

## RESEARCH ON THE DURABILITY OF INJECTION MOLDING TOOLS MADE BY SELECTIVE LASER SINTERING TECHNOLOGY

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The paper presents an Additive Manufacturing (AM) technology that is suitable for tooling preparation of the medium volume production. A case study developed within National Center of Rapid Prototyping from Technical University of Cluj-Napoca (TUC-N) and Plastor SA Company from Oradea, focused on the manufacturing of the injection molding tools by selective laser sintering (SLS) technology has been analyzed. Finite element analysis method has been successfully used to determine the technological parameters for the plastic injection into the SLS tools. These parameters were introduced within a second finite element analysis that has been done to determine the durability of the molds made by SLS technology by the theoretical point of view. The injection molding tools made at Technical University of Cluj-Napoca were successfully tested at Plastor SA Company from Oradea, proving the fact that the Selective Laser Sintering technology is a reliable solution in the case when tens of thousands of plastic parts needs to be rapidly injected.

*Key words:* additive manufacturing, rapid tooling, selective laser sintering, finite element analysis, injection molding.

### 1. INTRODUCTION

It is well known the Selective Laser Sintering (SLS) process and technology, which can be used to produce complex parts in different type of materials [1], [2]. Selective Laser Sintering (SLS) is a layer – wise material additive manufacturing (AM) technique that allows the possibility to manufacture complex 3D parts by selectively consolidating successive layers of powder material on top of each other, by using the thermal energy supplied by a focused and computer controlled laser beam [3, 4]. Over the last decade, the SLS process has gained a widely acceptance as an Additive Manufacturing technique. Due to technical improvements, better process control and the possibility to process all kind of metals, a shift to Rapid Tooling (RT) and Rapid Manufacturing (RM) came up in recent years [5, 6]. Many applications could take advantage of this evolution by using the SLS technology, not only for visual concept models and onetime functional prototypes, but also for tooling molds, tooling inserts and end-use functional parts with long-term consistency [7].

As related to the Selective Laser Sintering (SLS) process, there are a number of input parameters that can be controlled and modified in order to get different characteristics of the sintered parts [8, 9]. Systematic investigation of wear behavior of selective laser sintering (SLS) materials has been investigated by the researchers. One of the main conclusions was that the LaserForm metallic powder material (commercially available) is a better SLS wear material, as compared with DirectSteel material. The wear performance is governed not by the hardness of the materials, but by their composition [10]. There was also other reported research on the wearing of SLS metallic parts, which is influenced mainly by one of the typical phenomena that appears in the selective laser sintering (SLS) process during the second cycle that has to be followed in the oven, when at 1070 °C, bronze is infiltrated into the parts, The mechanical characteristics (mechanical resistance) of the SLS products are mainly influenced during this second stage of post-processing in the oven, due to the resulted porosity in the material structure, which in some cases could be more than 20% [11].

There are some solutions that could be applied in order to decrease the porosity of the metallic parts made by SLS, but the possibility of controlling the porosity is still representing an important issue to be solved [12, 13, 14]. The presented work focused on investigating the resulted porosity within the internal structure of metallic parts made by SLS. The main objective of the presented work was focused on the durability of the porous injection molding tools made by SLS process. Actually, by knowing several important mechanical and thermal characteristics of the metallic material (density, fracture strength, thermal expansion coefficient, etc.), and using finite element analysis method, the Moldflow and CosmosWorks FEA programs were successfully jointly used for predicting the durability of such an injection molding tool made by SLS, for medium volume production. The case study (lid component of a grass cutting machine (presented in Figure 1) has been analyzed, manufactured by SLS and finally experimentally tested, within a project work, jointly at the Technical University of Cluj-Napoca and Plastor Company from Oradea. The proposed method can be successfully applied on any other similar injection molding tool made by Selective Laser Sintering (SLS).

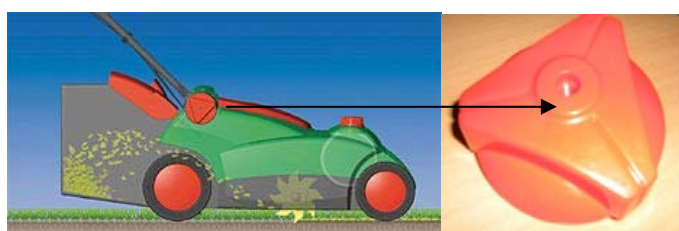


Fig. 1 – Lid component of a grass-cutting machine.

## 2. FINITE ELEMENT ANALYSIS TO DETERMINE THE TECHNOLOGICAL PARAMETERS FOR PLASTIC INJECTION INTO THE SLS TOOLS

The Moldflow software was used to simulate the molten plastic flowing to fill up the cavity. The main purpose of this simulation was to find out some information regarding the technological parameters that have to be used within the injection molding process.

The model of the part prototype has been loaded into the Moldflow finite element analysis program and a mesh with 8 097 elements and 4 050 nodes has been generated, as illustrated in Fig. 2. The next step of the analysis consisted in the specification of the type of plastic material that will be injected. On the Plastor SA (beneficiary request), the selected material was Schulamid PA6 (30% Glass), having 260°C as maximum melting temperature and 60°C, as the recommended mold's temperature.

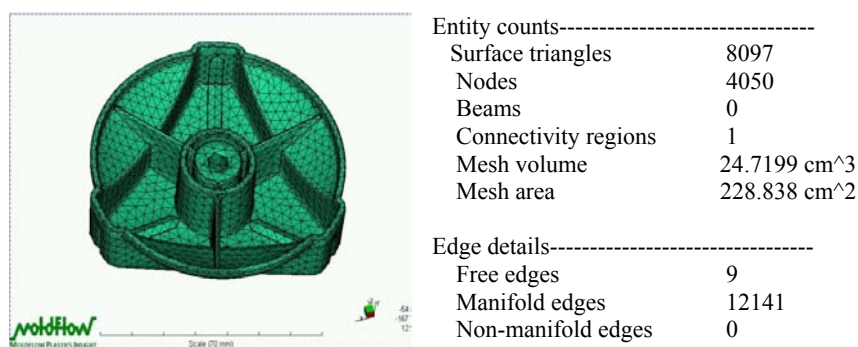


Fig. 2 – Mesh details (MoldFlow).

A preliminary analysis was made on this stage, related to the best gate location and the plastic fiber orientation during filling the molds, as illustrated in Fig. 3. After the gate location is selected, the filling analysis can continue with the purpose of finding the optimal technological parameters used within the injection molding process. The average velocity, the injection pressure, the filling time or the temperatures at flow are only few of these parameters that can be determined by using MoldFlow software (Fig. 4).

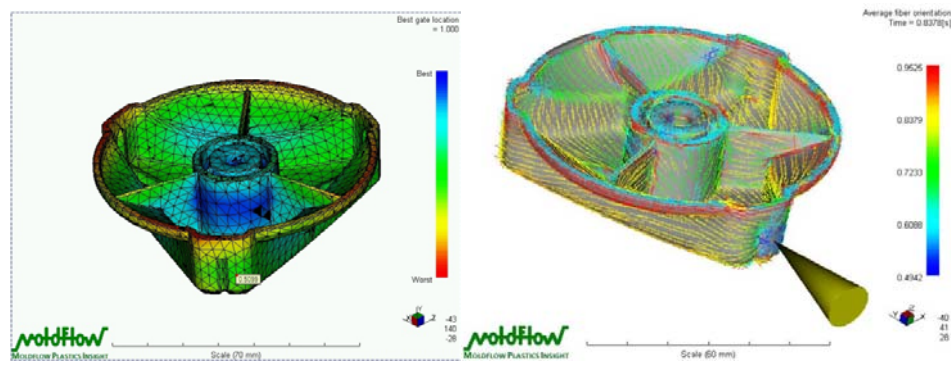


Fig. 3 – Best gate location and fiber orientation (Moldflow).

There are also other important parameters that were determined within the made analysis, such as the maximum clamping force and volumetric shrinkage at ejection (Fig. 5). The maximum clamping force value has been decisive in the selection of injection molding machine to be used for the experimental tests. A Krauss Maffei 90/340A injection molding machine has been selected for testing the SLS tools.

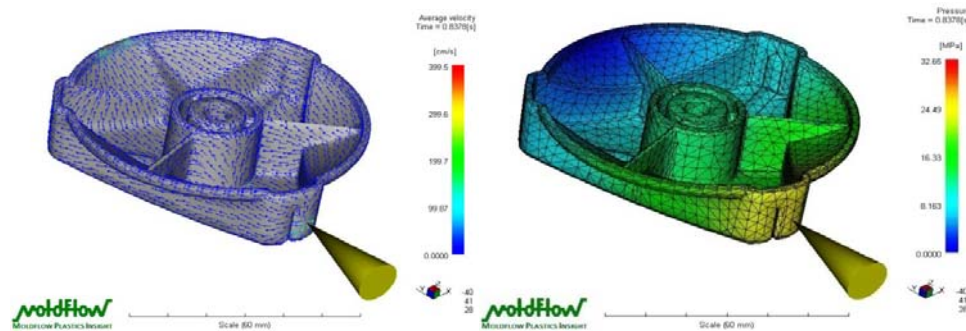


Fig. 4 – Velocity and injection pressure (Moldflow).

The volumetric shrinkage value has been decisive for compensating the shrinkage that occurs in the injection molding process, by applying supplementary scale factors onto the injection molding tools to be manufactured by SLS on the Sinterstation 2000 equipment from the Technical University of Cluj-Napoca.

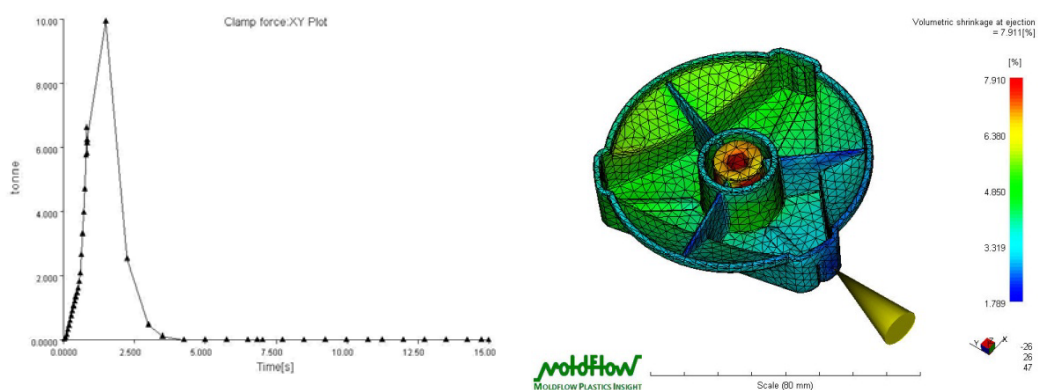


Fig. 5 – Maximum clamping force and volumetric shrinkage, as estimated by Moldflow.

The technological parameters that were determined within Moldflow software were used accordingly on the injection molding tests that were made at Plastor SA Company from Oradea, by using the tools that were manufactured by SLS at the Technical University of Cluj-Napoca, Romania. Meanwhile, the value of injection pressure and clamping force were needed for the second finite element analysis that has been done in order to determine the durability of injection molding tool made by SLS.

### 3. FINITE ELEMENT ANALYSIS TO ESTIMATE THE DURABILITY OF INJECTION MOLDING TOOLS MADE BY SLS

For performing the finite element analysis, first of all, the CAD model of the SLS tool (the punch) has been loaded into the CosmosWorks program and the mesh was generated, as illustrated in Figure 6.

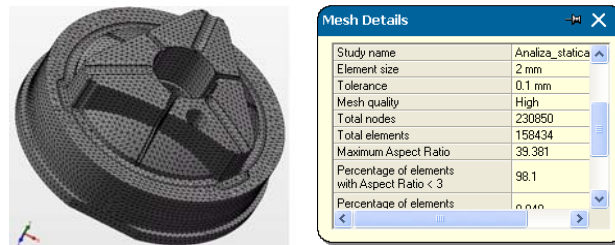


Fig. 6 – The mesh generated within CosmosWorks program.

The finite element analysis consisted in two stages, as presented below:

- the first stage consisted in a static analysis
- the second stage consisted in the fatigue strength analysis

Within the first stage of the made analysis, the mechanical and thermal characteristics of the metallic powder (Laserform St-100 material) presented below, were introduced into the finite element analysis, as illustrated in Fig. 7, as it were specified by the producer of this type of powder that is commercially available [15]: thermal expansion coefficient:  $\alpha = 12,4 \times 10^{-6} \text{ m/m/}^{\circ}\text{C}$ ; poisson coefficient:  $\nu = 0,3$ ; Young modulus:  $G = 137 \text{ GPa}$ ; mass density :  $\rho = 7.7 \text{ g/cm}^3$ ; fracture strength:  $\sigma_r = 510 \text{ MPa}$ ; Yield strength:  $\sigma_c = 305 \text{ MPa}$ ; Laserform St-100 material was the raw material used for the manufacturing of the punch on the SLS machine. Laserform St-100 metallic powder is basically a steel-alloyed material, having the chemical composition as indicated in Fig. 7.

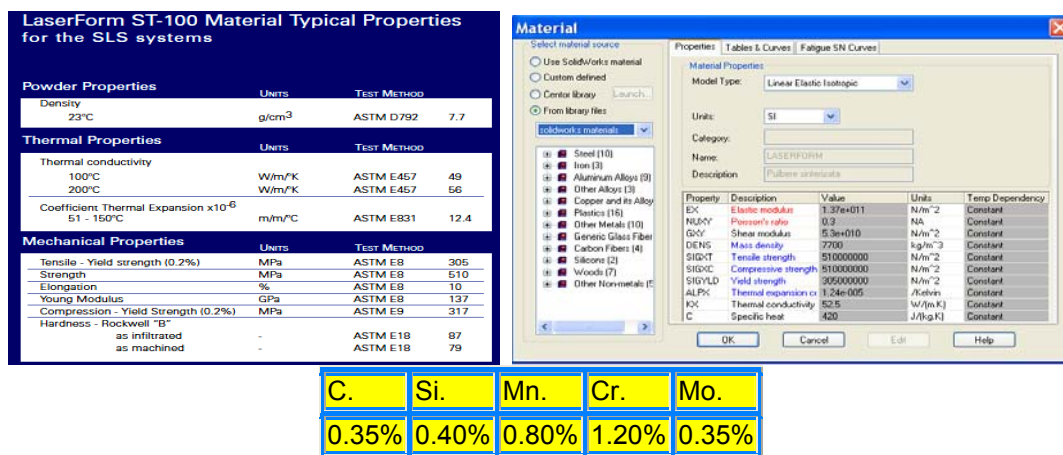


Fig. 7 – Materials characteristics of the Laserform St-100 metallic powder introduced within the finite element analysis.  
Chemical composition of Laserform St-100 material [15].

The next step of the analysis consisted in the establishment of the tool restrictions on X – Y and Z-axes that were specified, as it were determined within the Moldflow analysis.

The injection pressure determined within the MoldFlow analysis was 32 MPa (Fig. 4). For the determination of the pressure that is applied on the contact area of the SLS tool, a calculus was made, consisting in the dividing of the applied force (10 Tf, Fig. 5) and the area of the surface indicated in Fig. 8 (2 343 mm<sup>2</sup>, as can be determined with the Measuring tool option of SolidWorks program). By doing this calculus, the conclusion was that a pressure of 43 MPa will be applied on the indicated surface area (closing area of the SLS tool) indicated in Fig. 8.

The von Mises equivalent stress has been calculated according to the 5<sup>th</sup> theory of the material strength for multi-axial stresses:

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

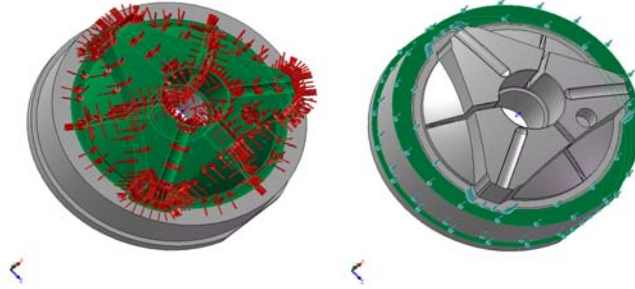


Fig. 8 – Injection pressure and applied pressure on the surface area (CosmosWorks).

In formula (1), if we consider that the tangent stresses are equal:

$$\tau_{xy} = \tau_{zx} ; \tau_{yz} = \tau_{zy} ; \tau_{xy} = \tau_{yx} \quad (2)$$

a particular state of uniaxial stress is obtained. This simplified formula is used within CosmosWorks program in order to perform the finite element analysis.

The stress energy was calculated in this case according to formula (3):

$$E_{def} = \frac{1}{2} \sigma_{ech} \times \varepsilon_{ech}, \quad (3)$$

where:  $E_{def}$  – represents the stress energy;  $\sigma_{ech}$  – equivalent stress von Mises;  $\varepsilon_{ech}$  – equivalent deformation. The results obtained within the static analysis illustrated in Figure 9 were in normal limits, with a tool stress and displacement, in accordance with the tolerances of the SLS equipment. The results obtained within the static analysis were needed for the second stage of the finite element analysis (fatigue strength analysis). In order to determine the lifetime of the SLS tool, the S-N characteristic material curve (Wohler's diagram) has to be determined, as illustrated in Fig. 10 [16], where  $S'_f$  represents the yield strength of the material ( $\sigma_c$ ), that, according to the characteristics of material provided by the metallic powder producer is  $\sigma_c = 305 \text{ N/mm}^2$  [15]. This value corresponds to a  $10^0 = 1$  cycle in the Wohler's diagram.

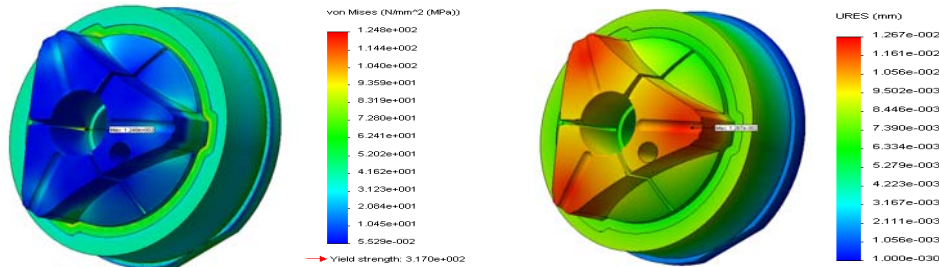


Fig.9. The results obtained within the static analysis (CosmosWorks)

The stress amplitude  $S_{FL}$  that corresponds to a number of  $10^6$  on the Wohler's diagram, can be calculated according to the formula (4):

$$S_{FL} = 0.25 \cdot HB \quad (4)$$



where HB represents the Brinell Hardness [15].

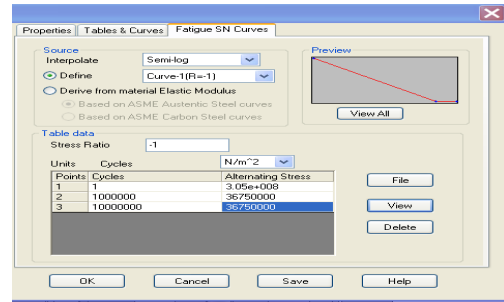
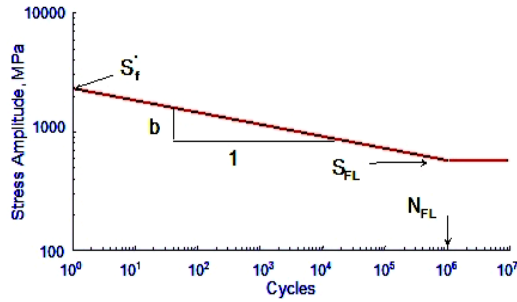


Fig. 10 – The S-N curve (Wohler's diagram) [15].

Fig. 11 – The S-N curve – characteristics defined within FEA.

According to the material characteristics provided by the producer of Laserform St-100 metallic powder, the hardness of the material is 79 HRB, where HRB represents the Rockwell B hardness [15]. Conversion from HRB to HB can be made, by using the formula (5) [17]:

$$HB = 2.394HRB - 42.7 = 2.394 \cdot 79 - 42.7 = 146.62HB. \quad (5)$$

For safety reasons, within the finite element analysis, a value of 147 HB has been considered. The stress amplitude can be now calculated according to formula (4), so as for 10<sup>6</sup> cycles, for  $S_{FL}$  it corresponds a value of  $36,75 \cdot 10^6$  N/m<sup>2</sup>. This value has been introduced within the finite element analysis as illustrated in Fig. 11. The finite element analysis can be performed now, so as at the end we could estimate the durability of the SLS tool (the life cycle) and the safety factor, as well. As we could observe from Fig. 12, as estimated, the durability of the SLS tool is 31,600 cycles, with a safety factor of 1.697.

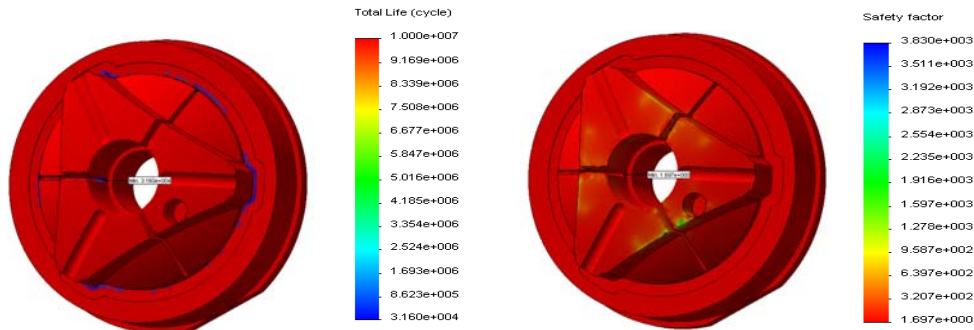


Fig. 12 – The total life-cycle and the safety factor, as estimated by CosmosWorks program.

#### 4. THE MANUFACTURING OF THE INJECTION MOLDING TOOLS BY SLS AND TESTS ON TOOL BEHAVIOR

The virtual model of the SLS tool was transferred to the Sinterstation 2000 machine from the Technical University of Cluj-Napoca, illustrated in Fig. 14 and manufactured from Laserform St-100 material, using the technological parameters indicated in Table 1. After manufacturing on the SLS machine, the SLS tools went into a post-process stage that is obligatory needed in the oven as illustrated in Fig. 14.

While post processing in the oven, the steps presented bellow was followed in a strictly way:

- Melting (burning out) the polymer (at 450°C–650°C), which was surrounding the metal grains.
- Get fully sintered metallic tools, while increasing the temperature to about 700°C.
- Infiltrating with bronze, at 1070°C (this temperature was maintained for 5 hours).
- Cooling down the tools (natural / slow cooling).

Table 1

Technical parameters used within the manufacturing process of the punch made by SLS

Parameter	Values and measuring units
Scale factors	X=1.02054, Y=1.02144, Z=1.00950
Fill laser power	28W
Slicer fill scan spacing	0.08 mm
Powder layer thickness	0.08 mm
Manufacturing temperature	98°C



Fig. 14 – Sinterstation 2000 equipment.



Fig. 15 – SLS post processing in the oven.

There were some dimensional contractions during the SLS process and post processing. That is why, it was necessary to carry out finishing operations to the punch and die afterwards. These finishing operations were performed at Plastor SA Company from Oradea, using some hand tools for finishing, in order to obtaining a perfect close of the tools.



Fig. 16 – Injection molding machine (Plastor SA) and punch (made at TUCN), at work.



Fig. 17 – The injection molded parts using the SLS tool.

The tests of the SLS tools behavior were made at SC Plastor SA, using a Krauss Maffei 90/340 A injection molding machine, using the technological parameters determined within the Moldflow analysis. The punch's plate was fixed onto the mobile assembly of the injection molding machine and the die's plate onto the fixed assembly of the injection molding machine, as illustrated in Fig. 16. The injection molding tests were made using a polyamide PA 6 + 30 % fiber glass material. Approximately 30,000 parts were successfully injected. Few injection molded parts (using the SLS tool) are presented in Fig. 17.

## 5. CONCLUSIONS

The innovative method presented in the paper has proved to be a very useful tool not only to determine the technological parameters needed in the plastic injection process, but also to determine the durability of the SLS tools, as well. This method can be easily applied on any other tool to be made by SLS technological process in order to estimate its durability. The experimental tests that were carried out at Plastor SA

Company from Oradea has shown the opportunity of the SLS technology in the field of injection molding, when only few tens of thousand parts needs to be rapidly injected. There are still many aspects to be analyzed in the future, such as the accuracy of the SLS tools in close connection to the technological parameters (laser power, scanning speed, etc) or porosity control, which affects the mechanical resistance and the durability of the SLS tools, as well. The current research is the first one made in Romania in the field of injection molding tools made by Selective Laser Sintering (SLS) technology.

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