater (roller) applies an even coating of metal powder in line with the prescribed layer thickness. Secondly, the powder bed is exposed to a laser beam. The absorption of the laser radiation causes the metal powder to heat up above the melting temperature of the metal, forming a melt pool. This causes the fusion of the exposed areas of the current layer. Thirdly, the molten layer is rapidly cooled in the range of 12000 – 40000 °C/s (Chastand et al., 2016; Gokuldoss et al., 2017; Liu & Shin, 2019), depending on the amount of energy supplied. The process is then repeated with a new layer of powder coated on the previous layer until a desired part is built from thousands of individual layers in succession.

Although the AM technology has been around for over 30 years with functional parts already applied in industries such as the aerospace, automotive and biomedical, the full commercialisation has not been realized. The widespread implementation of AM technology is hindered by process inherent attributes that result in the as-built parts not meeting industry requirements. In this work, the as-built condition refers to parts as they come out of the AM machine. It is at this point where the consideration of AM as a hybrid process for making functional parts becomes critical due to the incorporation of conventional subtractive manufacturing technologies to obtain a part which can be regarded as qualified for application. The key towards meeting specific industry requirements is understanding the influential input parameters, attributes of the as-built condition and suitable post-processing solutions. In contributing towards a higher technology readiness level for metal AM, this paper is a knowledge transfer contribution which addresses three categories of AM as a hybrid process (inputs, outputs and the integrity engineering). Thereby, contributing to the inclusive global drive for capacity building in higher education towards an accelerated transition from prototyping to commercialisation of AM technology. Understanding the AM technology in line with the strategies presented in this paper will effectively help smaller companies and end-users develop their own innovative designs and products towards a successful participation in digital futures.

Approach

The first part of the strategy was to identify key focus areas of the AM process chain. The schematic diagram showing this approach is shown in Figure 1. The approach follows a standard systematic literature inclusion/exclusion criterion which according to (Tranfield et al., 2003) ensures quality and scientific reproducibility.

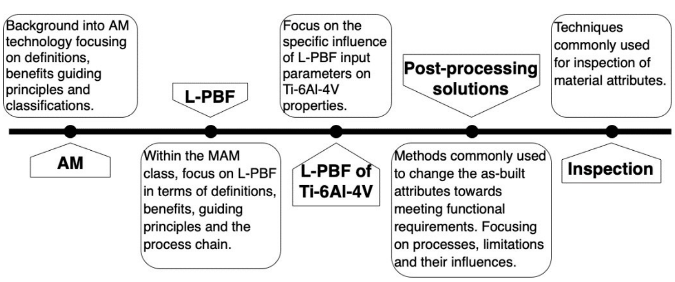

Figure 1. Schematic diagram showing strategy used to identify key aspects of AM for this work.

Since AM is broad and includes different techniques and materials, it was important to identify key areas in terms of definitions, classifications, foundations, and guiding principles. The second part of the strategy was to show the criterion in selecting the relevant literature. This meant identifying a combination of relevant keywords which were used as search terms. Table 1 shows these search terms and the reasoning behind each search term combination.

Table 1. List of chosen literature search terms and the respective reasons behind the choices.

Database search terms	Reasoning
Additive manufacturing (AM)	AM is a canopy term referring to a variety of techniques. It was important as a general broad understanding of the technology, particularly in comparison to subtractive manufacturing technologies.
Metal additive manufacturing (MAM)	AM is well-known for processing polymers. Hence, it was important to highlight focus on MAM.
Laser powder-bed fusion (L-PBF)	The focus of this project was on LPBF as one of many MAM techniques.
L-PBF/SLM and Ti-6Al-4V	L-PBF is used for processing many materials. Hence, this search term was important to specifically combine the technology with Ti-6Al-4V.
Ti-6Al-4V attributes (microstructure, porosity, residual stresses, and surface roughness) AND LPBF/SLM	These were the core search terms of this project. Combining each of the four attributes with the technology helped narrow and focus the research project into specific functional attributes.

The specific material chosen to explain the L-PBF is Ti-6Al-4V. The triangulation shown in Table 1 was intended to identify correlations in terms of the main structural aspects of the material, such as microstructure, porosity residual stress and surface roughness. This was done to understand what is known and established from the core contributions, highlight the extent to which consensus is shared, and provide a detailed audit trail back to the core contributions to justify the links between the correlations. A summary of the literature timeline and the types of literature contributions used in this work is shown in Figure 2 (a) and (b) respectively. The number of articles per year as shown in Figure 2 (a) is an indication of the database search output and not necessarily a reflection of the number of articles selected for this work. A significant number of these articles were excluded in this work following a successive screening by title, abstract and full article reading.

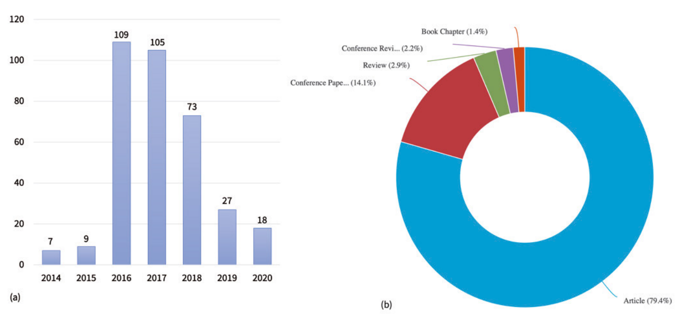

Figure 2. Literature timeline of articles which were screened for this study.

As shown in Figure 2 (b), majority of articles which contribute to the body of knowledge on AM are journal articles (roughly 79%). This can be seen as confidence boost in the quality of work presented in this paper. This is based on the high requirements for journal article publication.

Findings

Influential L-PBF input parameters

The influential L-PBF input parameters are classified as either powder specific (characterized in terms of particle-size and shape and powder flowability), laser parameters (characterized in terms of spot size, power, exposure strategy and scanning speed) and machine-specific parameters (characterized in terms of building path, layer thickness and system atmosphere) as shown in Figure 3. Although this is the case, it is important for the end-users of the technology to know that these parameters do not independently influence variables of L-PBF. This means there is no one possible set of processing parameters for a given material property. It is rather a collective influence of these parameters which needs to be considered. Generally, only about 10 % of L-PBF input parameters have about 90% impact (Schmidt et al., 2017).

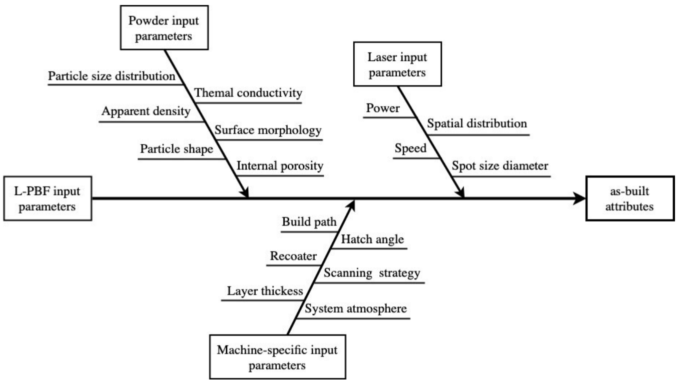

Figure 3. A schematic diagram showing a summary of L-PBF input parameters.

Different combinations of input parameters shown in Figure 3 have been widely explored to optimize the attributes of as-built parts. For instance, (Thijs et al., 2013) suggested optimum process parameter of 200W, 1400 mm/s, with scan spacing 105 µm for aluminium alloys. (Brandl et al., 2012) used 250W, 500 mm/s, 150 µm scan spacing, with 50 µm layer thickness to achieve defect-free parts. Table 2 gives an indication of how the optimized parameters for Ti-6Al-4V compare to the commonly used L-PBF input parameters.

Table 2. Summary of common process parameters compared to optimized process parameters for Ti-6Al-4V (Kasperovich et al., 2016; Kumar et al., 2018; Majumdar et al., 2019; Vilaro et al., 2011; Xu et al., 2015; Zhao et al., 2016).

Input parameter	Common usage range	Optimized
Laser power	80 – 280 W	~200 W
Laser scan speed	200 – 1200 mm/s	~500 mm/s
Layer thickness	20 – 50 µm	~30 µm
Particle size range	15 – 45 µm	~37 µm

With optimized process parameters, better L-PBF outputs can be expected such as global part density in the range of 99.0 – 99.9 % (Kasperovich et al., 2016; Kasperovich & Hausmann, 2015; Xu et al., 2015; Zhao et al., 2016). Additional process parameters shown to be effective include the preheating of the building platform to minimize residual stresses.

Output parameters of L-PBF

The L-PBF outputs refer to the characteristic aspects of a specific material in the as-built condition. The consensus of more than 90% of the selected literature studies reported that the L-PBF as-built Ti-6Al-4V inherently consists of martensitic microstructure, high porosity, high residual stresses and high surface roughness as shown schematically in Figure 4, and that these are not suitable for most industrial applications.

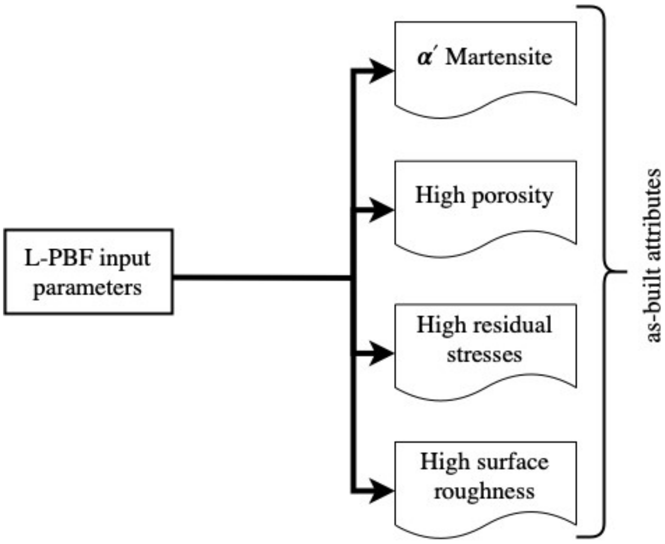

Figure 4. Schematic diagram showing typical L-PBF as-built attributes of Ti-6Al-4V.

The key when conceptualizing the L-PBF outputs is to understand the influential features of these attributes and how they affect material properties, which in turn determines whether the specific industry requirements are achieved or not.

Integrity engineering

Post-processing is inevitable for LPBF as-built Ti-6Al-4V parts because the minimum post-processing required to obtain the as-built part involves mandatory processes such as powder recover, stress relief heat-treatment, part removal from the build plate and the removal of support structures. Beyond the mandatory post-processing, the requirements for additional post-pro-

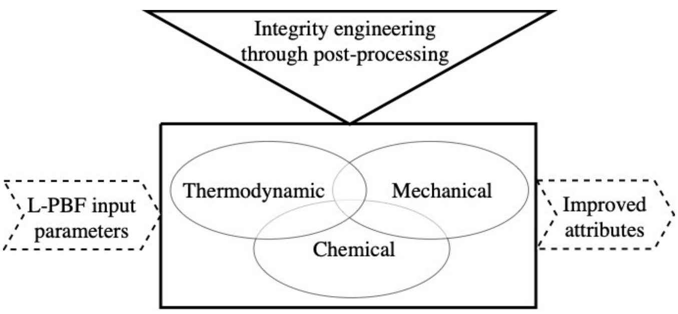

Figure 5. Schematic diagram showing where the integrity engineering fits within a typical AM process chain.

cessing solutions are material and industry specific. These can include a combination of thermodynamic, mechanical, and chemical treatments as shown schematically in Figure 5.

Thermodynamic processes are those that involve significant heat, such as heat-treatment strategies and Hot Isostatic Pressing (HIPing). Mechanical and chemical processes are surface treatments intended to improve surface finish and related properties. These categories are linked to each other through integrity engineering to emphasize that no single one is enough to achieve all material specific requirements for industry application. The choice and succession of application is often limited by availability and costs. The indication of how these solutions are used to address issues related to the four as-built attributes follows in the discussion section.

Discussion

Influential L-PBF input parameters

There is no consensus in terms of which parameters influence specific L-PBF as-built attributes. As such, the general recommendation is that a thorough optimization of L-PBF is the key to obtaining favourable as-built products. Such favourable products are dependent on specific industry requirements. This means designers would typically need to clearly define their design requirements and choose AM where it provides the most competitive advantage. Hence, understanding a proper balance of the input parameters shown in Figure 3 would need to be considered for each design requirement.

The paper brings awareness to designers to have some level of understanding of the impact of raw materials on their design requirements. In the current work, this means understanding for instance, the origin of influential parameters and be able to control such parameters to best fit the demands of their design requirements. For instance, it is important to understand that powder characteristics are a direct result of the technique used to produce that powder. Although there are several powder production techniques, the common ones include gas atomization (GA), rotary atomization (RA), plasma atomization (PA), water atomization (WA) and plasma rotating electrode process (PREP) (Anderson et al., 1991; DebRoy et al., 2018; Sames et al., 2016; Seki et al., 1990). All these powder production methods are capable of producing powder particle sizes in the range 10–60 μm (DebRoy et al., 2018), which is the size typically used in L-PBF. However, the quality of such particles is determined by characteristics such chemical composition, particle size distribution, shape, surface morphology, humidity, flowability, apparent density (packing density), melting temperature, thermal conductivity, and amount of internal porosity. Although the impact of each of these characteristics can be dissected further, ultimately, all powder characteristics determine the energy absorption characteristics of the powder-bed, porosity in parts and the surface morphology of final part. Generally, optimum properties are achieved as a result of good powder processability, which is in turn achieved by smooth particle surface morphology and uniform particle size distribution (DebRoy et al., 2018; Yadroitsev & Smurov, 2011). The main trade-off in the selection of powder size is cost vs surface finish. Smaller powder particles may cost more as a feedstock (than a larger size range) due to the cost of producing such particles.

The most influential of the laser-based inputs are scanning velocity and power input as they play the critical role in the degree of melting achieved, which can either be no melting, partial melting or complete melting (Hanzl et al., 2015; Mahamood et al., 2013; Zaeh & Ott, 2011). Understanding this offers designers an opportunity to select appropriate laser parameters to achieve optimum material properties. For instance, based on the study by (Shi et al., 2016), high velocity means low melt-pool temperature, while low velocity means the laser spends longer time at a specific spot, which means higher melt-pool temperature achieved. This trend was also shown by (Li & Gu, 2014), who observed a decrease in temperature of the melt-pool from ≈1500 to ≈1050 °C and a thermal gradient decrease from a maximum of ≈15 to ≈13.5 °C/μm, given an increase in scanning velocity from 100 to 400 mm/s during their study of parametric analysis of thermal behaviour during SLM processing of Al6061. (Li & Gu, 2014) also studied the influence of laser power on the melt-pool and reported that increasing laser power causes an increase in the size of the melt pool and the maximum temperature. The authors reported this after seeing an increase in the melt pool from 64.3 x 55.8 x 33.7 to 209.2 x 140.4 x 81.2 μm and an increase in maximum temperature from ≈60 to ≈1800 °C as well as temperature gradient from ≈10 to ≈22 °C / μm given an increase in power from 150 to 300 W (Li & Gu, 2014).

Machine-specific input parameters are perhaps the most influential on material properties of L-PBF parts (Seifi et al., 2016). Since there are so many L-PBF machines, the extent to which these characteristics influence material properties of L-PBF parts is machine-specific. The key is choosing the correct combination and understanding their influence on specific materials and the costs involved. For instance, different machines have specific patented scanning strategies associated with several advantages such as reduction of temperature gradient in the scan plane by distributing the process heat, which results in reduced residual stresses (Sames et al., 2016). Additionally, some scanning strategies have the advantage of having no major stress build up in one direction and so the anisotropy in fabricated components is reduced (Shipley et al., 2018).

Output parameters of L-PBF

The L-PBF outputs are often considered important if they play a significant role in determining the structural integrity of parts. For instance, two influential features of the martensitic microstructure are the acicular the α' laths (typically 300–500 nm thick) and the columnar prior-β grains (typically wide and long with the mid-length average width of about 103±32 μm) (Agius et al., 2018; Kumar & Ramamurty, 2019; Simonelli et al., 2014). Generally, the tensile properties associated with this type of microstructure are high ultimate tensile strength (UTS > 1000 MPa), high yield strength (YS > 900 MPa) and a low elongation at fracture ($\varepsilon < 8$ %). In terms of the influence, the acicular α' structure is responsible for retarding the movement of dislocations and cracks, thereby influencing strength associated with this microstructure. On the other hand, the prior-β grains are responsible for the anisotropic behaviour (in both tensile strength and elongation at fracture) usually associated with this type of microstructure.

Regarding porosity, the two types of pores common in L-PBF as-built Ti-6Al-4V are lack-of-fusion pores (typically 100-150 μm long and gas-entrapped pore (typically 10-100 μm) (Agius et al., 2018; D. Bourell et al., 2017). The global porosity in these parts typically ranges between 0.1–0.5 vol% (Agius et al., 2018). Considering that the requirement for global porosity in parts to qualify for application is less than 0.05 vol%, it is evident that porosity is higher in the as-built condition. Hence, the need for post-processing solutions.

Generally, residual stresses are classified according to the scale at which they occur, which can either be microscopic or macroscopic (Kandil et al., 2001). The microscopic residual stresses are usually more localized with minimal effect on mechanical properties. On the other hand, the macroscopic residual stresses typically vary over a very large distances (across the dimensions of the part) and as such, are typically associated with detrimental effects on material properties. The macroscopic residual stresses are inevitable in L-PBF processing due to high thermal gradients inherent to the process. The measure of how detrimental the residual stresses are is often depended on whether the stresses which occur in parts are either compressive or tensile residual stresses. Compressive residual stresses are generally beneficial, while tensile residual stresses are detrimental. The stresses referred to in this paper are the tensile residual stresses, as these are inevitable due to the temperature gradient mechanism (TGM) inherent to the L-PBF process. The residual stresses observed in the as-built parts are typically reported in the range 100 – 500 MPa (Vayssette et al., 2018). These stresses are higher than the maximum requirements in industries such as the aerospace for instance, which specifies a maximum of 100 MPa residual stresses for parts to qualify for application.

Surface roughness is commonly defined by mathematical parameters such as arithmetic average roughness (Ra), ten-point height roughness (Rz) and maximum height of the profile (Rt) (Gadelmawla et al., 2002). The Ra, calculated as the average value of several measurements carried out over a constant length, is the most universally accepted roughness parameter for general quality control. The Ra values of L-PBF as-built Ti-6Al-4V usually fall between 5–40 μm (Kasperovich & Hausmann, 2015; Palanivel et al., 2016; Townsend et al., 2016; Vaithilingam, Prina, et al., 2016), and this is too rough for most industrial applications. The detrimental effect of high surface roughness is an increased influence on fatigue crack initiation. Even though there is no consensus about the parameters which influence surface roughness the most, the poor surface quality of L-PBF parts is predominantly linked to three factors as, open pores and other defects on the surface, partially melted powder adhered onto the surface and the staircase effect.

Integrity engineering

Since the as-built microstructure does not always meet the industry requirements, the problem-solver of the martensitic microstructure is post-processing through annealing heat-treatments. These heat-treatments are usually carried out for two reasons; to decompose the α' martensitic microstructure into a dual-phase $\alpha + \beta$ matrix and to change the size and morphology of the prior-β grains. The common types of heat-treatments explored for this reason are sub-transus (≤ 980 °C), super-transus (≥ 980 °C) and duplex anneal heat-treatments. The latter which involves two annealing temperature stages combined with specific holding times followed by two stage cooling methods. An important consideration is that the heat-treatments carried out in AM are not typical. Therefore, depending on the type of heat-treatment, holding time and method of cooling, a variety of microstructures can be achieved.

If porosity is below the minimum specification, there is no detrimental effect on mechanical properties. This is because the smaller number of pores present in the part (microscopic) the denser a part is, which in turn means better quasi-static properties. However, if porosity is above the minimum specifications, the potential problem-solver is hot isostatic pressing (HIPing). Compared to the range of 0.1–0.5 vol% global porosity typically seen in the as-built conditions, a typical HIPing procedure can reduce porosity in parts produced by L-PBF to the range of 0.01–0.05 vol%, which is less than the minimum allowable global porosity of 0.05 vol%. A HIPing procedure is often specified along with functional requirements, but the procedure is alternatively available in standards such as the ASTM F2924-12A. The process has a combination effect whereby the pressure used enables the closure of internal pores and cracks to increase material density while the inherent heat-treatment effect influences microstructure refinement. Subsequently, both quasi-static and dynamic mechanical properties are improved.

Despite the efforts to reduce the residual stresses by input parameters such as base-plate pre-heating and re-scanning strategies, the residual stresses seen in the as-built parts still fall in the range of 100–500 MPa. Residual stresses in this range are a problem because they are still higher than the maximum allowable stresses of 100 MPa for most parts' application. Since residual stresses are a result of thermal gradients, the most effective way to reduce them is through high temperature stress-relief heat-treatments. In L-PBF parts, this is preferably carried out as a mandatory process before parts are removed from the baseplate to avoid the possibility of warping (Yang et al., 2017). These heat-treatments are specific to the material used and typically carried out at temperatures much lower than the recrystallization temperature so that the microstructure is not affected, but high enough to enable the desired atomic mobility. For instance, an effective reduction in residual stresses in Ti-6Al-4V produced by L-PBF is typically achieved after heat-treatments ranging between 480–650°C for 1–4 hours, followed by either furnace or air cooling.

The improvement of surface conditions of parts produced by L-PBF is crucial for most industry applications, particularly for parts designed for load-bearing applications because the crack initiation at the surface is minimized. Several surface treatment techniques in the literature have proven to be effective in reducing surface roughness (Vaithilingam, Goodridge, et al., 2016) thereby, improving the mechanical properties, in particular, improving dynamic properties. For instance, the reduction of surface roughness in L-PBF Ti-6Al-4V parts is typically achieved by mechanical and/or chemical polishing post-processing treatments. The operating principles and parameters of both treatments (mechanical and chemical) are widely known to the research and manufacturing communities and involve well-established standards and each with advantages and disadvantages towards achieving desired surface finish. Overall, mechanical treatments such as machining work best on flat surfaces. For complex, high-quality near-net parts, the polishing and chemical milling treatments become the ideal post-processing solutions to achieve desired surface finishes and geometrical tolerances.

Understanding AM as a hybrid manufacturing process

The process using AM to produce functional parts which qualify for industrial application needs to be considered as a hybrid manufacturing process because the AM parts in the as-built condition fail to meet most industrial applications. Hence, post-processing solutions are deemed essential to link the as-built parts with industry specific functional requirements. This is achieved by integrity engineering through the post-processing solutions discussed in this paper. An overview of a typical L-PBF hybrid process chain is shown schematically in Figure 6 to show the process chain of how to get to an AM part which can be considered as qualified for application. In summary, the process starts with input parameters which include the actual building process to obtain the as-built parts. The as-built parts are then post-processed to improve material properties. This is followed by inspection and validation to check whether functional requirements are met or not. If met, the parts qualify for application and if not met, the process repeats from post-processing or with new parts printed from scratch.

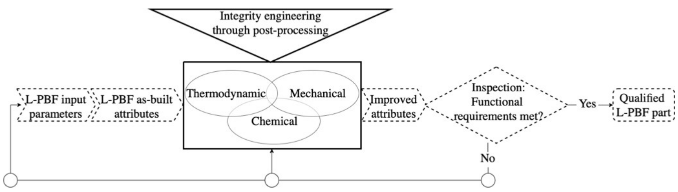

Figure 6. Schematic illustration of a typical L-PBF as a hybrid process chain to qualify parts.

Since there is a significant range of post-processing solutions available, some important considerations are as follows. The important parameters to consider when conducting thermodynamic processes include the type of heat-treatment, temperature, holding time, cooling method and pressure. The important parameters to consider when carrying out mechanical processes include operating speed, contact pressure and lubrication. The important parameters to consider when conducting chemical processes include the type of electrolyte concentration, applied voltage, temperature, and time of treatment. Authors in the field of AM have described and reported improved quality of L-PBF parts because of such post-processing approaches. The attempts have been successful in meeting specific functional material properties such as porosity (Fousová et al., 2017), tensile properties (Ter Haar & Becker, 2018), fatigue life (Chastand et al., 2016; Edwards & Ramulu, 2014; Kasperovich & Hausmann, 2015), surface finish (Kumbhar & Mulay, 2018; Strano et al., 2013; Townsend et al., 2016; Vaithilingam, Goodridge, et al., 2016) and geometrical accuracy (Umaras & Tsuzuki, 2017).

The importance of post-manufacture inspection included as part of Figure 6 is that it ensures the final, finished part meets all the required specifications. A variety of inspection methods exist and are often categorized as either destructive or non-destructive tests (NDT). Destructive methods are those which involve parts being destroyed to obtain material information and include standardized techniques such as tensile, compression, shear, metallography, hardness, fatigue, and fracture toughness tests. Since these tests are destructive, they are not performed directly on the finished parts. Instead, on representative test samples which are built and post-processed in the same conditions as the final part. Therefore, these types of tests are often regarded as precursors to the NDT as quality control techniques and statistical evaluations of product batches (Slotwinskic & Moylan, 2015). On the other hand, the NDTs are often used as inspection methods to detect and evaluate flaws (irregularities or discontinuities) in traditional manufacturing. While NDT techniques are well-developed and standardized for inspection of parts produced by traditional manufacturing processes, their inspection capabilities, and acceptance criteria for AM parts has not been fully established (Taylor et al., 2016). Nonetheless, some of the NDT methods have been investigated and shown to be applicable for inspection of AM parts. Although some of these methods have been widely investigated for inspection of metal AM parts in recent years, one of the major limitations of their use has to do with complex geometries typically produced by AM (Sharratt, 2015). Such geometries pose a challenge when it comes to the NDT techniques such as ultrasonic, eddy current, and radiographic test methods for instance. This is because accessibility to surfaces is not necessarily guaranteed for complex parts. Nonetheless, besides its limitations relating to detectability, sensitivity, accessibility and ease of use, x-ray computed tomography (XCT) remains the promising technology for examining parts of complex geometry (Sharratt, 2015). The key benefit of XCT is its ability to evaluate multiple criteria at once and to image the interior of samples or parts.

Conclusions

To give more insight and confidence in AM technology, quality assurance and life span of parts must be carefully investigated to understand the technology. This involves integration of three factors: technology, skills, and industry requirements. Currently, such understanding is not widely available and most of the time the focus on these factors is usually separated as opposed to being integrated. The work presented in this paper contributes to such understanding. Therefore, three conclusions can be drawn from the findings of this work. Firstly, it is important to consider the L-PBF as-built attributes as a collective that determines structural integrity of parts produced. Secondly, the paper summarises a body of knowledge through a technical review of the L-PBF processing of Ti-6Al-4V and highlights a definitive need for post-processing solutions to address the as-built issues predominantly seen in these parts. Thirdly, the paper proposes a strategy for understanding AM as a hybrid process instead of the common practice of using the technology as a prototyping procedure which ends with non-functional parts in most industries. The strategies presented in this paper are intended as knowledge transfer in higher education and aid the new end-users of the technology to quickly identify influential parameters of the various stages of AM as a hybrid process. Thereby, making it easy to know what to look for when designing for AM.

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