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SELECTIVE LASER MELTING FOR RAPID PRODUCT DEVELOPMENT

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Abstract: *Selective laser melting (SLM) is one of the most important technologies used when complex metallic parts need to be rapidly manufactured. There are some requirements related to the mechanical properties of the material, surface roughness, the accuracy of the manufactured part and the process control, in order to turn SLM process into a production technique. The presented work investigates if the SLM process, according to the state of the art, fulfills these manufacturing requirements, trying to show meantime few opportunities / applications of the metallic parts manufactured by means of SLM. The results of the developed research underline and recommend that compensation factors must be used, in order to get a good correlation between the SLM manufactured prototype and the CAD model dimensions. By doing so, the time needed for the Rapid Product Development process using the SLM manufacturing method will be significantly decreased. Finite element analysis (FEA) and Design Expert software were jointly used in order to determine the optimum process parameters and the compensation factors required to improve the accuracy of the SLM process. An interesting case study undertaken at the Technical University of Cluj-Napoca (TUCN) in cooperation with an industrial company from Romania, using our MTT Realizer II SLM 250equipment is also presented in the paper.*
Key words: *Additive Layer Manufacturing (ALM), Rapid Manufacturing (RM), Rapid Prototyping (RP), Selective Laser Melting (SLM), Finite Element Analysis (FEA)*

1. INTRODUCTION

Recent developments in Rapid Manufacturing (RM), e.g. the application of modern fiber laser beam sources, enable the additive layer manufacturing (ALM) to substitute conventional manufacturing processes. In this regard, metal based ALM methods show a large annual market growth and gradually gain influence in manufacturing and production technology [1]. First, this can be referred to system flexibility and feasible part complexity. Second, decisive technological advantages were obtained recently in such a way as to enable systems to process multiple metal powders (e.g. aluminum alloys, hot forming tool steel or titanium base alloys) [2-4]. Thus, variable classes of functional parts for almost all industrial sectors are achievable [5]. Representative examples are biocompatible implants [6], mould inserts [7] or components for the automotive and aerospace industry [8]. But, despite having extensive advantages compared to conventional manufacturing technologies (e.g. milling) so far, the SLM technology still comprehends several process deficiencies [9]. As a result of the locally concentrated energy input, the temperature gradient mechanism (TGM) and the related solidification lead to residual stresses and part deformations. On the one hand, the dimensional size and shape accuracy as well as the mechanical strength of parts are influenced thereby [10]. On the other hand, residual stresses contribute to crack formation or disconnection of parts from the base plate. The presented work comprehends different approaches to investigate residual stresses and part deformations caused by the SLM process. Numerical solutions by means of the finite element analysis (FEA) that comprise adequate algorithms were derived and the results of the finite element analysis simulation were compared to the experimental investigations. A set of optimum parameters for the SLM process was obtained further on within the Design Expert software. These parameters were successfully applied for the SLM manufacturing process of one prototype made for an industrial company in Timisoara (Romania), at the Technical University of Cluj-Napoca (TUCN). Anyhow, there is still a lot of work to be done in the future to increase the accuracy of the metallic parts produced by SLM. The obtained results will be used in the near future to develop an original software package at TUCN, that will be used for compensating the shrinkage of metallic parts (made from different type of materials, such as aluminum alloys, steel alloys, titanium alloys, etc), that occurs during the SLM manufacturing process.

2. RESEARCH ON HOW TO IMPROVE THE ACCURACY OF THE SLM PROCESS

2.1 SLM Parameters

There are several parameters having influence on the accuracy of the selective laser melting (SLM) process, such as the laser power, the scanning speed, the layer thickness, the lens focus position or the powder bed temperature. There is a limit for these parameters, according to the SLM 250 Realizer equipment manufacturer recommendations, like for example 100-200 Watts for the Laser Power, 100-500 mm/s for the scanning speed, 100-200 °C for the powder bed temperature.

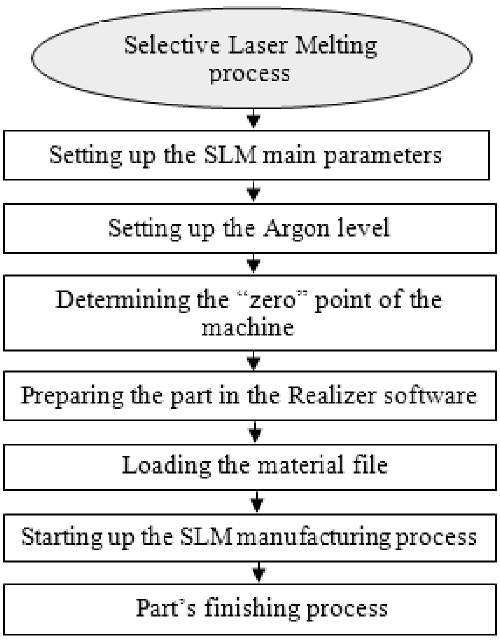

Fig. 1. The SLM process

For setting up the machine several steps needs to be followed as illustrated in Figure 1. If the preparing procedure looks quite simple at one first look, the SLM process control it is not so simple, especially when the total manufacturing time is more than 24 hours of effective work. It is not the laser system which could cause problems in this case, as it is the temperature control during the process. The manufactured part accumulates heat in time, so shrinkage phenomena occur during the SLM manufacturing process. If we consider that the machine is in the right focus position and the layer thickness we work with is set to the minimum value, we could consider that the SLM process is mainly influenced by the scanning speed, calculated as the minimum point distance (value that cannot be varied into the SLM program) over the exposure time (value that could be varied into the SLM program), the laser power we use and the powder bed temperature, that could be also varied into the SLM program.

2.2 Finite Element Analysis

The finite element analysis that has been done by using the ABAQUS software, consisted in the estimation of the thermal shrinkage that occurs during the laser scanning of several layers of 50 µm for the part illustrated in Figure 2. The analysis has been done along X-axis and Y-axis directions.

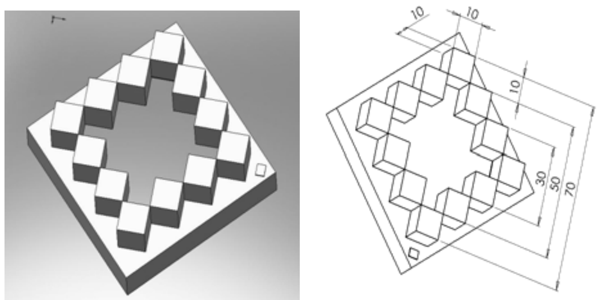

Fig 2. CAD model to be analyzed with the ABAQUS FEA software (SolidWorks 2010)

The distribution of the thermal flux associated to the laser scanning process, the coordinates of the laser spot and the material characteristics illustrated in Table 1 were described by means of a DFLUX routine. The material that has been considered for the FEA was Stainless Steel 316L.

Table 1

Stainless Steel 316L material properties

Property	Value
Density	8 (g/cm^3)
Brinell hardness	149
Rockwell B hardness	80
Vickers hardness	155
Fracture strength	515 MPa
Yield strength	205 MPa
Elongation	60.0%
Young modulus	193 GPa
Specific heat at 20°C	500 (J/kg K)
Thermal conductivity	16.3 (W/m/K)
Melting point	1420°C
Latent heat	247 (J/g)

According the results of the numerical simulation (see Figure 3), the part shrinkage ranges from -12.22 to -15.17 [µm] along the X-axis direction and from -14.76 to -18.35 [µm] along the Y-axis direction. The powder bed temperature variation has an insignificant influence on the accuracy of the SLM part.

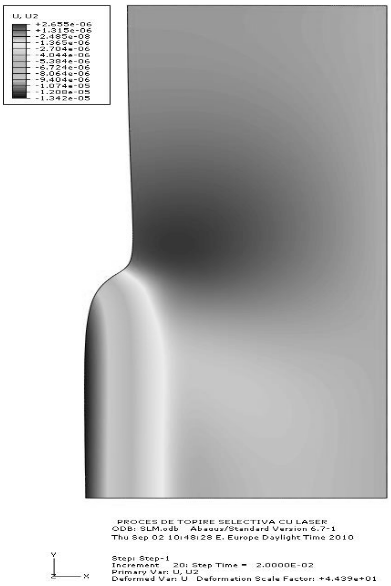

Fig. 3. Distribution of the displacement along the Y-axis

The minimum and maximum values of the shrinkage are comparable on both directions and correspond to a quite similar set of parameters. All the calculated values are negative, which means that we have an expansion of the scanned layers along both directions (X and Y-axes) (see Table 2). Further on, the results obtained in the FEA program were post-processed within the Design Expert software.

Table 2

Results of the simulation

Laser power [W]	Scanning speed [mm/s]	Powder bed temp. [°C]	Shrin-kage Δx [µm]	Shrin-kage Δy [µm]
175	300	176	-12.22	-
200	300	80	-15.17	-
190	250	152		-14.76
190	250	80		-18.35

2.3 Design Expert Software

Design Expert software uses several statistical methods, such as ANOVA in order to establish the optimum parameters we should use as input in order to have the best response, which is in our case the minimum residual deformation. As we established in our case, the laser power, the scanning speed and powder bed temperature were introduced into the software with the aim of finding those values that provide the minimum deformations along the X and Y directions. An experimental matrix is being created as illustrated in Figure 4. The software performs calculus by using 4 mathematical models, then overlaps the obtained results and finally displays the optimum regression coefficients.

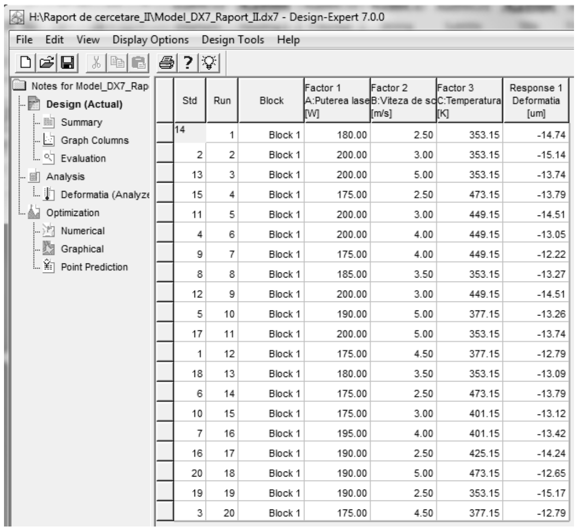

Fig 4. Experimental matrix constructed into the Design Expert software

Several plots as the ones presented in Figure 5 could be displayed into the Design Expert software. What we could state as a conclusion is the fact that the shrinkage is mainly influenced by the laser power we used into the SLM process. The laser power must be set between 175 W and 200 W. The scanning speed has also a significant influence on the accuracy of the SLM manufactured parts, even if the influence it is not so important as the influence of the laser power. The scanning speed value should be between 250 and 500 mm/s.

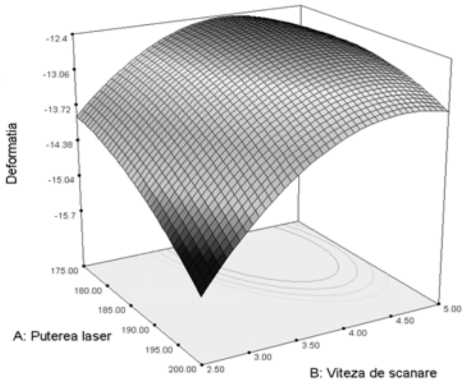

Fig. 5. Optimum laser power and optimum scanning speed versus shrinkage

3. TEST PARTS MANUFACTURED AT TUCN ON THE REALIZER II SLM 250 EQUIPMENT AND MEASUREMENTS

Three test parts as the one presented in Figure 1 were manufactured on the SLM 250 equipment from the Rapid Prototyping Laboratory of the Technical University of Cluj-Napoca (TUCN) (Figure 6).

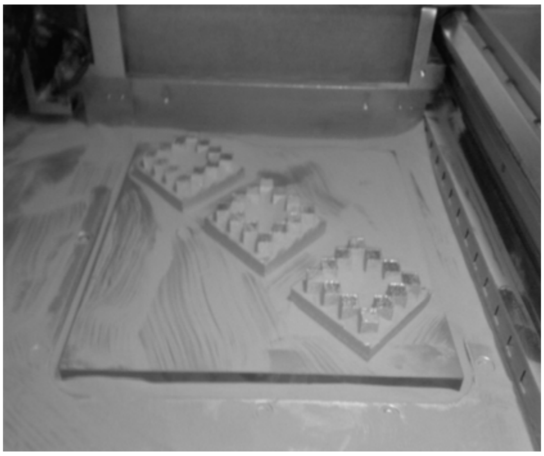

Fig. 6. Test parts manufactured by SLM at TUCN

The main technological parameters that were used for manufacturing the test parts by using the MCP Realizer II SLM 250 equipment from the (see Figure 7) were the ones obtained within the Design Expert Software, as presented in Table 3.

Fig. 7. MCP Realizer II SLM 250 equipment (TUCN)

Table 3

Optimum parameters for minimum shrinkage (Design Expert software)

Parameter	Value
Laser power [W]	180
Scanning speed [mm/s]	417
Powder bed temperature [°C]	100
Minimum shrinkage [μm]	12.07

The only difference consisted in the way of positioning of the test parts on the manufacturing plate. Finally, the test parts were measured on the Zeiss Eclipse 550 CMM equipment from the Technical University of Cluj-Napoca (Industrial Metrology Regional Centre) (see Figure 8).

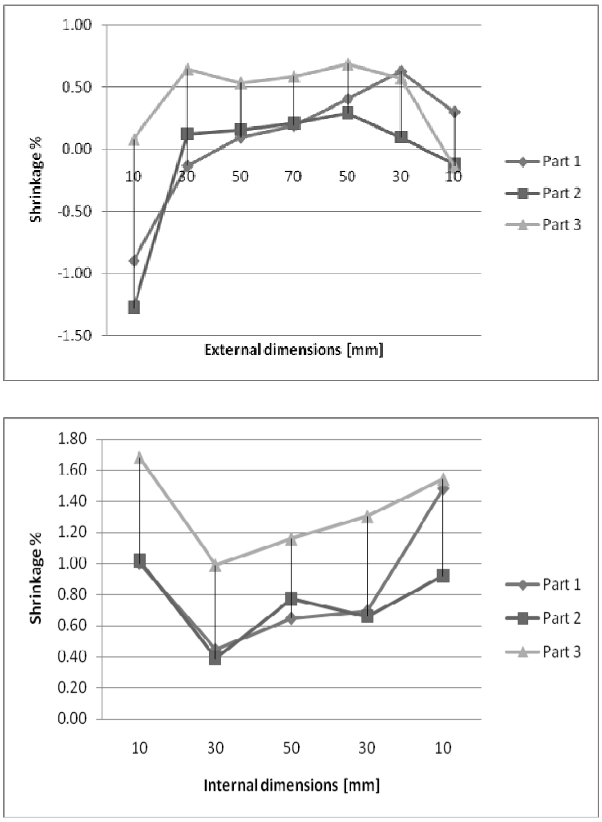

Fig. 8. Measurements undertaken by CMM

As we can notice from the results presented in Figure 8, it seems that there are some differences between the resulted shrinkage of the external and internal dimensions of the SLM test parts. First of all, the internal dimensions were expanded as compared to the designed ones. It seems that all parts were bended due to the fact that the temperature is different distributed in the building area and due to the part's geometry. Second of all, for both, external and internal dimensions, as we could notice from Figure 8, the test part number 3 has the highest shrinkage as measured. This fact has been caused by the fact that the SLM scanner gets cold constantly in the left edge area of the SLM building plate. Future research still needs to be done related to the optimum orientation of the building parts on the manufactured area in close connection to the part's geometry and characteristics of materials.

4. INDUSTRIAL CASE STUDY UNDERTAKEN AT TUCN ON THE REALIZER II SLM 250 EQUIPMENT

Figure 9 presents a case study of a "blade rotor" part that has been manufactured at the Technical University of Cluj-Napoca (TUCN) for an industrial company in Timisoara by using the SLM technology.

Fig. 9. Case study undertaken at TUCN for an industrial company from Timisoara (Romania)

The overall dimensions of the part where: height = 150 mm, internal diameter = 70 mm and external diameter = 80 mm. The CAD model has been realized by using SolidWorks 2010 modeling software package and has been post processed in order to be manufactured on the MCP equipment by using Magics 9 software package.
The main technological parameters that were used for manufacturing the "blade rotor" part were the ones presented in Table 3. The manufactured part accumulates heat in time, so shrinkage phenomena occurs during the SLM manufacturing process. Future research needs to be done in order to control the temperature during the manufacturing process. Figure 10 presents an intermediary layer of the "rotor blade". It is easy to observe the "raised up" supports in the right side of the image. The "rotor blade" part has been finished after 1700 layers as could be observed in Figure 9.

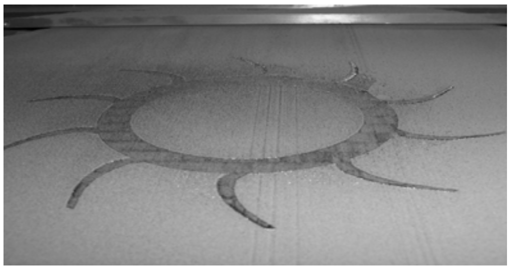

Fig. 10. "Rotor blade" intermediary layer (SLM)

The part has been measured afterwards by using an electronic caliper. The exterior diameter, the interior diameter and the height of the part has been measured 5 times, the mean being considered for each measure that was taken (see Table 4).

Table 4

SLM "blade rotor" measurements

Item	CAD dimension	Measured dimension	Deviation (mm)
External diameter	80	80.03	+0.03
Internal diameter	70	70.02	+0.02
Height	150	150.05	+0.05

5. CONCLUSIONS

In conclusion, we could state that a set of optimum parameters for the SLM process was obtained by using the finite element analysis in combination with the Design Expert software. This set of technological parameters, that provides the minimum shrinkage along the X and Y-axes, has been applied successfully to the manufacturing of the three test parts and the "blade rotor" case study undertaken for an industrial company in Timisoara (Romania), on the MCP SLM 250 Realizer equipment from the Technical University of Cluj-Napoca (TUCN). The tolerances we have obtained along the X and Y directions were comparable to the ones we have obtained in our FEA simulation. Research is still needed to be done in the future in order to improve the accuracy of the Realizer II SLM 250 equipment by determining the optimum scale factors needed to be applied on the manufactured parts. This research is the first one made in Romania, trying to improve the accuracy of the selective laser melting process of the metallic parts.

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METODA TOPIRII SELECTIVE CU LASER PENTRU DEZVOLTAREA RAPIDA A PRODUSELOR NOI

Rezumat: *Topirea selectiva cu laser (Selective Laser Melting - SLM) este una dintre cele mai importante tehnologii de fabricare rapida a pieselor metalice complexe. Pentru a putea vorbi insa de o tehnologie introdusa in fluxul tehnologic al proceselor industriale, tehnologia SLM trebuie sa raspunda inca la o serie de provocari, cum ar fi imbunatatirea proprietatilor mecanice ale materialelor utilizate in fabricatie, a rugozitatii suprafetelor obtinute,respectiv a preciziei pieselor fabricate prin acest procedeu. Lucrarea de fata prezinta o serie de cercetari efectuate in stransa legatura cu aceste provocari, incercand in acelasi timp sa arate cateva oportunitati ale acestei tehnologii moderne de fabricatie, cu precadere in domeniul industrial. Rezultatele obtinute subliniaza in acelasi timp faptul ca aplicarea unor factori de scalare asupra pieselor metalice fabricate este impetuos necesara pentru a putea obtine in final o buna corelare intre dimensiunile prototipului fizic fabricat prin SLM si cele ale modelului CAD. Procedand astfel, timpul necesar dezvoltarii de produse noi prin metoda SLM va fi in mod substantial redus. Metodele analizei cu element finit, precum si ale programului software de optimizare Design Expert au fost folosite cu success in vederea determinarii parametrilor optimi de fabricatie si a factorilor de scalare necesari pentru imbunatatirea preciziei procesului SLM.*

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