RAPID PRODUCT DEVELOPMENT USING ADDITIVE MANUFACTURING TECHNOLOGIES

PETRU BERCE[1], ARIK SADEH[2], RĂZVAN PĂCURAR[1],
CRISTINA MIRON-BORZAN[1]

Abstract. This paper presents research and case studies on the use of selective laser sintering (SLS) and selective laser melting (SLM) technologies in the development of new products and their applications in various fields, ranging from industry to medicine. This paper discusses the following topics: problems related to the materials used in applications (metallic and nonmetallic powders), properties of the products manufactured by SLS and SLM technologies, and optimization of the manufacturing parameters for obtaining controlled structures and properties. The experimental research results demonstrate the efficiency of SLS and SLM methods for the rapid manufacturing of new products made of metallic or nonmetallic materials, with applicability in the medical field (for the production of different types of customized prosthesis) and the industrial field (for the production of different types of tools for medium batch series production of plastic parts using injection molding). The study findings enhance the application of relevant AM technologies in the Industry 4 era.

Key words: Additive Manufacturing, Selective Laser Sintering, Selective Laser Melting, Rapid Product Development, Metallic and Nonmetallic Powders.

1. INTRODUCTION

Additive manufacturing (AM) technologies represent a new category of technologies used to produce new physical models. Many AM processes produce items from metallic and nonmetallic materials by adding consecutive layers starting from a virtual model designed in 3D [1]. The advantages of these new technologies are that they allow the production of very complex physical models that cannot be realized by conventional technologies in short production time, as well as entailing reduced costs. Thus, it is possible to design test, and approve a new product with minimal risk, substantially reducing the time-to-market required for newly developed product. The rapid evolution of these new AM technologies, especially in the materials science and information technology domains, makes manufacturing with a diverse range of materials and very complex geometric configurations possible for different prototypes or parts in small batch production, [2].

---

[1] Technical University of Cluj-Napoca, Faculty of Machine Building, B-dul Muncii 103-105, Cluj-Napoca, Romania

[2] Holon Institute of Technology, Faculty of Technology Management, 52 Golomb Street, Holon, Israel

Ro. J. Techn. Sci. – Appl. Mechanics, Vol. 64, N° 3, P. 189–207, Bucharest, 2019

In recent years, two technologies in particular have been applied successfully based on the performance–and–products developed: (i) selective laser sintering (SLS) technology, which is used mainly for the production of plastic parts made out of thermoplastic powder materials, and (ii) selective laser melting (SLM) technology, which is mainly used for the production of parts made out of different types of metallic powders with different characteristics. The properties of the physical models made by SLS and SLM technologies are influenced by the type of raw material (metallic or nonmetallic) and technological parameters used, and a series of post-processing operations.

This research was conducted in the National Centre of Innovative Manufacturing at the Technical University of Cluj-Napoca (TUCN). This center has both SLS and SLM apparatus, specifically geared to the development of different industrial and medical applications. The research results demonstrate the optimization of the technological parameters to obtain parts with high and predefined physical and mechanical properties.

The rest of the paper is organized as follows: in section 2, the materials and equipment used in the research are described. in Section 3, the experiments using SLS technology with respect to several materials are described and the results discussed. In Section 4, the SLM technology experiments are described and the results reported. The manuscript closes in Section 5 with a summary and conclusions.

The materials used for this research were developed at TUCN. These materials are metallic and nonmetallic powders, namely polyamide PA2200 for SLS and H13 tool steel for SLM. It is well known that polyamide (PA) materials used in fiber form as thermoplastic materials have been adopted for different engineering applications, as well as other applications in different domains. Different types of PA materials with a complex composition and not in fiber form are available on the market. This category includes crystalline plastic materials, amorphous plastic materials, adhesives, and rubbers, which are also classified as polyamide materials. PA material has favorable characteristics required mainly for the development of different tribology applications. These include: mechanical strength, stiffness and hardness, good fatigue strength, good mechanical properties, good shock absorption, and high resistance to wear. These properties make PA useful for different applications developed in the industrial field, [3].

PA2200 powder is based on the PA 12 polyamide powder structure and has very good biocompatibility with different types of cells and human tissue. [4]. The parts produced by selective laser sintering this type of material have good biocompatibility properties in accordance with the EN ISO 10993-1 and USP Class VI 121 °C standards, [5].

Due to the excellent mechanical properties of PA, it is used often to replace parts made of typical plastic materials using injection molding or casting technologies. Its biocompatibility characteristics also allow the use of this type of material in the production of customized prostheses and medical devices. Due to its high friction resistance, PA is also used for the production of connections between different mobile parts, [5].

The short-term influence of temperature on the mechanical properties of PA 12 (the base for PA2200) has been observed from analysis of dynamic shear modulus curves and the loss factor in line with temperature, according to the ISO 537 standard. In general, parts made of PA 12 have high mechanical strength and good elasticity when used in a normal working temperature range, from –40 ºC to +80 ºC. The loading of parts made of PA 12 in a short time frame without the appearance of stresses is possible up to a temperature of 160 ºC. Because PA 12 has a low friction coefficient and a very good resistance to abrasion, it is best used in manufacturing medical devices for the production of articular prostheses. If the part is used in increasing temperature conditions, the friction coefficient will increase linearly without modification of the viscosity of PA 12, [6].

A group of researchers from the Technological Indian Institute of New Delhi [7] has analyzed the production of a “scaffold” type structure implemented through SLS using the EOS 380P Sinterstation equipment. Their published conclusions highlight that the “scaffold” structure is necessary for adapting the geometric shape of implants to bone structure. The dimensions of the implant pores are adapted to the dimensions of the bone cell structure to allow for the possibility of developing osteoblasts (cells with a single nucleus that synthesize bone) in the manufactured structure.

Recent research performed in the field of mold manufacturing using laser additive manufacturing technologies has focused on the development of molding tools with efficient cooling systems. This not only reduces the time of production, but also helps to improve the quality of the parts produced [8–11]. The cooling characteristics of a mold depend primarily on the design and location of cooling channels and the thermal conductivity properties of the material from which the mold is made, [12–13]. H13 is one of the materials most commonly used in research projects conducted in this field. H13, also known as Tool Steel 1.2344, is a chromium martensitic material used in tooling applications that require high strength and resistance to thermal fatigue cracking. The tensile strength of H13 is 1525 MPa, the elongation is 3%, and the Young’s modulus is 217 GPa [14]. The thermal conductivity of the material is acceptable (50 W/m*K). This is the main reason why the latest research were focused on the development of molds with lattice structures integrated and adapted by the designing point of view (in terms of the size and shape of the cells) to the mold shape to be manufactured by SLM. The conformal cooling channels were optimized in this way in order to improve the heat transfer of the molds with the help of the lattice structures designed in this way as described, [15–17]. The type of the lattice structure to be used, size of the cells, the inclination of the unit cell structures, and the manufacturability of the cooling channels have been investigated in recent years. Circular and self-supporting cross-sections in close connection with the stress concentrations associated with the cooling channel layouts and the corresponding cooling variations have also been investigated in recent years.

It has been identified that the process parameters for the part density H13 are limited. It has also been found that the processing parameters for H13 in SLM processing can reduce the porosity and avoid thermal stress, vaporization, and spheroidization of the material as well, [18].

The research performed to produce the physical models made from PA2200 through SLS Selective Laser Sintering technology, with applicability in the medical domain was implemented using the Sinterstation 2000 (DTM) equipment of the National Centre of Innovative Manufacturing at TUCN. The main characteristics of the SLS equipment include: maximum build size given by a cylinder 304 mm in diameter by 381 mm high, layer thickness of 0.08–0.1 mm, and maximum CO_2 laser power of 50 W. The research projects conducted the National Centre of Innovative Manufacturing at TUCN dealing with the manufacturing of the molding tools made by SLM were implemented using the MCP Realizer SLM 250 equipment. The maximum size of parts that can be manufactured using this system consist of a 200 mm^3 volume. Other important characteristics of this equipment are: layer thickness (0.05 mm), maximum laser power (200 W), and maximum scanning speed (20 m/s). Other equipment used in the experiments included a NitroFlowR Basic Mobile type nitrogen generator, a vibrating table and an exhaust system required for cleaning and brushing the parts after the process was concluded.

2. AM TECHNOLOGY EXPERIMENTS USING SLS

2.1. MANUFACTURING OF PROTOTYPES MADE FROM PA2200 BY SLS

An important stage of the research consisted of optimizing the technological parameters of the SLS process required for the production of different models made from PA2200 with physical and mechanical properties similar to those of implants that currently are being made from Simplex Bone Cement. This material (PMMA) is a biocompatible material used for actual cranial implants and for the fixation of prosthesis to living bone in orthopedic musculoskeletal surgical procedures.

Starting from the premise that the PA2200 was specifically designed to be processed on the EOS P equipment and through the specificity of the Sinterstation 2000 equipment, there was a need to change and optimize the recommended parameters for this material in order to be processed on other equipment.

When using a new type of material (PA2200) on the Sinterstation 2000 equipment, it is important to set the glazing temperature required for the use of the new type of Polyamide material. It were tested different temperature for glazing and the optimal temperature recommended to be used has proved to be 181 ºC (based on own experimental tests). Starting from this value, it was decided that the working temperature during the build-up stage would be 170 ºC.

Taking into consideration the technological parameters determined in previous experiments [19] for determining the physical and mechanical properties of PA2200, five sets of samples with different values for laser power (3.5 W, 4 W, 4.5 W, 6 W, and 7.5 W) were produced for each mechanical test required: (a) tensile, (b) bending, and (c) compression. The other technological parameters for the production of samples in the DTM Sinterstation 2000 are as follows: building temperature 170 ºC; layer thickness 0.1 mm; scanning speed 1257.30 mm/s; slicer fill scan Spacing 0.15 mm.

The 3D CAD models of the samples were designed using the SolidWorks program, in accordance with the standards in the field for mechanical tests of samples made of plastic materials (SR EN ISO 527–4 for tensile tests, SR EN ISO 178:2011 for bending tests, and SR EN ISO 604:2004 for compression tests). The samples made by SLS are presented in Fig. 1.

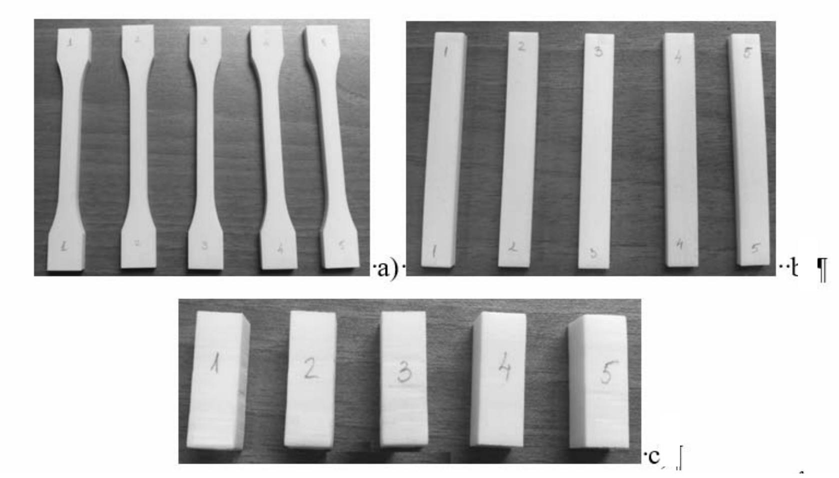


Fig. 1 – Sets of samples made of PA2200 for mechanical tests: a) tensile; b) bending; c) compression.

Identical samples were produced from PMMA using a silicone rubber mold designed and manufactured especially for this purpose (the PMMA material was casted into the mold). All mechanical tests were performed using INSTRON 3366 (10 kN) equipment. For the tensile tests, the INSTRON 3560 mechanical extensometer was also required. The testing speeds were: 2 mm/min for the tensile strength testing, and 5 mm/min for the bending and compression tests. The tensile test results are presented in Table 1 in mean values. As can be seen from Table 1, there is an increase in the mechanical characteristics of PA2200 with an increase in laser power up to 6 W. The maximum tensile stress value of 52.41 MPa was obtained with a laser power of 7.5 W, while the minimum value of 31.57 MPa was reached with a laser power of 3.5 W. The sample produced with 6 W laser power, required a maximum force of 2606.16 N, as shown in Table 1.

Table 1

Mean values of the properties obtained from the tensile tests

Type of material & laser power	Maximum load [N]	Maximum stress [MPa]	Total elongation [%]	Young's modulus [MPa]	Poisson's ratio
PMMA	1846.77	32.70	1.48	2392.19	0.36
PA2200 3.5 W	1704.79	31.57	5.88	1060.46	0.35
PA2200 4 W	2163.00	40.06	7.39	1375.60	0.32
PA2200 4.5 W	2404.46	44.53	10.60	1400.35	0.35
PA2200 6 W	2606.16	52.00	11.07	1626.37	0.35
PA2200 7.5 W	2124.47	52.41	12.33	1646.50	0.37

The mean value of the maximum stress for tensile stress testing of the PMMA samples was 32.70 MPa. This value is close to the minimum value reached for samples made of PA2200 by SLS with a laser power of 3.5 W (31.57 MPa). A higher rate of increase in the maximum stress values was observed for samples made from PA2200 as laser power increased from 4 W to 6 W. From 6 W to 7.5 W, a much slower increase was recorded, with stress values from 52 MPa to 52.41 MPa. When reviewing the Young's modulus, a higher mean value was determined for the PMMA samples (2 392.19 MPa) compared to those obtained for PA 2200 samples. The values from PA 2200 were much lower: between 1060.46 MPa (3.5 W) and 1 646.50 MPa (7 W). Although the Young's modulus for the PMMA samples is about 45% higher than that of the PA2200 samples with a laser power of 7.5 W, the values for PA2200 are in the range of those found in the scientific literature for parietal bone. The mean values of the Poisson's ratio obtained in the PA2200 samples are comparable those obtained for samples made of PMMA (0.36). The mean values for stress and strain that are specific to bending tests for samples made from the aforementioned types of materials are presented in Table 2.

Table 2

Mean values of the characteristics obtained from bending tests

Type of material & laser power	Maximum loading [N]	Maximum stress [MPa]	Specific strain [mm/mm]	Young's modulus, [MPa]
PMMA	153.82	57.86	0.02	2664.87
PA2200 3.5W	72.37	45.71	0.07	1284.04
PA2200 4W	101.53	64.13	0.07	1613.81
PA2200 4.5W	100.97	63.77	0.07	1637.14
PA2200 6W	127.00	73.52	0.08	1665.62
PA2200 7.5W	137.02	74.48	0.08	1687.05

A higher maximum loading force for bending tests was measured in the case of samples made from PMMA–153.82 N, compared to those obtained for all samples made of PA2200. It can be seen that the maximum force required for bending tests of samples made from PA2200 increased with an increase in the laser power used for the production of the samples. The maximum force was increased from 72.37 N (3.5 W) to 137.02 N (7 W). The same tendency was also observed for the maximum stress levels reached during the bending tests. The maximum stress levels increased from 45.71 MPa (3.5 W) to 74.48 MPa (7.5 W). The samples made of PMMA reached a maximum value of 57.86 MPa for the bending stress; these values are below those reached for samples made of PA2200 with a laser power between 4 W and 7.5 W, but superior to that of PA2200 made with a laser power of 3.5 W.

The mean values of stresses and strains specific to the compression tests of samples made of PA2200 and PMMA are provided in Table 3.

Table 3

Mean values of the characteristics obtained from compression tests

Type of material & laser power	**Maximum load [N]**	**Stress [MPa]**	**Specific strain [mm/mm]**	**Young's modulus [MPa]**
PMMA	**7404.00**	**77.77**	**0.08**	**1766.95**
PA2200 3.5 W	4129.59	45.88	0.16	928.43
PA2200 4 W	5320.70	59.12	0.18	1234.99
PA2200 4.5 W	5521.60	61.35	0.15	1297.39
PA2200 6 W	6250.88	63.29	0.12	1403.15
PA2200 7.5 W	6326.96	62.39	0.10	1378.57

As can be seen by analyzing the values presented in Table 3, the mean values of the maximum forces required for the compression tests recorded for the samples made of PA2200 with laser power values between 3.5 W (4 129.59 N) and 7.5 W (6 326.96 N) are lower than those required for samples made of PMMA (7 404 N).

The same tendency is also observed for the value of mean stresses determined in the compression tests. The mean value of the stress levels for PMMA samples (77.77 MPA) were higher compared to those for PA2200 samples. The stress value for PA2200 samples increases from a value of 45.88 MPa, for 3.5 W, to a value of 63.29 MPa for 6 W. As can be seen, the mean value of stresses decreases from 63.29 MPa for samples made of PA2200 with 6 W laser power to 62.39 MPa when the samples are sintered with a laser power of 7.5 W.

The lowest values of the specific strains determined by the compression tests are attained for samples made of PMMA (0.08 mm/mm), while the highest values of the specific strain are obtained for samples made of PA2200 with a laser power of 4 W (0.18 mm/mm), followed by the value reached for SLS with a laser power of 3.5 W (0.16 mm/mm). The increase in the laser power from 4.5 W to 7.5 W results in a decrease in the mean values of specific strain levels in the case of samples made of PA2200 material, from 0.15 mm/mm to 0.10 mm/mm (Fig. 2). The mean values of Young's modulus from the compression tests for samples made of PMMA are the higher (1 766.95 MPa) than the values attained for the samples made of PA2200. In the latter case, the values of Young's modulus increase progressively with an increase in the laser power values. It should be noted that the values of Young's modulus for samples made of PA2200 are within the limits stated in the literature regarding the compression test characteristics determined for parietal bone, [20–22].

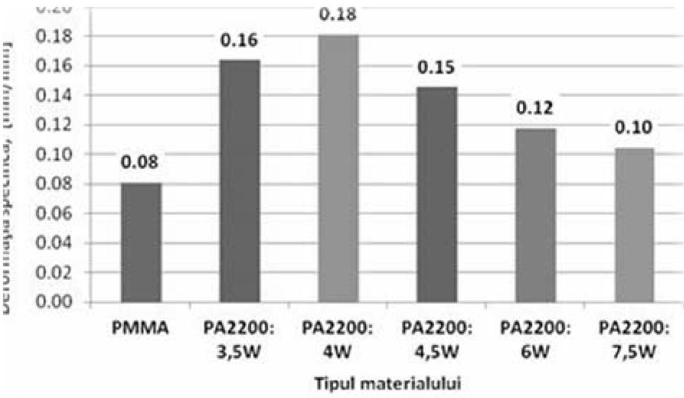


Fig. 2 – Mean values of strain obtained from the compressions tests.

2.2. USE OF EXPERIMENT RESULTS IN A HEALTHCARE MEDICAL DEVICE

From the experimental data regarding the physical and mechanical properties of the two types of material analyzed, it can be concluded that a prototype made from PA2200 by SLS with a laser power of 7.5 W assures the properties and characteristics of a future implant similar to those of a medical implant made of PMMA material by vacuum casting using silicone rubber molds.

All these aspects justify the SLS process as a reliable direct method solution that can be used when a medical implant is required that can be rapidly produced from PA2200. In Fig. 3 an example of a customized medical implant made of PA2200 using SLS for a skull reconstruction surgical operation is presented, employing the Sinterstation 2000 equipment from the National Center of Innovative Manufacturing at TUCN.

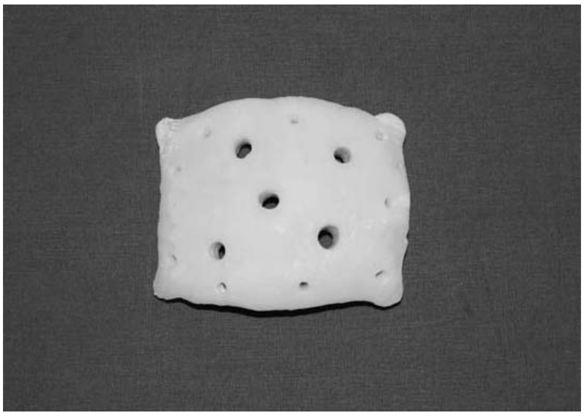


Fig. 3 – Customized medical implant made of PA 2200 using the SLS manufacturing process.

3. RESEARCH EXPERIMENT USING SLM

3.1. TOOLING INSERTS MADE BY SLM

As a case study, the lid component of a grass cutting machine, Fig. 4, manufactured by SLM and experimentally tested, is analyzed. This project comprised a joint effort by TUCN and the Plastor SA Company in Oradea.

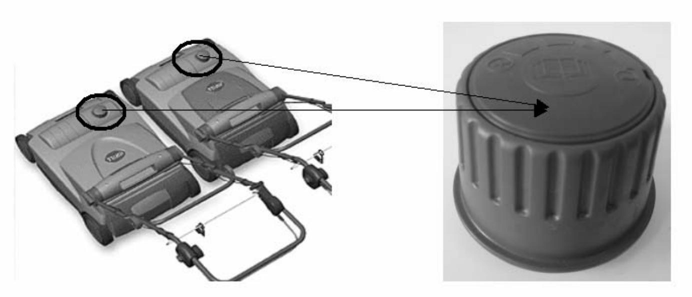


Fig. 4 – Lid component of a grass-cutting machine.

3.2. FINITE ELEMENT ANALYSIS TO DETERMINE THE TECHNOLOGICAL PARAMETERS FOR PLASTIC INJECTION IN THE SLM TOOLS

Finite element analysis (FEA) was used not only to simulate the flow of plastic material to fill the cavity, but also to determine the main process parameters to be used for the injection molding process at Plastor SA Company in Oradea.

This was done for the experiments, and in particular, to determine the clamping forces and injection pressure, characteristics that were required for a second FEA that was undertaken to identify the durability of the injection molding tools made by SLM. Four types of plastic materials were considered for the experiments: acrylonitrile butadiene styrene (ABS), polypropylene (PP), polyamide mixed with glass fibers 30% (PA+30%GF), and polyoxymethylene (POM). The characteristics of these materials were available within the FEA program (MoldFlow) database. The CAD model of the plastic part was loaded into the MoldFlow program, and a mesh with 93,036 elements and 150,06 nodes was generated, as shown in Fig. 5.

Fig. 5 – Mesh details (MoldFlow).

The next important step in the analysis consists of determining the best gate location and fiber orientation during the filling stage of the process. As can be noted from Fig. 6, the program offers as an optimal solution the gate location in the mid area of the part. Thus, the die of the mold will be properly filled and the presence of defects, such as voids in the internal structure of the part, can be avoided. Regarding the fiber orientation, as one may note in the second image of Fig. 6, the fibers are oriented toward the extremities of the part and are uniformly distributed.

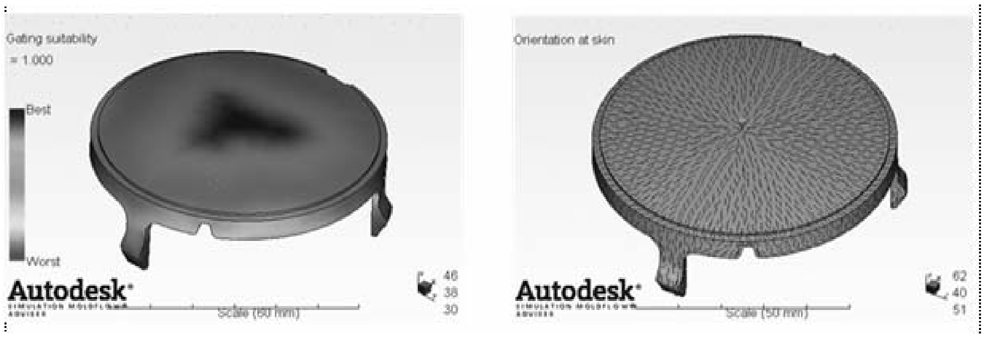


Fig. 6 – Optimal gate location and fiber orientation (Moldflow).

The next stage of the analysis consists of determining of the optimal parameters for all four types of materials to be injected into the molds made by SLM

(ABS, PP, PA + 30% GF and POM). The most important parameters determined are the filling velocity, injection pressure, filling time, cooling time, volumetric shrinkage, and melting temperature at the beginning and end of the filling process. These parameters were determined using Moldflow software based on the injection molding tests undertaken at Plastor SA Company in Oradea, a large manufacturing company in Oradea, using tools manufactured by SLM at TUCN, Romania.

Regarding the values of the injection pressures presented in Fig. 7, it can be noted that these values are not very high. The lowest value of 7.87 MPa was obtained for PP, while the highest value of 29.2 MPa was obtained for ABS. Therefore, the lowest value of the clamping force is needed for PP (1.52 Tf) and the highest value of the clamping force is required for ABS (5.2 Tf). The lowest value of volumetric shrinkage is for ABS (6.9 %), while the highest value of volumetric shrinkage has been reached for POM (14.21 %). The volumetric shrinkage values are important for determining the scaling factors that need to be applied to the injection molding tools manufactured by SLM using the MCP Realized equipment, while the injection pressure and clamping force values are used in the second FEA that was made to estimate the durability of the molds to be made by SLM.

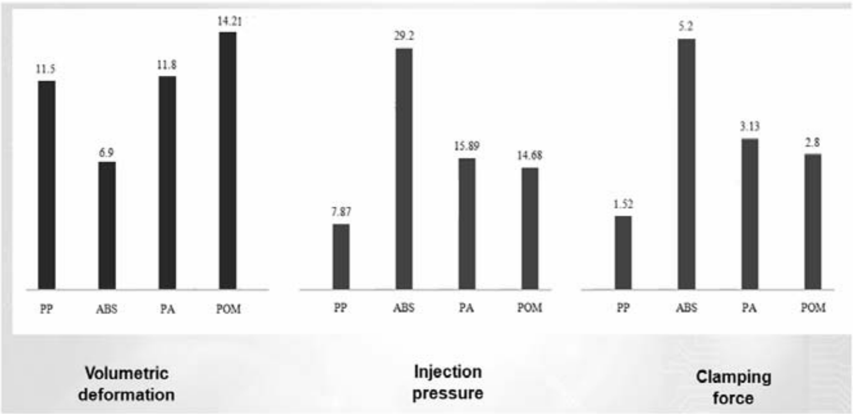


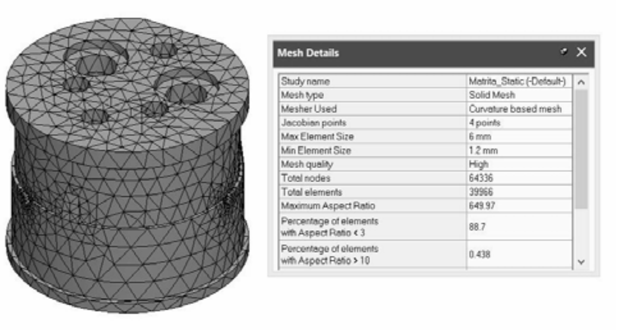
Fig. 7 – Maximum clamping force, injection pressure, and volumetric shrinkage estimated by Moldflow.

3.3. FINITE ELEMENT ANALYSIS TO ESTIMATE THE DURABILITY OF THE INJECTION MOLDING TOOL MADE BY SLM

The first step of the analysis, made using the SolidWorks simulation program, was an estimation of the durability of the injection molding tool made by SLM. This step consisted of loading the CAD models of the punch and die (as an assembly unit) into the program, and mesh generation as shown in Fig. 8.

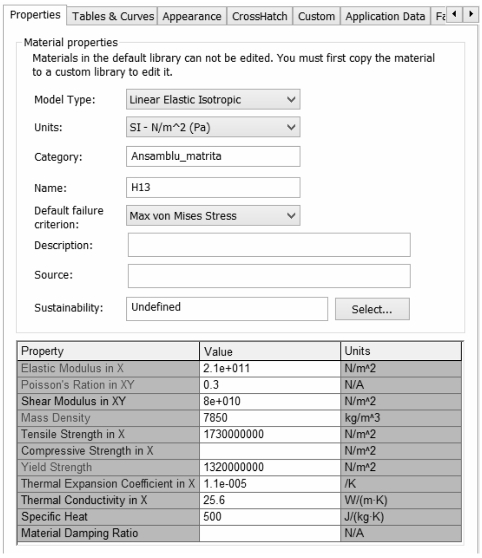
The FEA consisted of two stages: (i) static analysis, and (ii) fatigue analysis.

Within the first stage of the analysis, the mechanical and thermal characteristics of the metallic powder (H13 material) were introduced into the FEA, as illustrated in Fig. 9. The values, as specified by the producer of this type of powder, which is commercially available [www 01], were as follows: thermal expansion coefficient, $\alpha = 25.6$ W/m/K; Poisson coefficient, $\upsilon = 0.3$; Young's modulus, $G = 137$ GPa; mass density, $\rho = 7.85$ g/cm^3; fracture strength' $\sigma_r = 1\ 730$ MPa; yield strength, $\sigma_c = 1\ 320$ MPa.



Study name	Matrita_Static (-Default-)
Mesh type	Solid Mesh
Mesher Used	Curvature based mesh
Jacobian points	4 points
Max Element Size	6 mm
Min Element Size	1.2 mm
Mesh quality	High
Total nodes	64336
Total elements	39966
Maximum Aspect Ratio	649.97
Percentage of elements with Aspect Ratio < 3	88.7
Percentage of elements with Aspect Ratio > 10	0.438

Fig. 8 – Mesh generated in the SolidWorks program.



Material properties

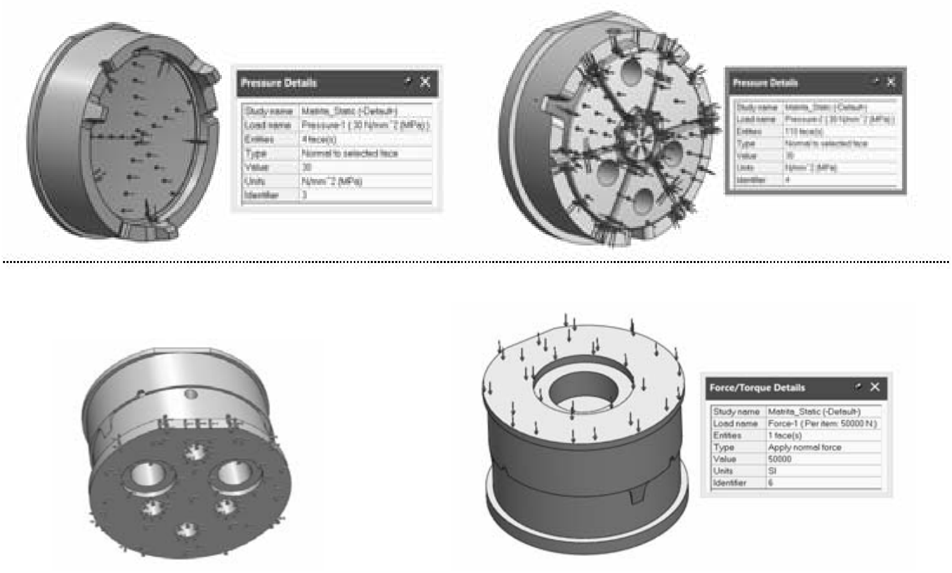
Materials in the default library can not be edited. You must first copy the material to a custom library to edit it.

Model Type: Linear Elastic Isotropic
Units: SI - N/m^2 (Pa)
Category: Ansamblu_matrita
Name: H13
Default failure criterion: Max von Mises Stress
Description:
Source:
Sustainability: Undefined

Property	Value	Units
Elastic Modulus in X	2.1e+011	N/m^2
Poisson's Ration in XY	0.3	N/A
Shear Modulus in XY	8e+010	N/m^2
Mass Density	7850	kg/m^3
Tensile Strength in X	1730000000	N/m^2
Compressive Strength in X		N/m^2
Yield Strength	1320000000	N/m^2
Thermal Expansion Coefficient in X	1.1e-005	/K
Thermal Conductivity in X	25.6	W/(m·K)
Specific Heat	500	J/(kg·K)
Material Damping Ratio		N/A

Fig. 9 – Characteristics of the H13 material used in the finite element analysis.

The next step of the analysis consisted of establishing constraints, including the movement restrictions (the punch is fixed in the injection molding process, and the die element is mobile), and technological restrictions shown in Fig. 10. The injection pressure and clamping force values were input as they were determined within the analyses performed in MoldFlow. The higher stress conditions given by the maximum values of the pressures and forces determined were taken into consideration as acting on the active surfaces of the molding tools shown in Fig. 10.



Pressure Details

Study name	Matrita_Static (-Default-)
Load name	Pressure-1 (30 N/mm^2 (MPa))
Entities	4 face(s)
Type	Normal to selected face
Value	30
Units	N/mm^2 (MPa)
Identifier	3

Pressure Details

Study name	Matrita_Static (-Default-)
Load name	Pressure-2 (30 N/mm^2 (MPa))
Entities	110 face(s)
Type	Normal to selected face
Value	30
Units	N/mm^2 (MPa)
Identifier	4

Force/Torque Details

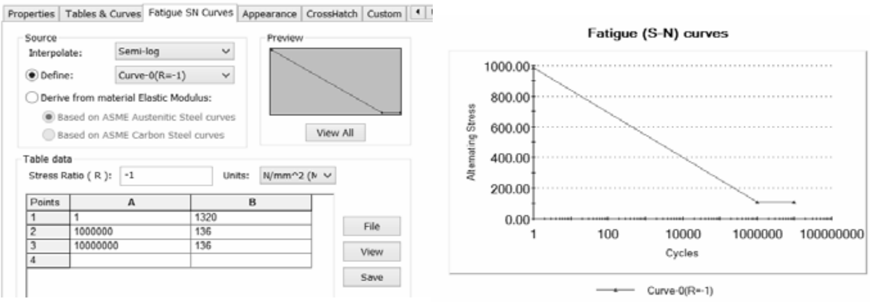
Study name	Matrita_Static (-Default-)
Load name	Force-1 (Per item: 50000 N)
Entities	1 face(s)
Type	Apply normal force
Value	50000
Units	SI
Identifier	6

Fig. 10 – Constraints imposed for the finite element analysis.

After running the static analysis, the values obtained for the displacements and the von Mises stresses and strains (see Fig. 11) were relatively low (e.g., maximum displacement was lower than 0.05 mm; this value refers to the tolerance limits of the SLM machine, as specified by the equipment manufacturing company). The value of the maximum stress obtained (418.83 MPa), as shown in Fig. 11, was within admissible limits (σ_c =1 320 MPa; see Fig. 9).

Fig. 11 – Results obtained from the static analysis (SolidWorks simulation).

For the second analysis, focusing on estimating the durability of the molds, the results of the static analysis and the S-N material curve are presented in Fig. 12.



Source
Interpolate: Semi-log
● Define: Curve-0(R=-1)
○ Derive from material Elastic Modulus:
● Based on ASME Austenitic Steel curves
○ Based on ASME Carbon Steel curves

Table data
Stress Ratio (R): -1
Units: N/mm^2 (N

Points	A	B
1	1	1320
2	1000000	136
3	10000000	136
4		

Fig. 12 – S-N curve defined within finite element analysis.

According to the literature, the first cycle of the S-N curve corresponds to the yield strength of the material ($\sigma_c = 1320$ MPa). The stress amplitude corresponding to several 10^6 cycles on the S-N curve was determined using the hardness of the material ($\sigma_{10^6} = 0.25 \cdot \mathrm{HB} = 136$ MPa).

The results presented in Fig. 13 show that the mold has a durability of 149,942 cycles, with a safety factor of 2.241. This is an acceptable value that can be considered suitable for the rapid product development of parts to be injected in a medium batch using molds produced by SLM.

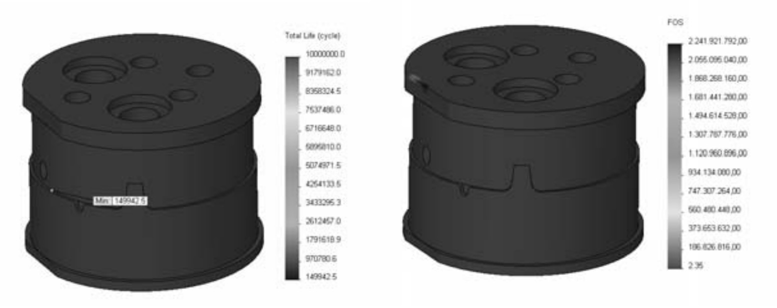


Fig. 13 – Total life-cycle and safety factor estimated by the SolidWorks simulation program.

3.4. MANUFACTURING OF THE INJECTION MOLDING TOOLS BY SLM AND TESTS ON TOOL BEHAVIOR

To manufacture tools using SLM, the models were transferred to the MCP Realizer SLM 250 machine and the required supports were generated as shown in Fig. 14. “Block” type supports were used for both the punch and die; this type of support is strong enough to sustain the parts and easy to remove after the manufacturing process completed.

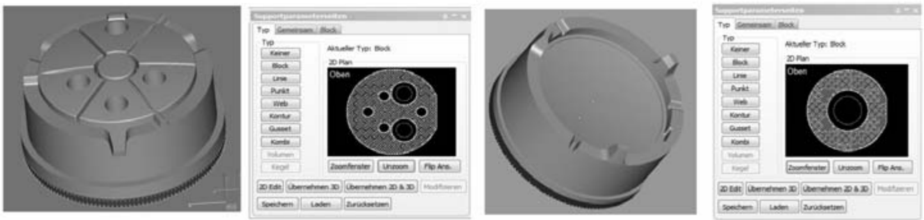
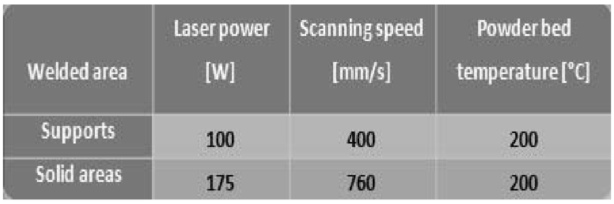


Fig. 14 – Supports generated by Magics software.

The next important step was to upload the parts and the supports generated in the controlling software of the machine, placing and orienting the parts in the working platform, and the slicing the model (the layer thickness was 50 µm in this case). The scanning strategy “stripes with skin” was considered suitable for these types of tooling elements (the scanning of layers in this strategy is done consecutively along the X and Y-axes at two consecutive layers), and the technological parameters in terms of the laser power and scanning speed were set as presented in Fig.15. As can be noted from Fig. 15, the parameters used were different for the solid areas of the manufactured parts and the supports. The working platform (powder bed temperature) was preheated and set at 200 °C, this value being constant throughout the entire process until the last layer of the manufactured parts (the maximum Z-level) was reached.



Welded area	Laser power [W]	Scanning speed [mm/s]	Powder bed temperature [°C]
Supports	100	400	200
Solid areas	175	760	200

Fig. 15 – Technological parameters used in the manufacturing of the punch by SLM.

The atmosphere in working chamber of the machine was inert. Argon gas at a high pressure (10 bar) was used and the admissible level of oxygen was 0.2%. The tooling parts made by SLM using the MCP Realized SLM 250 equipment from TUCN are presented in Fig. 16.

To perform the injection molding tests, Plastor SA Company in Oradea manufactured the fixing plates shown in Fig. 17. The injection molding tests were performed using the Arburg 370CMD 800–325 plastic injection machine from Oradea with the technological parameter settings as determined in the analysis that was undertaken in MoldFlow.

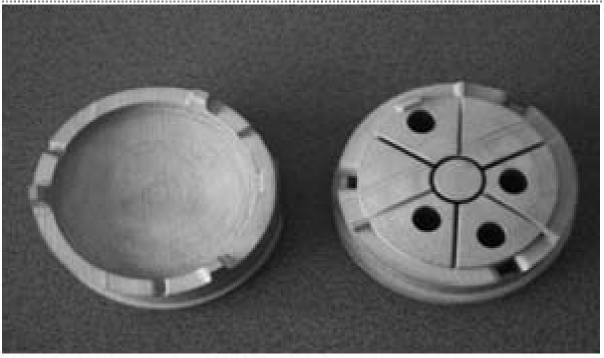


Fig. 16 – Tooling parts made by SLM at TUCN.

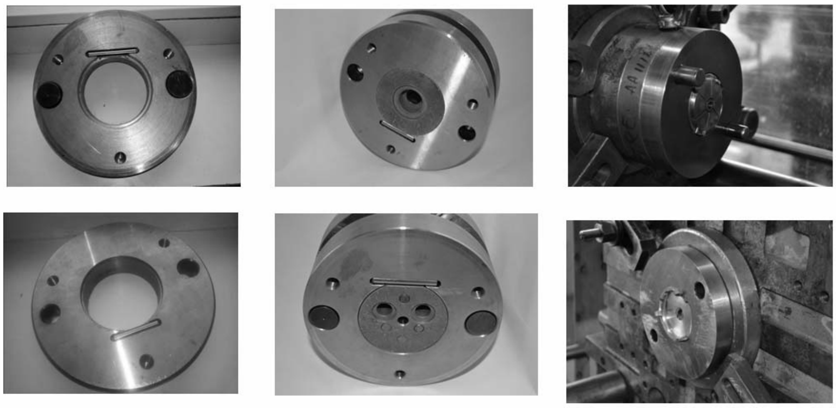


Fig. 17 – Tooling plates and tooling inserts made by SLM at TUCN mounted onto the plates.

The main aim of the tests was to determine the behavior and reliability of the tools made by SLM for the injection process of the 4 types of plastic material (ABS, PP, PA +30% GF, POM). Some dimensional contractions were observed, especially in the case of ABS. Much better rigidity was observed for PA compared to the other materials tested. The higher rigidity could be explained by the composition of the material (this type of material has 30 % GF in its composition). PP was acceptable in terms of shrinkage and rigidity. POM proved to be the best from the point of view of shrinkage, rigidity, and general behavior in the injection molding process. In this case spraying for demolding was not required before each injection process of a part. The good behavior of this type of plastic for the plastic injection process is explained by the elasticity modulus which is much higher than the other materials that were tested. The tools and plastic injected parts made of ABS, PP, PA +30% GF and POM using molding inserts made by SLM at TUCN are presented in Fig. 18.

Fig. 18 – Tooling plates and tooling inserts made by SLM at TUCN mounted onto the plates.

4. SUMMARY AND CONCLUSIONS

This study examines two technologies, SLS and SLM, related to AM. AM is one of the principal factors in the Industry 4 era, and this study demonstrated effective usage in both laboratory settings and in real-world production of such technologies. The Industry 4 era is associated with the need for manufacturing organizations to fit their technology and adjust their manufacturing processes to fast changes in the global markets. However, there are knowledge gaps and tremendous costs. This study contributes to a reduction in the knowledge gap in applying AM in the Industry 4 era.

SLS technology with relevant materials is used in a set of experiments described in this paper. The other technology, SLM, is used in a second series of experiments to produce an injection molding tool. These experiments are followed by FEA and a set of experiments to identify optimal injected plastic materials.

The SLS technology is analyzed first, as described in Section 3. This includes an analysis of the comparative physical and mechanical properties of samples made of PA2200 compatible powder using different values of laser power (from 3.5 W to 7 W). A comparison is made with samples made of PMMA produced by vacuum casting using silicone rubber molds. It is demonstrated that most of the physical and mechanical properties obtained for samples made of PA2200 are superior to those obtained for samples made of PMMA, even though Young’s modulus values determined by testing the tensile strength of the samples are 45 % higher for PMMA than for PA2200 material with a laser power of 7.5 W. The values obtained are within the interval limits of values recommended in the literature for parietal bone.

The conclusion is that by using SLS technology it is possible to manufacture different types of prosthetic elements made of PA2200 in a direct variant method that is rapid and efficient, and presents physical and mechanical properties that are adequate and even superior to those of PMMA manufactured using an indirect variant method by vacuum casting in silicone rubber molds. The SLM experiments are described in Section 4. It is demonstrated that this process is suitable for the production of tooling inserts and molds when several thousand parts need to be rapidly produced by injection molding.

The finite element analysis method combined with the MoldFlow program proves useful: (i) in determining of the technological parameters to be used for testing the mold, and (ii) as a very powerful tool for the estimation of the durability (tool life) of a mold made by SLM from H13 tool steel material. As estimated by the SolidWorks simulation analysis performed using the technological parameters obtained in the MoldFlow program for the injection process (injection pressure and clamping force), such a tool made by SLM from H13 tool steel has a durability of a maximum of 149,942 cycles in the experiments in this case, in which four types of plastic used for these experiments (ABS, PP, PA + 30 % GF and POM) are used for injection molding of the lid component of a grass cutting machine. This has been tested and produced by a large manufacturing organization, Plastor SA Company in Oradea, Romania.

The injection molding tools made by SLM from H13 tool steel at the Technical University of Cluj-Napoca, using the MCP Realizer II SLM 250 equipment are the first to have been made and tested in Romania. This fact, together with the experiments conducted at Plastor SA Company in Oradea, reduce the knowledge gap in applying AM. The methodology presented in the article for estimating the durability of a mold produced by SLM and determining the appropriate type of plastic and technological parameters to be used in the injection molding process, has proved to be a reliable solution. This solution could be followed in other cases in which a rapid decision needs be made for developing a new product. The appropriate metallic material should be selected. Also, the plastic of which the product is made should be closely linked to the functional role of the part, its shape, and the durability (tool life) of the injection molding tool.

The experimental research developed and performed has provides results and conclusions that demonstrate the efficiency of the AM methods SLS and SLM for the rapid manufacturing of new products made of nonmetallic and metallic materials, with applicability in the medical field (for the production of different types of customized prosthesis) and the industrial field (for the production of different types of tools for medium batch series production of plastic parts using the injection molding process).

Acknowledgements. This paper was supported by Romanian Ministry of Research and Innovation (UEFISCDI), Project cod PN-III-P1–1.2–PCCDI–2017–0224 (no. 77PCCDI/2018, DigiTech) within PNCDI III programme

Received on December 5, 2019

REFERENCES

1. Royal Academy of Engineering, *Additive manufacturing: opportunities and constraints*, A Summary of a round table, Royal Academy of Engineering, 2013, www.raeng.org.uk/am

2. BERCE, P., BALC, N., CAIZAR, C., PACURAR, R., RADU, A.S., BRATEAN, S., FODOREAN, I., *Additive manufacturing technologies and their applications*, Rom. Acad. P. House, Bucharest, 2014.
3. PODARU, G., *Studies regarding the behavior of the sealing cuff from the pneumatic cylinders with rods made of polymeric materials*, Dissertation, "Dunărea de Jos" University of Galaţi, 2013.
4. ZHANG, J. C., LU, H. Y., LV, G.Y., MO, A.C., YAN, G., HUANG, C. (2010) *The repair of critical size defects with porous hydroxyapatite/polyamide nanocomposite: an experimental study in rabbit mandibles*, Journal of Oral and Maxillofacial Surgery, **39**, pp. 469–477, 2010.
5. EOS GmbH, *Material data sheet: PA2200* -https://www.protolabs.de/media/1012845/pa-2200.pdf
6. BREUNINGER, J., BECKER, R., WOLF, A., ROMMEL, S., VERL, A., *Generative Fertigung mit Kunststoffen, Konzeption und Konstruktion fur Selectives Lasersintern*, Springer Vieweg, Berlin Heidelberg, 2013.
7. SINGH, J.P., MOHAN, P.P., *Fitment study of porous polyamide scaffolds fabricated from selective laser sintering*, 3rd International Conference on Tissue Engineering, (ICTE2013); Procedia Engineering, **59**, pp. 59–71, 2013.
8. HOPKINSON, N., DICKENS P., *Conformal cooling and heating channels using laser sintered tools*, Proceedings of the Solid Freeform Fabrication Symposium, pp. 490–497, 2000.
9. AHN, D.G, *Applications of laser assisted metal rapid tooling process to manufacture of molding & forming tools – state of the art*, International Journal of Precision Engineering and Manufacturing, **12**, pp. 925–938, 2011.
10. HONG-SEOK, P., XUAN-PHUONG, D, *Development of a smart plastic injection mold with conformal cooling channels*, Procedia Manufacturing, **10**, pp. 48–59, 2017.
11. COSMA, C., BALC, N., BERCE, P., POPAN, A., COSMA, A., BURDE, A., *Direct manufacturing of customized implants from biometals by 3D printing*, Acad. J. of Manufact. Eng., **15**, pp. 42–49, 2017.
12. DIMLA, D.E, CAMILOTTO, M., MIANI, F, *Design and optimization of conformal cooling channels in injection molding tools*, Journal of Mat. Process. Technology, **164–165**, pp. 1294–1300, 2005.
13. SAIFULLAH, A.B.M., MASOOD, S.H., SBARSKI, I., *Thermal-structural finite element analysis of injection molding dies with optimized cooling channels*, Mat. Sci. Forum, **654–656**, pp.1646–1649, 2010.
14. SLM Solutions GmbH – *H13 material datasheet and characteristics* – https://slm-solutions.com/sites/default/files/downloads/201en171023-01-001-powder_web.pdf
15. JACOBS, P. F., *New frontiers in mold construction: High conductivity materials & conformal cooling channels*, Rapid Prototyping, Rapid Tooling, and Solid Freeform Fabrication for the Next Millennium, ASME-Publications-MED, **11**, pp. 389–396, 2000.
16. AU, K.M., YU, K.M., *A scaffolding architecture for conformal cooling design in rapid plastic injection molding*, Int. Journal of Adv. Manufacturing Technology, **34**, pp. 496–515, 2007.
17. SANJAY, K, SISA, P., *Laser-based additive manufacturing of metals*, Advanced Materials Research, **227**, pp. 92–95, 2011.
18. MAZUR, M., MARTIN, L., McMILLAN, M., BRANDT, M., *SLM additive manufacture of H13 tool steel with conformal cooling and structural lattices*, Rapid Prototyping Journal, **22**, pp. 504–518, 2016.
19. BORZAN, C., *Theoretical and experimental research regarding manufacturing by selective laser sintering of custom implants from biocompatible materials*, PhD Thesis, UTCN, 2014.
20. ROBBINS, D.H, WOOD, J.L., *Determination of mechanical properties of the bones of the skull,* Experimental Mechanics, **9**, *5*, pp. 236–240, 1969.
21. McELHANEY, J.H, FOGLE, J.H, MELVIN, W.J, HAYNES, R.R, ROBERTS, L.V., ALEM, N.M., Mechanical properties of cranial bone, Journal of Biomechanics, **3**, pp. 495–511, 1970.
22. BORUAH, S., HENDERSON, K., SUBIT, D., SALZAR, R.S., SHENDER, B.S., PASKOFF, G., *Response of human skull bone to dynamic compressive loading*, 2013 IRCOBI Conference Proceedings, Gothenburg (Sweden), September 11–13, 2013.