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FINITE ELEMENT ANALYSIS TO COMPENSATE THE ERRORS OF THE SELECTIVE LASER MELTING PROCESS

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ABSTRACT

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, etc. 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 that were done on the MCP Realizer SLM 250 equipment at the Technical University of Cluj-Napoca (Romania). At the end, a set of optimum parameters for the SLM process has been derived by post-processing the results obtained from the FEA simulation within the Design Expert Software tool. This research is the first one made in Romania, trying to improve the accuracy of the metallic parts made by the SLM process.

Keywords: Additive Manufacturing, Selective Laser Melting (SLM), Finite Element Analysis (FEA)

1. INTRODUCTION

The Selective Laser Melting (SLM) process is a complex one and there are different types of errors that might be involved, caused by: the scanning system, material contractions, layers scanning, etc. M. Yan et al analyzed the machine accuracy for rapid prototyping (RP) and pointed out the most common sources of errors in the rapid prototyping and manufacturing systems [1]. Fadel and Kirschman discussed the accuracy issues when a CAD file was translated into rapid prototyping control codes [2]. J. Y. Choi, et al studied the errors in medical rapid prototyping models and discovered that the laser diameter, laser path, and thickness of the layer are other sources of errors [3]. As one of the rapid manufacturing technologies, the selective laser melting (SLM) technology faces its own particular error sources. 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 tool.

2. FINITE ELEMENT ANALYSIS TO ESTIMATE THE ERRORS OF THE SLM PROCESS

The test part illustrated in Figure 1 has been designed within the SolidWorks 2010 software package in order to perform the finite element analysis (FEA) that was done with ABAQUS software in order to estimate the deformations that occurs during the Selective Laser Melting (SLM) manufacturing process. The FEA that has been done 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 1. The analysis has been done along X-axis and Y-axis directions. The distribution of the thermal flux associated to the laser scanning process has been described by means of a DFLUX routine.

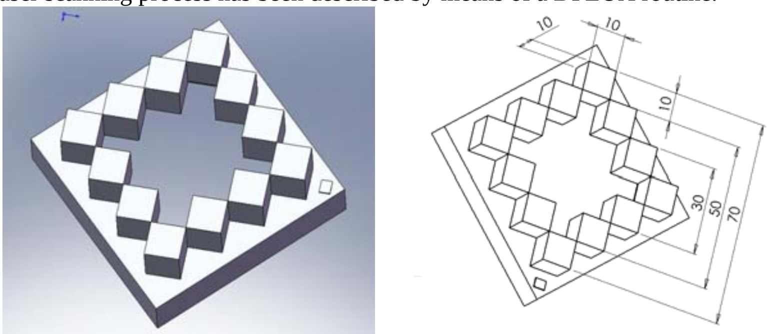

Figure 1. a. CAD model to be analyzed with the ABAQUS FEA software (SolidWorks 2010); b. CAD model imported in SolidWorks Drawing (Dimetric View)

The DFLUX routine starts with the description of several characteristics that are related to the laser system, followed by the establishment of the laser beam position that is changing during the scanning of the current layer and ends with the definition of the heat flow that it is spread by the laser beam. The current coordinates of the laser spot are calculated as follows:

$$\begin{cases} x_c = x_0 + v\left(t_{total} - n \cdot \tau\right) \\ y_c = y_0 + n \cdot \delta \end{cases} \quad (1)$$

where: X_0 and Y_0 represents the initial coordinates; t_{total} is the total time of the process (as estimated by the ABAQUS FEA program); n is the number of scanning cycles of one layer and δ represents the distance between two consecutive scans / neighbour paths.

The volumetric flux of the heat flow was calculated according to the formula:

$$q_{med} = \frac{P_{med}}{V} = \frac{P_{med}}{\frac{\pi d^2}{4} s} = \frac{4P_{med}}{\pi d^2 s} = \frac{4P\zeta\upsilon}{\pi d^2 s} \quad (2)$$

where: V is the volume that it is exposed by the laser source at a specified moment; d is the beam diameter and s is the layer thickness.

The average powder bed temperature was introduced into the DFLUX routine together with the other material characteristics illustrated in Table 1.

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 to the results of the numerical simulation, 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 minimum and maximum values of the shrinkage are comparable on both directions and corresponds 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 and Figure 2). Further on, the results obtained in the FEA program were post-processed within the Design Expert software.

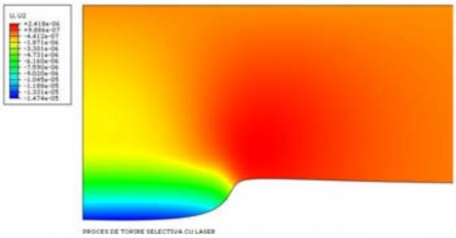

Figure 2. Distribution of the displacement along the X-axis.

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

3. DESIGN EXPERT SOFTWARE TOOL TO DETERMINE THE SLM OPTIMUM PARAMETERS

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 provides the minimum deformations along the X and Y directions. An experimental matrix is being created as illustrated in Figure 3. The software performs calculus by using 4 mathematical models, then overlaps the obtained results and finally displays the optimum regression coefficients.

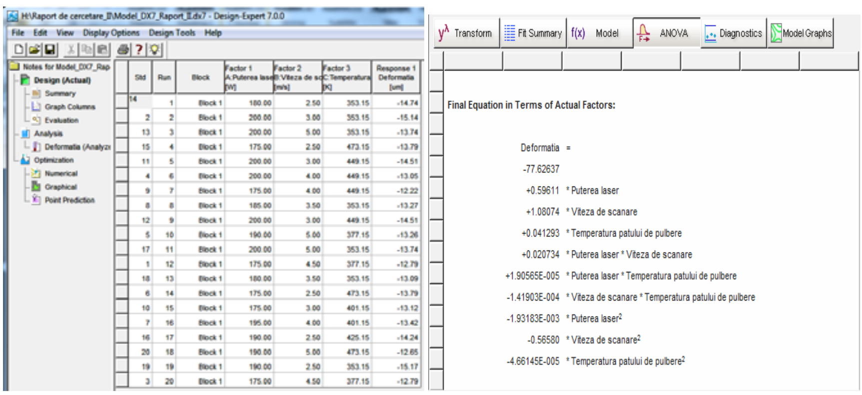

Figure 3. a. Experimental matrix constructed into the Design Expert software; b. The obtained results (regression coefficients for the SLM shrinkage) using Design Expert software

Several plots as the ones presented in Figure 4, a and Figure 4, b 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 0.25 and 0.5 m/s. The powder bed temperature has the smallest influence on the accuracy of the SLM metallic parts, because the temperature gradients do not vary so much.

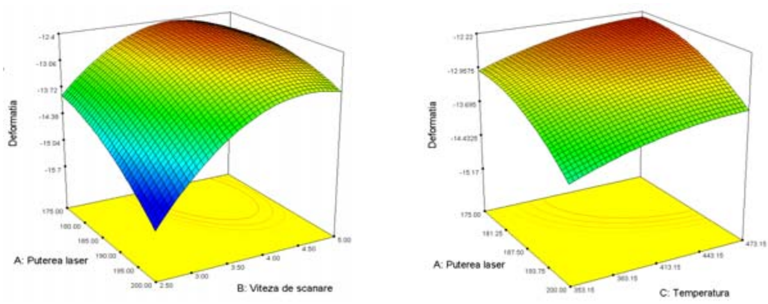

Figure 4. a. Optimum laser power and optimum scanning speed versus shrinkage; b. Optimum laser power and optimum powder bed temperature versus shrinkage

4. CONCLUSIONS

Three 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 (TUC-N) by using the optimum parameters determined within the ABAQUS finite element analysis and Design Expert software tool and were measured afterwards on the Zeiss Eclipse 550 CMM equipment from TUC-N (Industrial Metrology Regional Centre). As we can notice from the results presented in Figure 5, there are some differences between the resulted shrinkage of the external and internal dimensions of the SLM test parts caused by the fact that the scanner gets cold constantly in the margins area of building plate. Future research needs to be done related to the optimum orientation of the building parts in closed connection to the part's geometry and type of metallic powder materials we are working with.

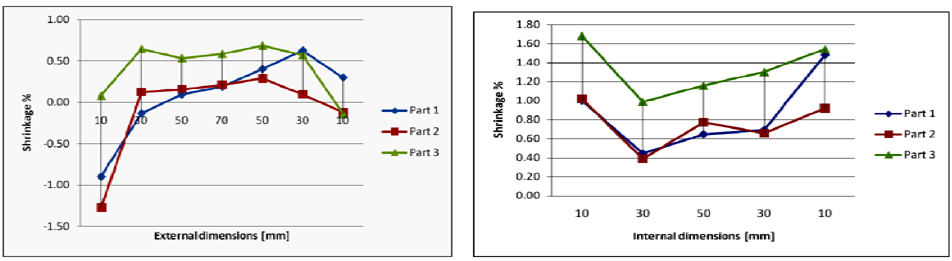

Figure 5. Measurements taken by CMM

5. ACKNOWLEDGMENT

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