Chapter 8

Applications of the Selective Laser Melting Technology in the Industrial and Medical Fields

Pacurar Razvan and Pacurar Ancuta

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/63038

Abstract

The existence of an MCP Realizer II SLM 250 equipment at the National Centre of Innovative Manufacturing from the Technical University of Cluj-Napoca (TUC-N) facilitated the starting of different research activities in this field at TUC-N with the aim of improving the Selective Laser Melting (SLM) process capability for a better transfer of the technological gained knowledge to different partners from the industrial and medical fields. Reaching this goal has been also facilitated by the fact that in the period 2010–2013 at the Technical University of Cluj-Napoca, within a postdoctoral project financed by European Commission (E.U.), it was possible to activate with the program entitled "Research regarding the manufacturing of metallic parts by Selective Laser Melting (SLM) technology." Part of the results obtained in this postdoctoral program are presented within this chapter of the book, being addressed not only to the engineers, PhD students, researchers, medical doctors, but also to anyone who might be interested about this Additive Manufacturing (AM) method and its possible applications in the industrial and medical fields.

Keywords: selective laser melting, SLM, additive manufacturing, tool steel, H13, customized medical implants, titanium, TiAl6V4, finite element analysis, FEA

1. Introduction

Nowadays, the Selective Laser Melting (SLM) technology is widely used in different domains of the industry, such as aerospace, automotive, consumer goods and medical field. This additive manufacturing technology method offers an important series of advantages as compared to the conventional manufacturing methods that consists in the capability of realizing different parts with high complexity of the shape, the reduced manufacturing time, etc. By using the SLM method, it is possible to manufacture finite parts without necessarily using other supplementary manufacturing processes. The mechanical properties of the realized parts are acceptable, being dependent on the composition and the size of the metallic powder grains, and also on the internal structure of the parts, process parameters, and the manufacturing strategy used. These factors also have an important influence on the surface roughness and the accuracy of the manufactured parts.

The working principle of the SLM process is easy to understood, as could be observed in **Figure 1**. There are several steps that have to be fulfilled. Before starting the process, an inert gas (nitrogen or argon) will be introduced in the SLM machine chamber through a circulating system as presented in **Figure 1**, until an inert atmosphere will be obtained inside the working chamber (the maximum level of oxygen admitted inside is 0.1%). Furthermore, the inert gas will be circulated through the system during the entire process until the end with a level of 0.1% of oxygen maintained constant.

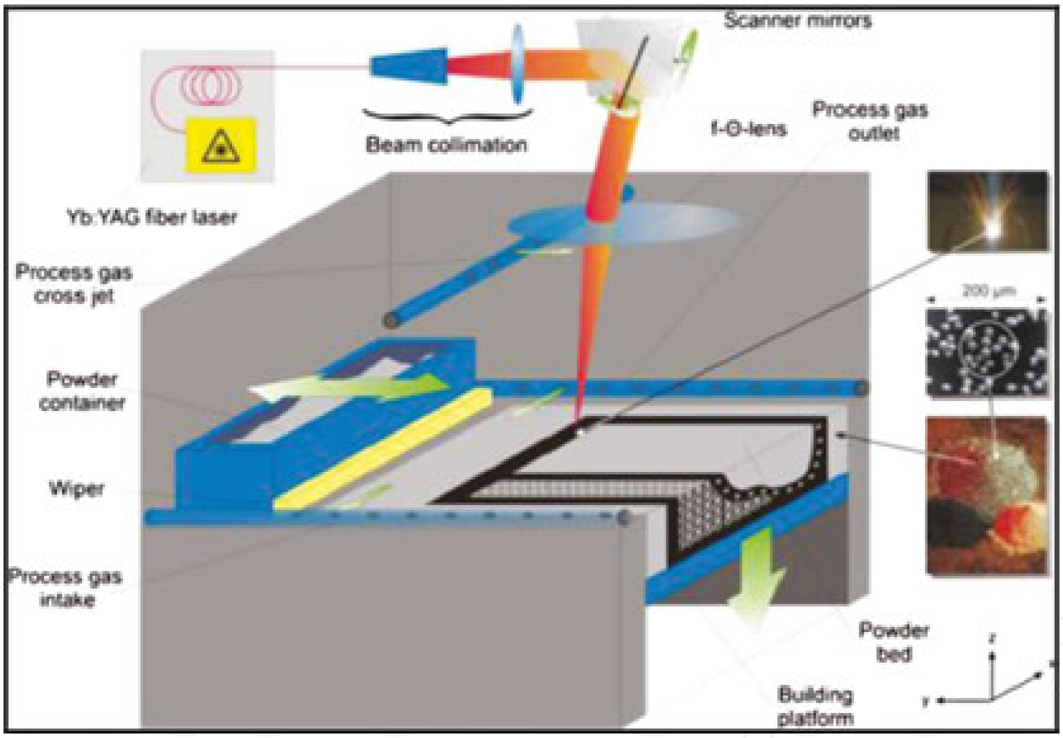


Figure 1. Working principle of the SLM process [1].

The process continues with the deposition of the raw material from the powder container over the building platform by using a wiper that moves along the Y-axis direction. The thickness of the deposited material is around 20–100 μm for the first few layers. The process is repeated until the powder covers the entire building platform uniformly. Then the layer thickness will be set to a constant value of 30–50 μm and the process continues with the scanning of the first layer according to the first slice of the model, and then this will continue with the scanning of the next slice and so on until the part will be finished on the machine.

http://dx.doi.org/10.5772/63038

The building platform is moved along the Z-axis after the scanning process of every layer. Finally, when the maximum height of the building packet is reached, the building platform is moved to the start position and the manufactured packet is removed from the platform after sucking the non-melted metallic powder and after eliminating the metallic supports that were generated within the control software of the SLM system. The metallic supports have a wired structure and are needed in the manufacturing process in order to maintain the built part onto the manufacturing platform.

The SLM technology looks quite simple in theory, but the process control is not so simple from the experimental point of view. Experts' opinions regarding the technological parameters that have a significant influence onto the accuracy and the mechanical properties of a manufactured part made by SLM are quite different [1]. There are researchers who state that these characteristics are directly influenced by the laser system. So, the laser power or the laser beam diameter is important when speaking about the accuracy or porosity of a manufactured part [2, 3]. There are other researchers that state that the optical system in close connection to the scanning strategy is the most important when speaking about the accuracy or porosity of the manufactured part using the SLM equipment. The possibility of cooling-down the optics or optic's design is one of the most important issues in this case [4, 5]. Other researchers state that the scanning speed, the layer thickness or the building temperature have a direct influence over the SLM process and the accuracy or porosity of the manufactured parts as well [6–9]. There are also a series of researchers which consider that the properties of the raw material (particle size, particle distribution, etc.) are important within the SLM process, especially in the case when the resulted porosity of the material has to be precisely controlled [10–11]. Other researchers state that innovative technologies should be used in combination with the classical manufacturing technologies in the so called "hybrid technologies" [12–15]. This means, for example, that the parts have to be manufactured by using the SLM technology and finishing of the part can be done on the same equipment by using conventional manufacturing methods, such as milling. In this way, the accuracy of the manufactured part and the surface roughness will be improved significantly. Looking on all these various researches reported by the authors, it is very difficult to state who is right and who is not right regarding the best control of the SLM process.

The existence of an MCP Realizer II SLM 250 equipment (see **Figure 2**) at the National Centre of Innovative Manufacturing from the Technical University of Cluj-Napoca (TUC-N) facilitated the start of different research activities in this field at TUC-N with the aim of improving the Selective Laser Melting (SLM) process capability for a better transfer of the technological gained knowledge to different partners from the industrial and medical fields. Reaching this goal has been also facilitated by the fact that in the period 2010–2013 at the Technical University of Cluj-Napoca, within a postdoctoral project financed by European Commission (E.U.), it was possible to activate with the program entitled "Research regarding the manufacturing of metallic parts by Selective Laser Melting (SLM) technology."

Figure 2. MCP Realizer II SLM 250 system from the Technical University of Cluj-Napoca.

Part of the results obtained in this postdoctoral program, in cooperation with the SLM Solutions GmbH Company from Luebeck, Germany (best practice examples) are presented in this chapter of the book.

2. Injection moulding tools made from H13 material using the selective laser melting technology (industrial case study)

One of the most important applications of the Selective Laser Melting (SLM) technology is the manufacturing of tools for the injection moulding process. Besides the advantages of the SLM process that consists in the fact that it is rapid, does not depend on the shape of the tool and it has reasonable costs as compared to the classical manufacturing technologies, there are some disadvantages as well. One of the major disadvantages of the SLM process is the accuracy, which is below the accuracy provided by some well-known classical technologies, such as grinding. The SLM technology looks quite simple in theory, but the process control is not so simple from the experimental point of view. The research started within the Technical University of Cluj-Napoca, in cooperation with Plastor SA Company from Oradea (Romania) and SLM Solutions GmbH Company from Luebeck (Germany) has proved the complexity of the SLM technology in the manufacturing of the injection moulding tools process. There are many important aspects that have to be taken into account, as mentioned above, when speaking about the accuracy of the manufactured injection moulding tools, in close-connection with the accuracy of the SLM process.

2.1. Finite element analysis used to estimate the shrinkage of the SLM tools

The case study to be analyzed refers to the injection moulding tool components (punch and die) for a lid button of a grass-cutting machine manufactured by Plastor SA Company from Oradea (Romania) (see **Figure 3**).

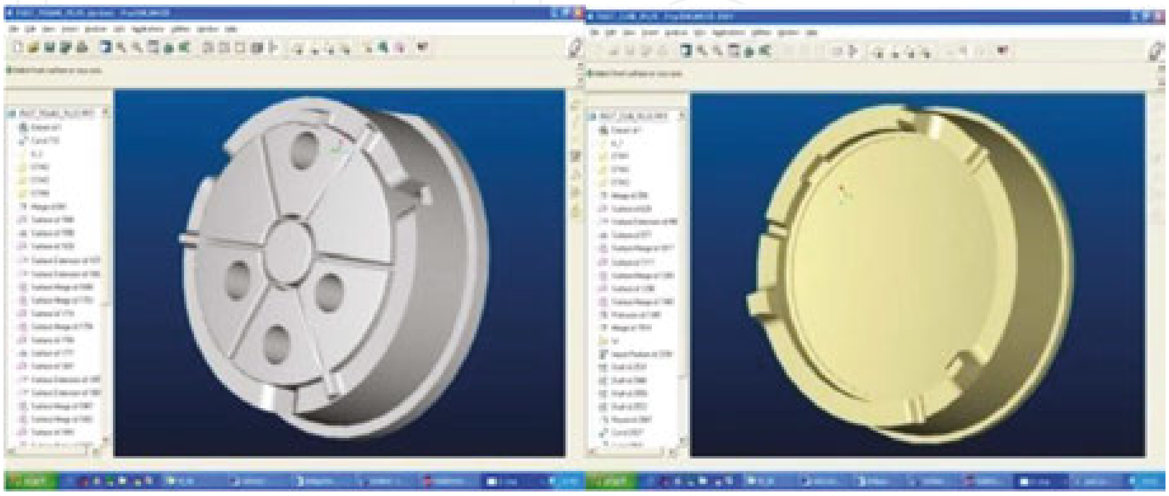


Figure 3. Injection moulding tools for a lid button (ProEngineer design).

The 3D CAD models were imported afterward into the Ansys FEA program and the mesh was generated as illustrated in **Figure 4**. A mesh with a total number of 31.930 nodes and 18.618 elements for the punch and 28.276 nodes and 15.118 elements for the die, respectively, were generated within the FEA program.

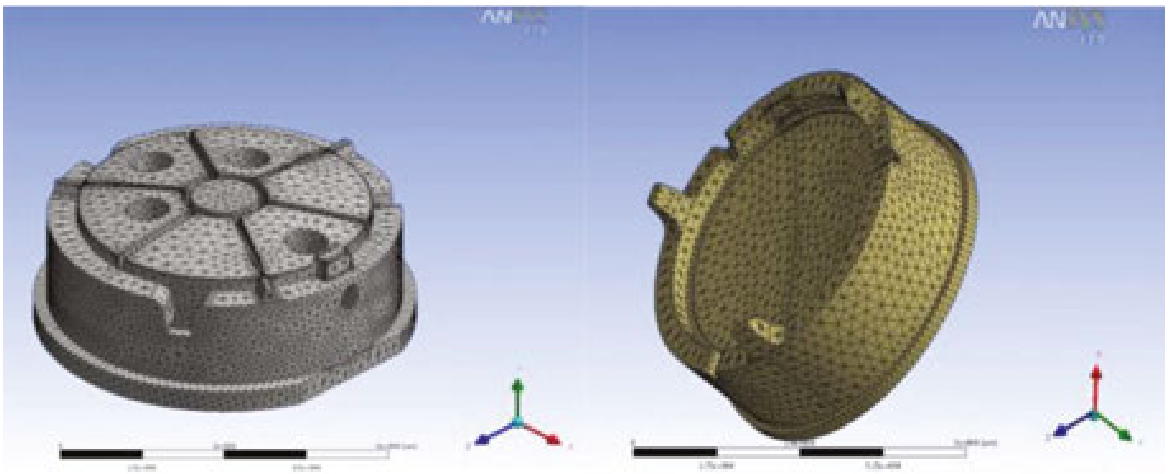


Figure 4. The mesh generated for the injection moulding tools—punch and die (Ansys 13).

Another important aspect consists in the introduction of thermal and mechanical characteristics of the raw material, as it was specified by the producer of the type of metallic powder that is commercially available for such applications: H13 Tool Steel material (see **Table 1**) [16–17].

The injection moulding tools were manufactured using the SLM 250 HL equipment from SLM Solutions GmbH Company in Luebeck, Germany from this type of material, having the same characteristics as the ones that were introduced within the finite element analysis (H13 Tool Steel material).

The next step of the finite element analysis consisted in the introduction of technological parameters within the Ansys program. The laser power, scanning speed and powder bed temperature were introduced as a subroutine into the analysis within the ANSYS APDL Heat Transfer Module.

Twenty finite element analyses were done using varied values of the technological parameters specified in **Table 2**, in order to find the combination of parameters that leads to an optimum closing of the active elements of moulds (see **Figure 5** and **Table 3**).

Property	Value
Density	7.80 (g/cm^3)
Rockwell C hardness	54 HRC
Tensile strength	1730 MPa
Elongation	10.0%
Specific heat at 20°C	460 (J/kg K)
Thermal conductivity	28.6 (W/mK)
Melting point	1020°C
Poisson coefficient	0.3
Elastic modulus	200 GPa

Table 1. H13 Tool Steel material properties.

Technological parameter	Varied value					
Laser power [W]	175	180	185	190	195	200
Scanning speed [mm/s]	250	300	350	400	450	500
Powder bed temperature [°C]	80	104	128	152	176	200

Table 2. Technological parameters introduced in analysis using the APDL Heat transfer module.

Besides these technological parameters that were varied within the finite element analysis, there were also other important parameters that were specified, but were maintained constant during the analyses, such as the layer thickness (30 μm) and the hatching distance (20 μm). As it is possible to observe from the analysis, the value of technological parameters that leads to a minimum shrinkage in the case of punch and die made by SLM are different. If the temperature of the powder bed has the same value in both cases (176°C), the laser power and the scanning speed should be different, such as at the end the punch and die would fit by the closing point of view.

Item	Laser power [W]	Scanning speed [mm/s]	Powder bed temperature [°C]	Shrinkage Δx [μm]	Shrinkage Δy [μm]
Punch	175	300	176	70.162	66.439
Die	200	400	176	71.496	73.231

Table 3. Results of the finite element analyses.

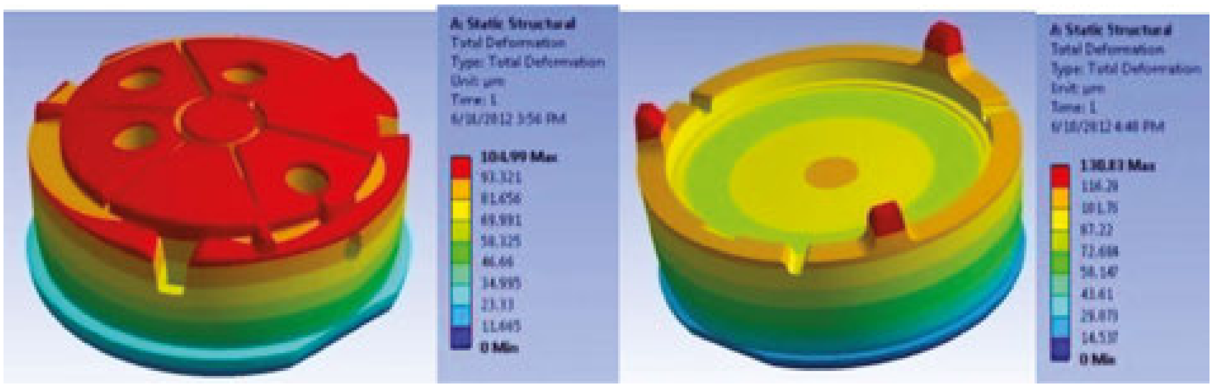


Figure 5. The resulted shrinkage of the punch and die.

One may conclude that in the case of SLM technology it is very difficult to find a set of technological parameters that would be unique and universally valid in all cases of moulds manufactured by SLM from H13 Tool Steel material. The technological parameters to be used within the SLM process have to be different, according to the type and the shape of the metallic tools to be manufactured. The laser power and the energy density being applied on the scanned surface are obviously different if the injection moulding tools have thin walls or these tools are solid and massive in the entire structure of the material.

2.2. Injection moulding tools made by SLM equipment and measurements

Besides setting up the technological parameters, there is another important aspect regarding the accuracy issue, such as the support generating stage that is actually a pre-processing stage needed in the SLM process, in order to sustain the manufactured part onto the building platform of the machine.

The metallic supports have a wired structure and are needed because of the high stresses that occur during the welding process, having the tendency of severely deforming the manufactured models during manufacturing process, especially if welded connection is not good on the building platform starting with the first layers of the manufactured parts while manufacturing. The metallic supports were generated, for the punch and die, using the Magics 15 software, as one may observe in **Figure 6**. The metallic supports are removed within the post-processing stage.

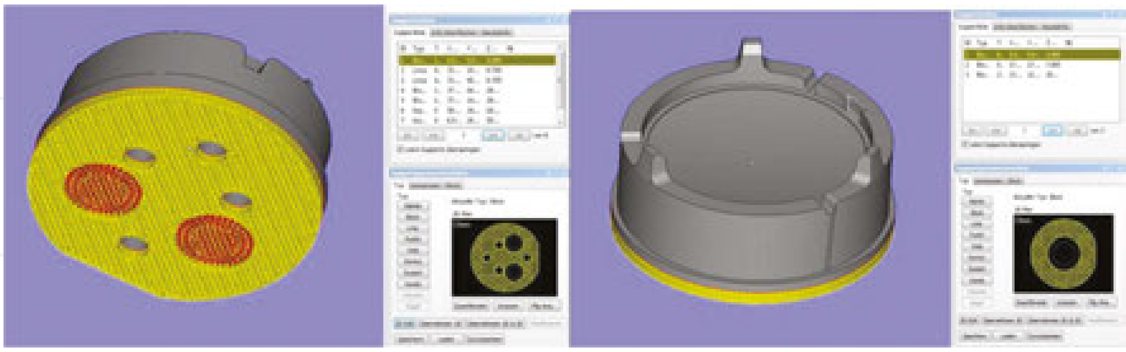


Figure 6. Supports generated for the punch and die using Magics 15 software.

The punch and die illustrated in **Figure 7** were manufactured on the SLM 250 HL equipment from SLM Solutions GmbH Company from Luebeck (Germany) presented in **Figure 8**, using the technological parameters presented in **Table 3**, as they were determined within the finite element analyses.

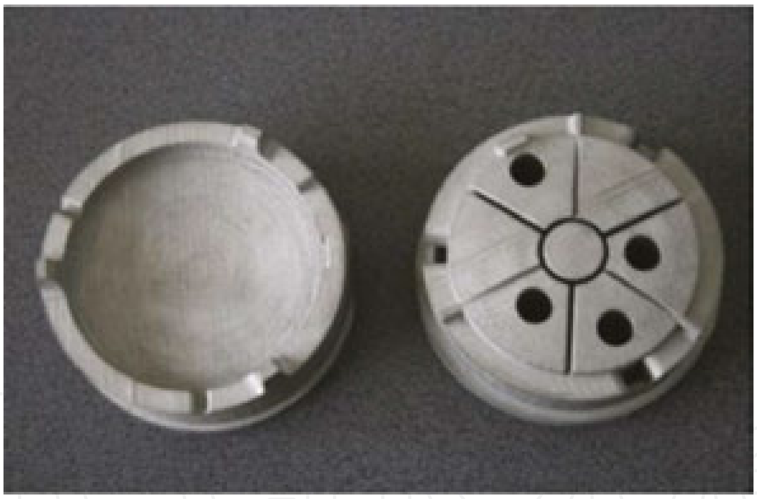


Figure 7. The injection moulding tools made by SLM equipment.

Some measurements of the injection moulding tools were also made at the Technical University of Cluj-Napoca using a Zeiss Eclipse 550 CMM equipment. The conclusion was that the obtained results are comparable to the ones estimated within the finite element analysis (designed dimensions). The maximum value of shrinkage that has been experimentally determined has a value of approximately 80 μm, both in the case of the punch and die (see **Figures 9** and **10**).

The lowest values of deformations (less than 10 μm) were obtained in the case of the dimensions H1, used for the correct positioning of the punch and die. The mean value of the punch

http://dx.doi.org/10.5772/63038

and die shrinkage has been determined in the interval of 30–40 μm, values that are comparable to the ones obtained in the case when the punch and die are produced by using similar technologies dealing with metallic powders such as Selective Laser Sintering (SLS) and Classical Sintering (CS).

Figure 8. The SLM 250 HL equipment at SLM Solutions GmbH Company from Luebeck, Germany.

There are still other issues to be investigated in the near future such as finding a way for a better control of the SLM process.

The errors that occur during the SLM process can be compensated if precisely calculated scale factors would be applied in the pre-processing stage onto the 3D model that has to be manufactured using the SLM equipment.

IntechOpen

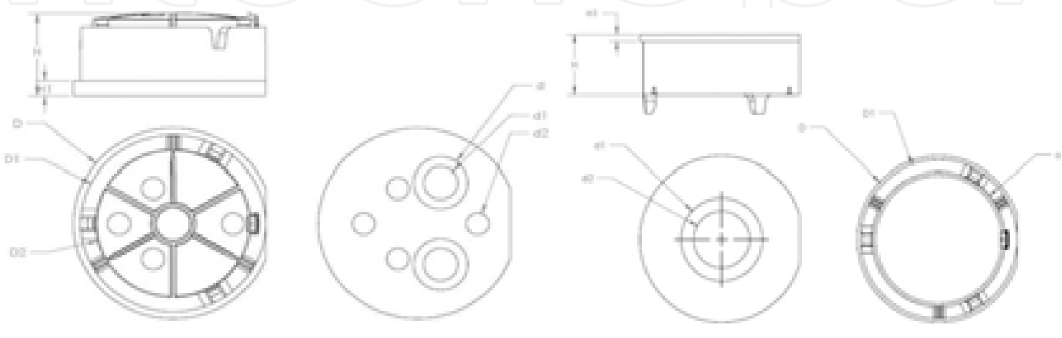


Figure 9. Schematic draw of the dimensions measured in case of punch and die.

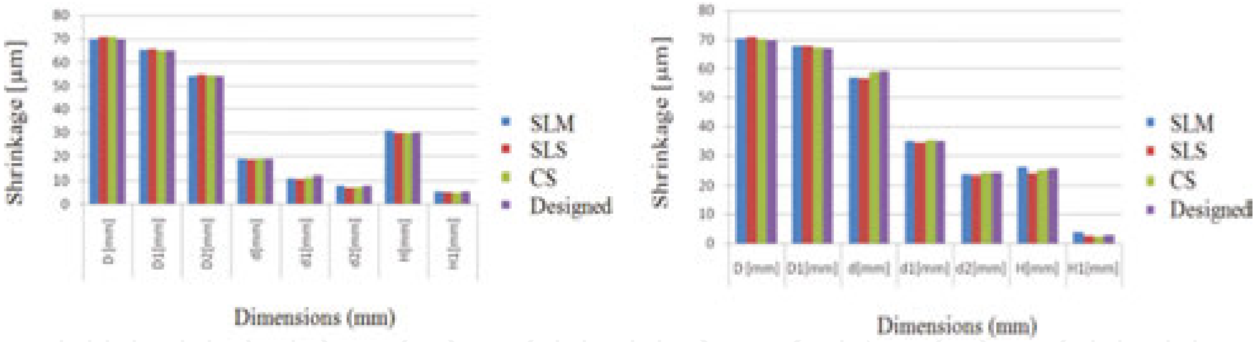


Figure 10. Shrinkage values in microns determined in the case of punch and die.

2.3. Testing the active element of moulds made by SLM at S.C. Plastor S.A. Oradea (injection moulding company from Romania)

In order to test the active elements of the mould made by SLM technology within the Plastor S.A. company from Oradea, it was required the manufacturing of additional fixing plates using conventional technologies at Plastor SA, as it is possible to observe in **Figure 11**. These plates were mounted onto the injection moulding machine Arburg 370 CMD 800-325 - type that is available within Plastor SA Company from Oradea.

Before the injection moulding experiment were made, tests were required to be done using different finite element analyses through the Autodesk Simulation Moldflow Adviser program, in order to determine the plastic injection parameters, such as the injection pressure, filling speed, etc. Four types of plastic materials were tested, such as Acryl Butadiene Styrene – ABS, Polypropylene – PP, Polyamide armed with glass fibers - PA+30% GF and Poly Oxy Methylene– POM.

Figure 11. Active elements of moulds made by SLM mounted onto the plates manufactured at Plastor S.A. company from Oradea.

http://dx.doi.org/10.5772/63038

Figure 12. Arburg 370 CMD 800-325 injection moulding equipment (Plastor SA Company Oradea).

After the mesh was generated and the optimum injection point was specified, as one could be observed in **Figure 13**, in accordance with the fiber plastic material orientation, the next step consists in determining of the injection moulding technological parameters, such as the filling speed, injection pressure, cooling time, etc.

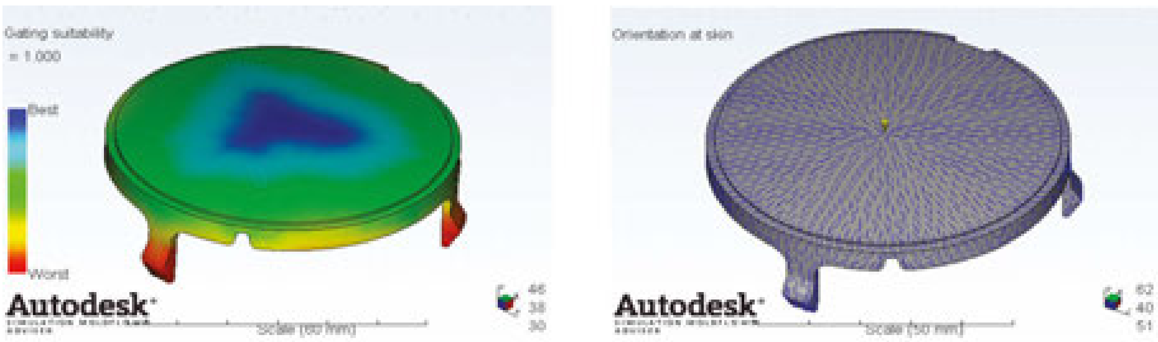


Figure 13. Optimum injection point and plastic material fiber orientation.

Figure 14 presents the values obtained for the injection pressure and the filling time in the case of ROTEC® ABS 1001 FR V0/4 material. As it is possible to observe in these images, the injection pressure required in this case is 5.130 MPa and the filling time is 0.7437 seconds.

Regarding the other plastic injection technological parameters (filling speed, melting temperature, cooling time), it is important to specify the fact that these parameters have a significant importance in the plastic injection process. Filling speed depends on the injection pressure and the properties of the plastic material. The cooling time is directly correlated with the capacity of injection moulding tool to conduct the thermal energy at the end.

An important aspect regarding the finite element analysis that has been performed is represented by the volumetric shrinkage at the end of the injection moulding process. As it is possible to observe in **Figure 15**, the volumetric shrinkage in the case of ABS plastic material were less than 4% for more than 90% of total part surface. In the clamping areas, the volumetric shrinkage values were higher, being closed to a value of 7%.

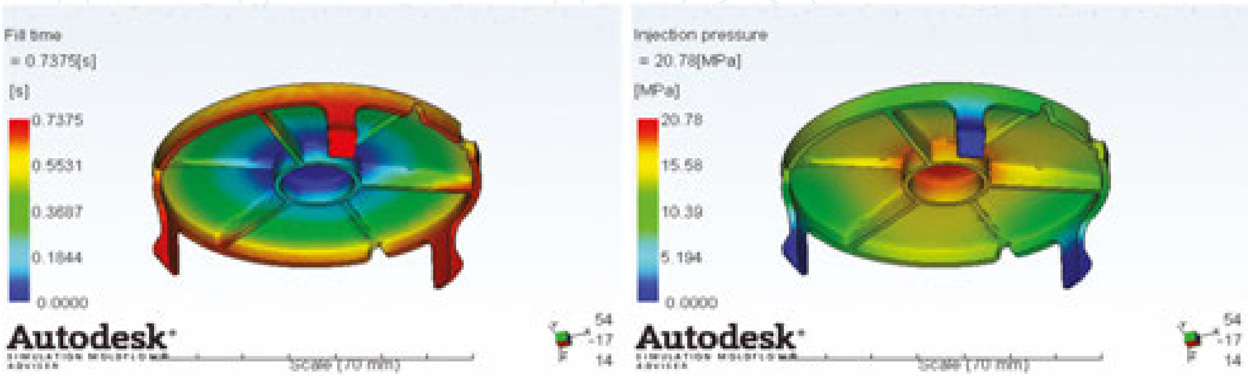


Figure 14. Injection pressure and filling time in the case of ABS plastic material.

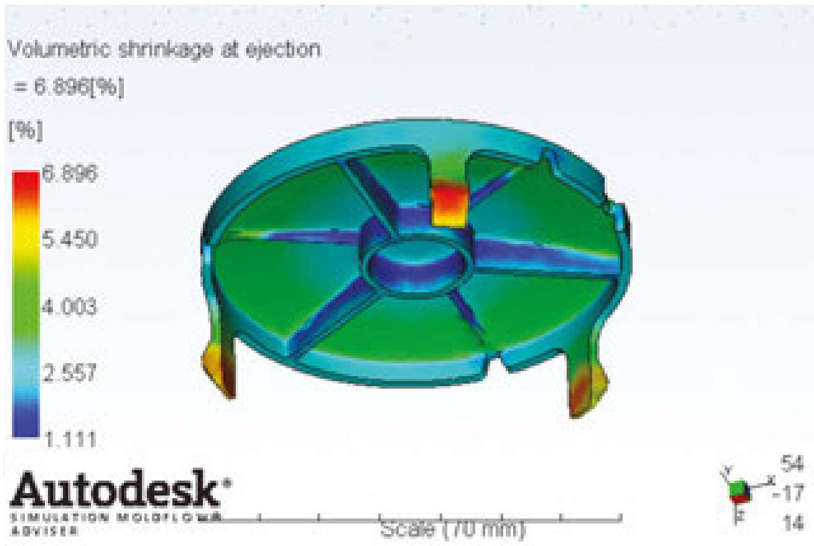


Figure 15. Volumetric shrinkage at ejection at the end of injection moulding process.

The results obtained using the finite element analyses made using the MoldFlow program in the case of all plastic materials – Acryl Butadiene Styrene – ABS, Polypropylene – PP, Polyamide armed with glass fibers - PA+30% GF and Poly Oxy Methylene– POM- are presented in **Table 4**.

The technological parameters presented in **Table 4** were used for the injection moulding tests that were made at Plastor SA Company from Oradea. All plastic materials were dried in an oven for three hours at a temperature of 80°C, with the exception of the Poly-propylene (PP) material which is not required to be dried. The maximum clamping force used during the injection moulding tests was 5 T for all four types of plastic materials that were tested.

Type of material / Parameter	PP	ABS	PA	POM
- Injection pressure [MPa]	5.13	20.78	10.32	10.39
- Filling time [s]	0.74	0.74	0.84	3.7
- Cooling time [s]	39.73	26.48	18.33	63.91
- Injection temperature [°C]	230	220	280	200
- Volumetric shrinkage [%]	11.52	6.89	11.76	14.18
- Clamping force[T]	0.99	3.8	2.02	2.01

Table 4. Results obtained using finite element analyses made by using Mold Flow program.

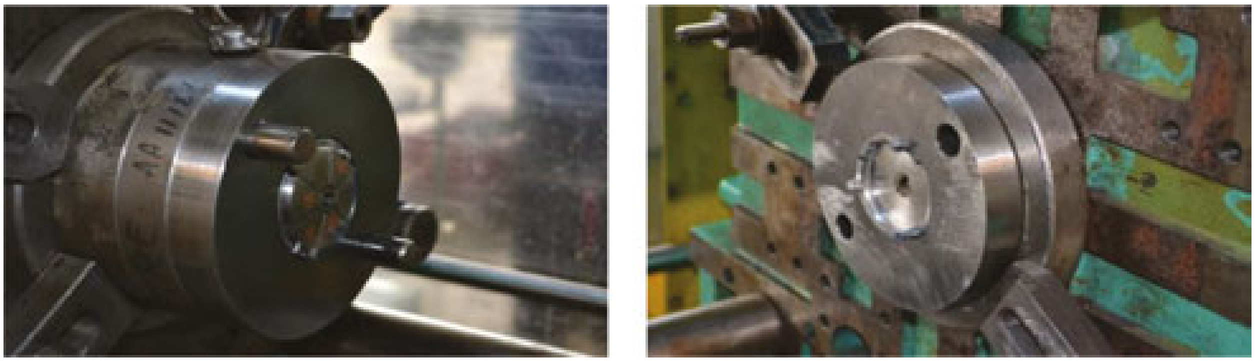


Figure 16. Injection moulding tools mounted on the Arburg 370 CMD 800-325 testing machine from Plastor SA Oradea.

The injection pressure is different in accordance with the type of the plastic material that was tested. The injection pressure was for example 50 bars in the case of PP material and 210 bars in the case of ABS material. This fact was mainly caused by the fact that the PP material had a density of 0.9 g/cm^3 as compared to the ABS material which had a density of 1.2 g/cm^3. In order to fill in the cavity with plastic material in the second case, a pressure difference of 160 bars is necessary.

The cooling time was adjusted differently in accordance with the plastic material that was injected into the mould. In the case of PA plastic material, a total time of 15 seconds is required, as compared with the ABS plastic material where the cooling time required is 50 seconds. This can be explained by the fact that the thermal conductivity coefficient is different in these cases. In the case of PA material, the thermal conductivity coefficient is 0.36 W/mK, while in the case of the ABS plastic material the value of this coefficient is 0.17 W/mK. The difference of 0.19 W/mK is transformed to the time difference required to cool-down the material in a supplementary period of 35 seconds.

2.4. Conclusion

As a conclusion of made research, it is possible to state that the Selective Laser Melting technology is easy to be understood in principle, but it is not so easy to be controlled. There are a lot of aspects that have to be taken into consideration when speaking about the accuracy of the injection moulding tools made by Selective Laser Melting (SLM), starting with the properties of the raw material, the optical system and ending with the scanning strategy or the technological parameters that are used in the manufacturing process. As related to the technological parameters (laser power, scanning speed, powder bed temperature, etc.), as it has been proven by the finite element analyses that were made, it is very difficult to find a set of technological parameters that would be unique and universally valid in all cases of moulds manufactured by Selective Laser Melting from H13 Tool Steel material. The accuracy of the injection-moulded tools made by Selective Laser Melting technology will be different, being dependent on the geometry of the tools (the size and the shape) and the accuracy of the process. Research still needs to be done in the future regarding the determination of scale factors that can be applied in the pre-processing stage onto the 3D model that has to be manufactured using the Selective Laser Melting equipment. The injection moulding tools were successfully manufactured on an SLM 250 HL equipment in the SLM Solutions GmbH Company from Luebeck (Germany) and tested in the injection moulding process of four type of plastic materials (Acryl Butadiene Styrene – ABS, Polypropylene – PP, Polyamide armed with glass fibers - PA+30% GF and Poly Oxy Methylene– POM) at Plastor SA Company from Oradea (Romania), as it is possible to observe in **Figure 17**.

Figure 17. Injected plastic materials obtained at Plastor SA Oradea using the injection moulding tools made by SLM.

http://dx.doi.org/10.5772/63038

3. Medical implants with lattice structures made from Titanium by using the Selective Laser Melting Technology (medical case study example)

3.1. Introduction

The recent researches developed in the bio-medical field proved the high interest that exists in this field regarding the possibilities of manufacturing customized medical implants using Additive Manufacturing (AM) methods, such as Selective Laser Sintering (SLS), Selective Laser Melting (SLM) or Electron Beam Melting (EBM) [18–22]. These types of AM methods allow the manufacturing of fully dense metallic parts with complex geometrical shape, starting from a 3D model realized with a computer aided design (CAD) program and exported in an "*.stl" format [23]. Fully dense metallic structures are required to be produced in the case of customized medical implants made by SLM, especially in some regions where the implants needs to be fixed into the human bone with titanium screws. There are also regions of the implants where the porous structure is required for a better osseointegration process of the human tissue through the surface of the medical implant made by SLM. Obtaining structures with a well-controlled level of porosity in this case is very important and could be achieved in different ways, such as by designing an implant having different types of lattice structures (geometrical configuration of cells) by adjusting the technological parameters (laser power, hatching distance, etc.) and the scanning strategy during the SLM manufacturing process, or by mixing in different ratios the raw powder material (titanium, in this case) with other types of biocompatible materials (e.g. hydroxyapatite, PMMA, etc.) [24]. The research presented in this chapter, made at the Technical University of Cluj-Napoca (TUC-N), was focused on the finite element analysis of the strain and stress of several models that were especially designed to have different types of lattice structures (size and geometrical configuration of cells). The samples designed and made by SLM at TUC-N using the MCP Realizer II SLM 250 equipment were analyzed afterwards by using a Scanning Electron Microscope JSM – 5600 LV (JEOL) type, in order to determine which is the optimum size and configuration of the cells to be recommended from the structural point of view to be used within the design and manufacturing process of a customized medical implant to be made by SLM. Taking into account the results obtained at TUC-N, a customized medical implant was manufactured by SLM from TiAl6V4 material for a German Medical Institute, by using the SLM 250 HL equipment from SLM Solutions GmbH Company (Luebeck, Germany), at the end.

3.2. Design of the lattice structures using the SolidWorks CAD program

Six types of models similar to the ones presented in **Figure 18** were designed using SolidWorks, with different types of lattice structures (geometrical features), as following:

- rhombic shape (size of a single cell=1 mm)
- hexagonal shape (diameter of a single cell=Φ1.45 mm)
- square shape rounded at the edges (size of a single cell: l=0.8 mm; r=0.1 mm)
- rectangular shape (size of a single cell: l_1=1 mm; l_2=0.6 mm)

- circular shape (diameter of a single cell: d=1 mm)
- pyramidal shape (base size of a single cell: l=1.5 mm).

Figure 18. Models with different geometrical features designed using SolidWorks.

The extrusion and width of the cells was designed as having 0.2 mm in the case of all models that were designed using SolidWorks. The cellular structure has been obtained by copying the shape of a single cell along the X and Y-axes directions. The models designed in this way were further analyzed using the Abaqus finite element program, in order to determine the stress and strain of the samples and their mechanical behaviour, in the case of a particular pressure load that has been applied in the uniaxial direction onto the top surface of the designed models.

3.3. Estimating the mechanical behaviour of samples with different types of lattice structures manufactured by SLM

The mechanical behaviour of all models presented in **Figure 18** was analyzed using the Abaqus 6.9-3 FEA program. Several material characteristics, such as the elastic modulus (E=114 GPa), Poisson ratio (υ=0.31) and yield strength (σ_c= 775 MPa) for the TiAl6V4 metallic powder material were taken into consideration in the analyses, as they are specified in the datasheet of the material provided by the supplier company on its website. [17]

The next step consisted in establishing the movement restrictions along the X, Y, and Z-axes, as illustrated in **Figure 19**.

http://dx.doi.org/10.5772/63038

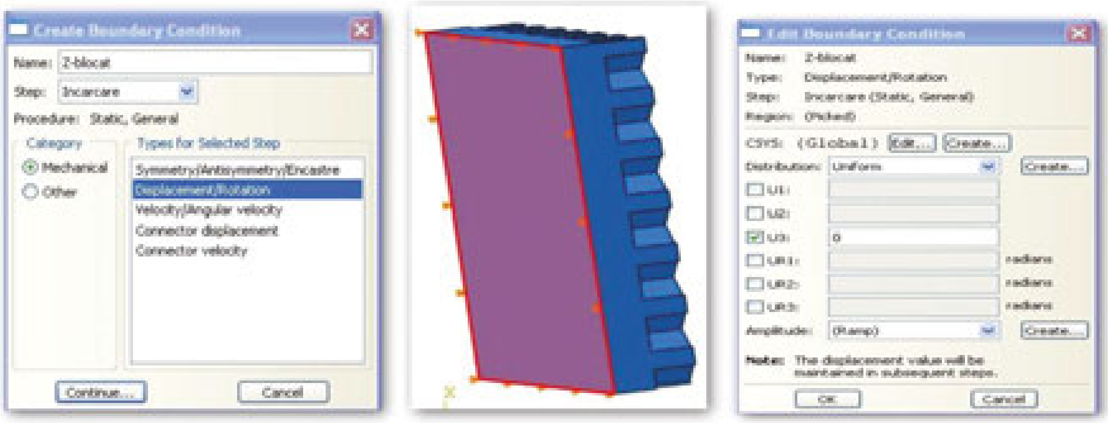


Figure 19. Movement restriction applied on the Z-axis direction.

As one may notice, the "Displacement" type of restriction has been selected in this case. The degrees of freedom were locked accordingly along all three axes by selecting the adequate facet of the model and by setting up the corresponding displacement value to zero.

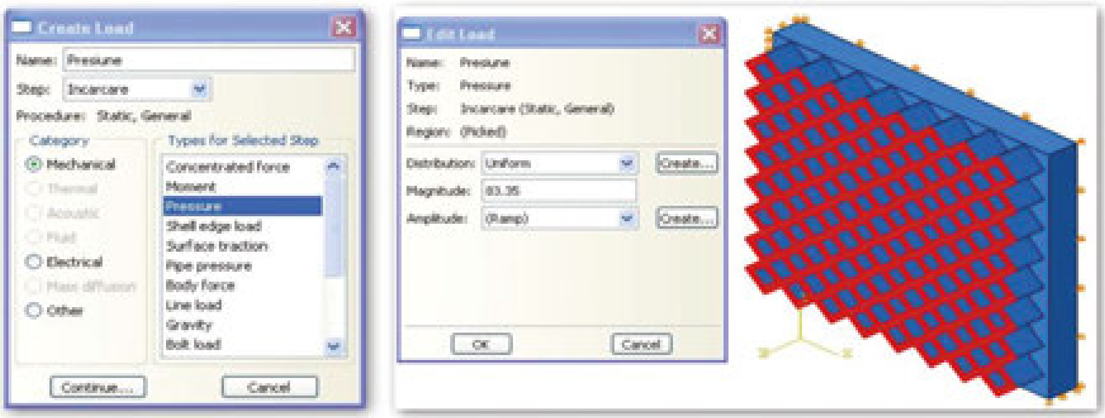


Figure 20. Applied load specified in the analysis.

The pressure applied in a single direction onto the top surface of the model was determined by using formula (1):

$$P = \frac{F}{A_p} \tag{1}$$

A force value F = 3200 N, which corresponds to four-times higher the force exerted by a person weighing 80 kg has been considered in all analyzed cases. The value of the contact area A_p in mm² was different from case to case, due to the fact that the geometrical configuration of the cells was different. The A_p value was determined for each case by using the tools that are available within the SolidWorks CAD program. The pressure load determined by using formula (1) was introduced for each particular case, as shown in **Figure 20**.

The mesh has been generated as illustrated in **Figure 21**. The selected shape of the finite elements was tetrahedral, with an approximate global size of 0.25 mm and a maximum curvature control having a deviation factor of about 0.1 mm.

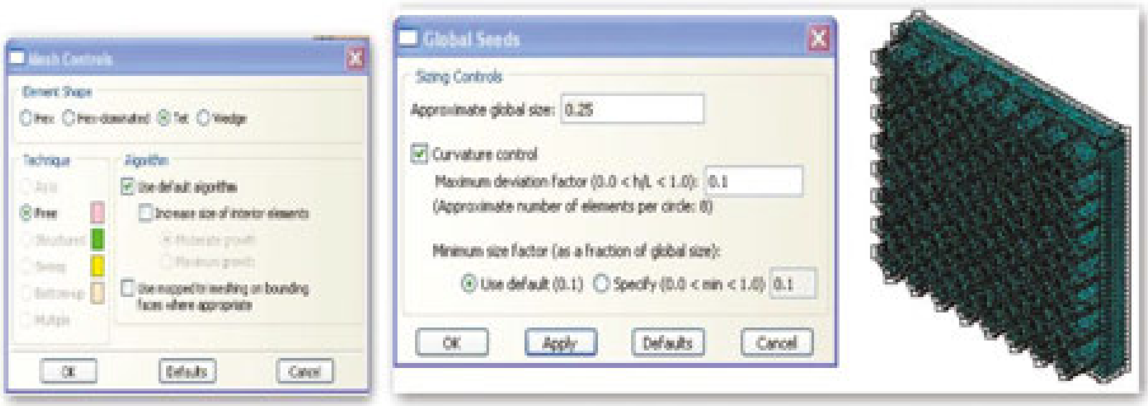


Figure 21. Element-type control and mesh-size control defined for the FEA.

3.4. Results of the finite element analyses made with Abaqus

The equivalent von Mises stress, displacement and equivalent strain were determined for all the six samples presented in **Figure 18**, using the finite element analysis method. The analysis allowed formulating recommendations with reference to the optimum values ranging in the standard limits that exist in this field.

In order to determine the equivalent von Mises stress, for the calculus made within Abaqus FEA program, it has been considered the fifth theory for multiaxial stresses:

$$\sigma_{ech} = \sqrt{\frac{1}{2}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 3(\tau_{xy}{}^2 + \tau_{yz}{}^2 + \tau_{zx}{}^2)]} \geq 0; \sigma_{ech} \leq \sigma_c \qquad (2)$$

If we consider in formula (2) that the tangential stresses are equal,

$$\begin{cases} \tau_{xz} = \tau_{zx} \\ \tau_{yz} = \tau_{zy} \\ \tau_{xy} = \tau_{yx} \end{cases} \qquad (3)$$

a particular state of uniaxial stress is obtained. The simplified formula was used within Abaqus FEA program in order to perform the interpretation of the stress results.

The stress energy was also calculated according to formula (4):

$$E_{def} = \frac{1}{2}\sigma_{ech} \times \varepsilon_{ech} \tag{4}$$

where E_{def} - represents the stress energy; σ_{ech} - equivalent stress von Mises; ε_{ech} - equivalent strain.

As one may notice in **Figure 22**, the values of the equivalent stress von Mises were lower than the yield strength σ_c= 775 MPa specified in the material datasheet provided by the supplier of the TiAl6V4 material. The minimum value of the equivalent stress von Mises (102.50 MPa) has been determined in the case of the sample with lattice structure designed as having cells with a rhombic shape, while the maximum value (278.56 MPa) was obtained in the case of the sample designed with cells having a conical shape. If we consider a value of 212 MPa for the mechanical resistance of the trabecular bone, the adequate solution would be to design and produce the medical implant as having a rhombic shape of the cell, in this case [25].

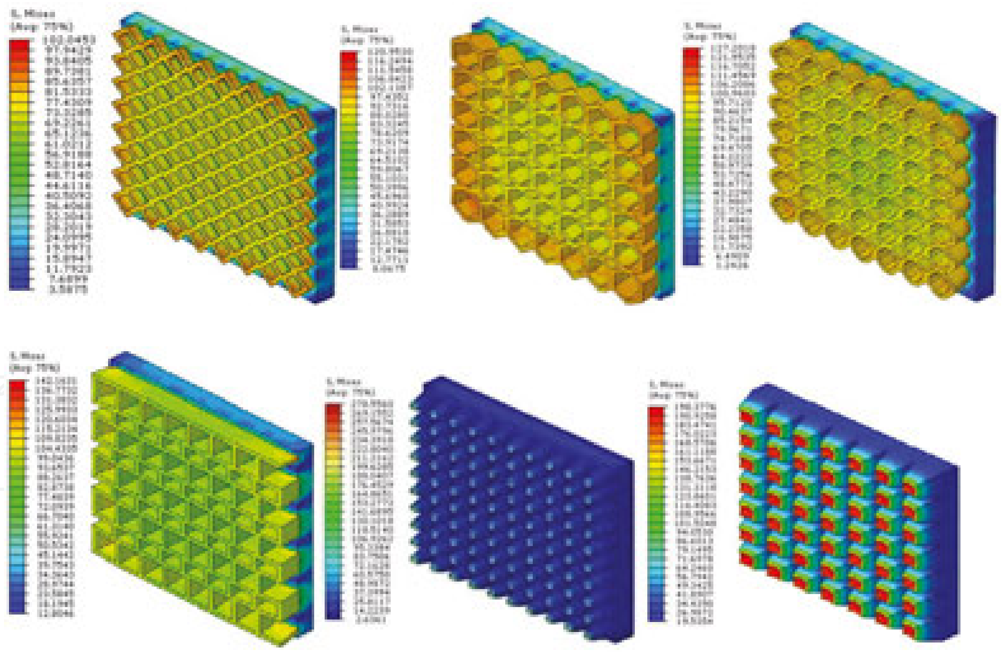


Figure 22. Distribution of the equivalent stress von Mises as computed by the Abaqus FEA program.

The displacement and equivalent strain values were negligible in all cases that were analyzed, being considered too low for affecting the bone or customized medical implant made from titanium powder by SLM [25].

3.5. Manufacturing samples with lattice structures and medical implant by SLM

The manufacturing of the six samples was realized using the MCP Realizer II SLM 250 from the National Centre of Innovative Manufacturing from the Technical University of Cluj-Napoca (TUC-N) presented in **Figure 2**. After the metallic supports were removed, the manufactured samples made by SLM were obtained as presented in **Figure 23**.

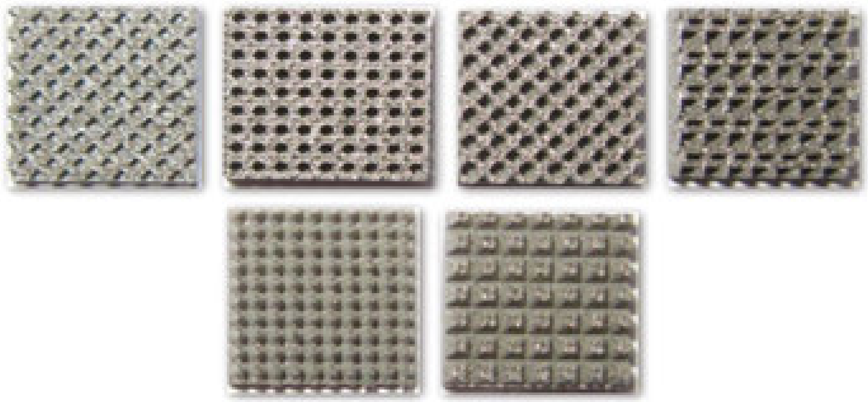
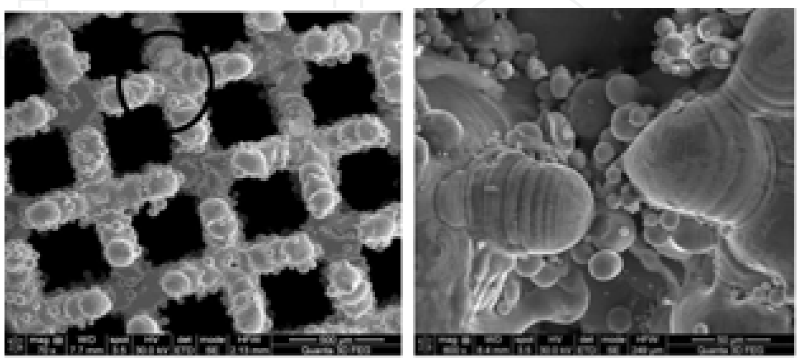


Figure 23. Samples manufactured using the MCP Realizer II SLM 250 equipment [26].

After the manufacturing process, the structure of the samples was analyzed by using a Scanning Electron Microscope (SEM) JSM-5600 LV (JEOL) – type that is available at the Technical University of Cluj-Napoca (TUC-N).

The best geometrical configuration of the lattice structures that were manufactured by SLM was the rhombic one (see **Figure 24**). By analyzing the image presented in **Figure 24.a**, a series of appreciations regarding the metallic grains distribution on the surface of the sample was made. As it is possible to observe in this image, the grains are distributed in a uniform manner.



(a) Sample realized by SLM (70 X) (b) Sample realized by SLM (600 x]

Figure 24. Metallographic analysis of the sample with rhombic geometrical shape manufactured by SLM. (a) Sample realized by SLM (70X) (b) Sample realized by SLM (600 x).

http://dx.doi.org/10.5772/63038

By zooming in the surface analyzed area (600x), it was possible to observe that the presence of secondary pores was at the lowest level in this case, conferring higher resistance connections of the grains in the lattice structure. By analyzing the image presented in **Figure 24b** it is possible to observe that the grains that were partially melted formed bridge connections with the grains stated in a semi-liquid phase of about 50 μm.

Taking into account the obtained results, a customized medical implant was manufactured by SLM from TiAl6V4 material for a German Medical Institute, using the SLM 250 HL equipment from SLM Solutions Gmbh Company from Luebeck, Germany, presented in **Figure 8**.

This equipment was selected for the manufacturing process of the customized implant presented in **Figure 25**, due to the fact that this type of equipment, as compared to the MCP Realizer SLM 250 equipment from the Technical University of Cluj-Napoca allows the possibility of using different type of scanning strategies in the same deposited layers, in such way that at the end, in some areas of the implant (e.g. the area where fixing screws are required) this areas will result with a density of 100%, while in other areas (e.g. areas where the medical implant is getting in contact with the human tissue), the areas will be a porous one, the osseointegration process being facilitated in a significant way in that region.

Manufactured area	Scanning strategy	Laser power [W]	Scanning speed [mm/s]	Layer thickness [μm]
Supports	Hatch Solid	100	500	30
Solid areas	Stripes with skin	100	550	30
Porous structure	Stripes with skin	175	470	30

Table 5. Technological parameters used for manufacturing the customized medical implants by SLM using the SLM 250 HL equipment.

Figure 25. Customized medical implant manufactured from Ti6Al4V material using the SLM 250 HL equipment.

A metallographic analysis of the medical implant was made using the JSM-5600 LV (JEOL) Scanning Electron Microscope (SEM) from the Technical University of Cluj-Napoca. The analyzed area was a mixed area that is close to the contact area of the fixing screws (an area with 100% density of the material) and an area with a controlled porosity given by the geometrical shape of the lattice structure, as it is possible to observe in **Figure 26**.

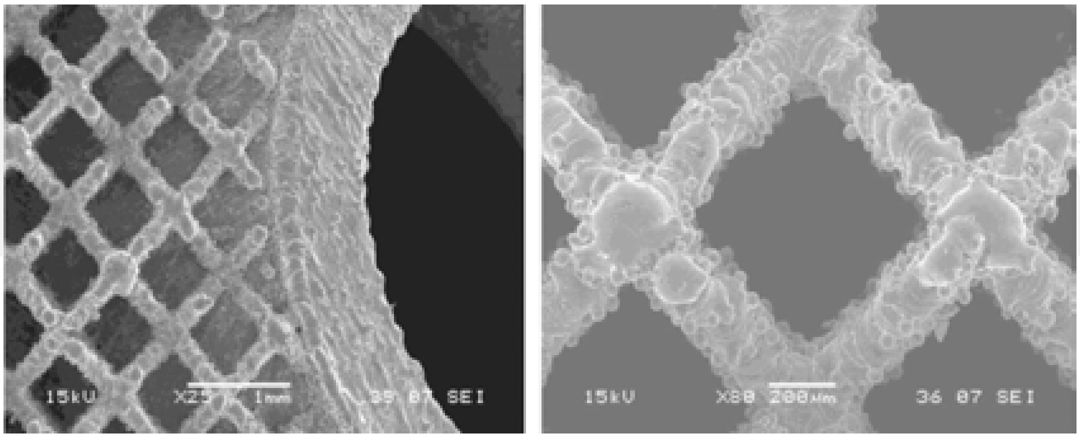


Figure 26. (a) Lattice structure (2x), (b) welding lines (25x) of the customized medical implant made by SLM.

As it is possible to observe in **Figure 26.a**, the laser beam has followed very accurately the geometrical path of the bore that was designed for fixing the implant with screws. The density in this area is 100%, conferring a higher mechanical strength that is required for fixing the medical implant onto the femoral head.

By zooming in the image of the analyzed area, as it is possible to observe in **Figure 26.b**, the size and the distribution of the pores resulted in the structure of the material was homogenous and uniformly distributed (wall thickness of the cells was approximately 1 mm), an aspect that is important for the future proliferation of the human tissue within the structure of the medical implant within the osseointegration process, at the end.

3.6. Conclusions

As it was possible to observe by analyzing the results obtained after the finite element analyses, the sample with the cells having a rhombic shape has proved to be optimal from the mechanical resistance point of view as compared to the results obtained in the case of the other analyzed samples. Taking into account the obtained results, a customized medical implant was manufactured by SLM from TiAl6V4 material for a German Medical Institute, using the SLM 250 HL equipment from SLM Solutions GmbH Company from Luebeck. A metallographic analysis of the medical implant was made using the JSM-5600 LV (JEOL) Scanning Electron Microscope (SEM) from the Technical University of Cluj-Napoca, proving the fact that the laser beam has followed very accurately the geometrical path of the bore that was designed for fixing the implant with screws, and that the size and the distribution of the pores resulted in the structure of the material which is homogenous and uniform, with positive consequences for the future proliferation of the human tissue within the structure of the medical implant within the osseointegration process. Further researches are required to be done in the future regarding the possibilities of manufacturing customized medical implants with a well-controlled level of porosity, made from new types of biocompatible materials (e.g. titanium samples coated with hydroxyapatite or PMMA). Finding a proper method for the stress-release of customized medical implants made from titanium based alloys, during or after the Selective Laser Melting (SLM) process still presents an important challenge for the future researches, as well.

Author details

Pacurar Razvan* and Pacurar Ancuta

*Address all correspondence to: razvan.pacurar@tcm.utcluj.ro, ancuta.costea@tcm.utcluj.ro

Faculty of Machine Building, Department of Manufacturing Engineering, The Technical University of Cluj-Napoca, Cluj-Napoca, Romania

References

[1] Păcurar, R., Păcurar, A., "finite element analysis to improve the accuracy of parts made by stainless steel 316L material using selective laser melting technology", Applied Mechanics and Materials, vol. 657, (2014), pp. 236–240

[2] Tolosa, I., Garciandía, F., Zubiri, F., Zapirain, F., "Study of mechanical properties of AISI 316 stainless steel processed by "selective laser melting", following different manufacturing strategies", International Journal of Advanced Manufacturing Technology, vol. 51, (2010), pp. 639–647

[3] Badrossamay, M., Yasa, E., Van Vaerenbergh, J., Kruth, J.P., "Improving productivity rate in SLM of commercial steel powders", Proceedings of SME RAPID 2009 Schaumburg, Illinois, USA, 12-14 May, 2009

[4] Mahesh, M., Wong, Y., "Benchmarking for Comparative Evaluation of RP Systems and Processes", Rapid Prototyping Journal, vol. 10, Issue 2, (2004), pp. 123–135

[5] Childs, T.H.C., Hauser, C., and Badrossamay, M., "Mapping and modelling single scan track formation in direct metal selective laser melting", CIRP Annals – Manufacturing Technology, vol. 53 (1), (2004), pp. 191–194

[6] Dong-Gyu A., "Applications of laser assisted metal rapid tooling process to manufacture of moulding & forming tools — state of the art", International Journal of Precision Engineering and Manufacturing, vol. 12 (5), (2011), pp. 925–938

[7] Morovič, L., Pokorný, P., "Optical 3D Scanning of Small Parts", Advanced, Materials Research, vols. 468-471, (2012), pp. 2269–2273, Trans Tech Publications, Switzerland, doi: 10.4028/www.scientific.net/AMR.468-471.2269

[8] Gower, H.L., Pieters, R.R.G.M., Richardson, I.M., "Pulsed laser welding of metal–polymer sandwich materials using pulse shaping", Journal of Laser Applications, vol. 18 (1), (2005), pp. 35–41

[9] Kruth, J.P., Froyen, L., Van Vaerenbergh, J., Mercelis, P., Rombouts, M., Lauwers, B., "Selective laser melting of iron-based powder", Journal of Materials Processing Technology, vol. 149 (1–3), (2004), pp. 616–622

[10] Kruth, J.P., Levy, G., Klocke, F., Childs, T.H.C., "Consolidation phenomena in laser and powder-bed based layered manufacturing", CIRP Annals-Manufacturing Technology, vol. 56 (2), (2007), pp. 730–759

[11] Levy, G.N., Schindel, R., Kruth, J.P, "Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives", Annals of the CIRP, vol. 52 (2), (2003), pp. 589–609

[12] Li, R., Shi, Y., Liu, J., Yao, H., Zhang, W., "Effects of processing parameters on the temperature field of selective laser melting metal powder", Powder Metallurgy and Metal Ceramics, vol. 48 (3–4), (2009), pp. 186–195

[13] Moures, F., Cicala, E., Sallamand, P., Grevey, D., Vannes, B., Ignat, S., "Optimization of refractory coatings realised with cored wire addition using a high-power diode laser", Surface and Coatings Technology, vol. 200 (7), (2005), pp. 2283–2292

[14] Sparks, T., Ruan, J., Fan, Z., Bap, Y., Liou, F., "Effect of structured laser pulses on grain growth in H13 tool steel", Solid Freeform Fabrication Symposium, Austin, TX, (2006), pp. 261–267

[15] Tolochko, N.K., Mozzharov, S., Yadroitsev, I.A., Laoui, T., Froyen, L., Titov, V.I., Ignatiev, M.B., "Balling process during selective laser treatment of powders", Rapid Prototyping Journal, vol. 10 (2), (2004), pp. 78–87

[16] AISI Type H13 Hot Work Tool Steel material characteristics http://www.matweb.com/search/DataSheet.aspx?MatGUID=e30d1d1038164808a85cf7ba6aa87ef7&ckck=1, accessed: 15.09.2015

[17] SLM Solutions GmbH, SLM Materials Characteristics, available at: http://www.slm-solutions.com/cms/upload/pdf/120923_SLM_Materialien.pdf, accessed: 15.09.2015

[18] Păcurar, R., Păcurar, A., Petrilak A., Bâlc. N., "Finite element analysis to predict the mechanical behaviour of lattice structures made by selective laser melting technology", Applied Mechanics and Materials, vol. 657, (2014), pp. 231–235

[19] Lin, C.Y., Kikuchi, N., Hollister, S.J., "A novel method for biomaterial scaffold internal architecture design to match bone elastic properties with desired porosity", Journal of Biomechanics vol. 37 (5), (2004), pp. 623–636

[20] Maričić, S., Pavičić, D.K., Perinić, M., Lajnert, V., "The use of technological documentation in vestibuloplasy fixture plate production", Medicina Fluminensis, vol. 47 (3), (2011), pp. 294-298

[21] Marcincinova, L., N., Fecova, V., Marcincin, J.N., Janak, M., Barna, J., "Effective utilization of rapid prototyping technology", AIP Conference Proceedings, vol. 1431, (2012), pp. 834-841

[22] Marcincinova, L.N, Marcincin, J. N., "Selected testing for Rapid Prototyping technology operation", Applied Mechanics and Materials, vol. 308, (2013), pp. 25-31

[23] Yan, C., Hao, L., Hussein, A., Raymont, D.,"Evaluations of cellular lattice structures manufactured using SLM", International Journal of Machine Tools & Manufacture, vol. 62, (2012), pp. 32–38

[24] Hussein, A., Hao, L., Yan, C., Everson, R., Young, P.,"Advanced lattice support structures for metal additive manufacturing", Journal of Materials Processing Technology, vol. 213, (2013), pp. 1019–1026

[25] Toan, T. L., MD, "Biomechanics of Fractures and Fixation", 2005, available at: http://www.docslide.com/biomechanics-of-fractures-and-fixation/, accessed: 18.09.2015

[26] Mager, V., "Research regarding the manufacturing of customized medical implants made from composite materials, by using the selective laser melting technology" PhD Thesis, Technical University of Cluj-Napoca, 2014

IntechOpen