Finite Element Analysis to Improve the Accuracy of Parts Made by Stainless Steel 316L Material Using Selective Laser Melting Technology

PĂCURAR Răzvan\textsuperscript{a} and PĂCURAR Ancuţa\textsuperscript{b}

Technical University of Cluj-Napoca, B-dul Muncii no.103-105, 400641, Cluj-Napoca, Romania
\textsuperscript{a}razvan.pacurar@tcm.utcluj.ro, \textsuperscript{b}ancuta.costea@tcm.utcluj.ro

Keywords: Additive Manufacturing, Selective Laser Melting, Stainless Steel 316L, Finite Element Analysis, Accuracy.

Abstract. One of the serious problems in the Selective Laser Melting process, using metallic powders is the thermal distortion of the model during forming. As a result of the locally concentrated energy input, the temperature gradient mechanism and the related processes lead to residual stresses and part deformations. Since the solidified part is cooled rapidly, the model tends to be deformed and cracked due to the thermal stresses. All these aspects were considered for a series of analyses that were made using the finite element method in order to determine the optimum process parameters (laser power, scanning speed, powder bed temperature) that are required in order to improve the accuracy of the metallic parts made by Stainless Steel 316L material using the Selective Laser Melting process.

Introduction

One of the major disadvantages of the Selective Laser Melting (SLM) process is the accuracy of the manufactured parts, the accuracy control and the repeatability of the process in terms of accuracy [1, 2]. There are several issues that have an important influence on the accuracy of the Selective Laser Melting process and the accuracy of the manufactured parts, as well [3]. The researcher’s opinions are quite different regarding the technological parameters that have a significant influence on the resulted deformations of the manufactured parts, at the end. Some of the researchers consider that the accuracy of the Selective Laser Melting process is directly influenced by the laser system that is used in the scanning process, other researchers states that the optical system in close connection with the scanning strategy that are used in the scanning process are important and there is a category that consider the technological parameters used in the manufacturing process (e.g. the scanning speed, the layer thickness, etc) as having a direct influence on the accuracy of the manufactured parts at the end [4, 5, 6]. The presented work tries to investigate by using the finite element method, how the SLM process can be optimized in order to improve the accuracy of the metallic parts made by Stainless Steel 316L material at the end.

Design of a Test Part by Using SolidWorks CAD Program

In Fig. 1 is presented a test part that has been designed by using SolidWorks CAD program in order to improve the accuracy of the metallic parts made by S technology. As it is possible to observe in this image, the model has been designed with specific elements, which are different on every side, due to the fact that the manufactured part has been used to analyze also other important characteristics of the parts, such as roughness, porosity, etc. Only
two sides were used basically to analyze the accuracy – the side that contains holes with sizes varying from 1 up to 12 mm and the side that contains inner and outer rectangular walls with sizes varying from 0.25 up to 1.55 mm.

Finite Element Analyses to Estimate the Deformations of Metallic Parts Made by SLM

The deformation analysis of parts made by Stainless Steel 316L material using the SLM technology was made using the ANSYS 13 FEA program. The mesh of the two sides of interest were generated in ANSYS as illustrated in Fig. 2, having the following characteristics: total number of nodes: 15086, total number of elements: 7889 (in the case of side with rectangular walls) and total number of nodes: 12127, total number of elements: 6259 (in the case of side that contains holes).

![Fig. 2. The mesh of the two sides of model generated in ANSYS 13 FEA program](image)

The next important step of the made analyses consisted in the specification of the main characteristics of the Stainless Steel 316L powder material, as there are presented by the producer of this type of metallic powder that is commercially available (SLM Solutions GmbH Company from Lubeck, Germany) (see Fig. 3) [7]. Beside the characteristics presented in Fig. 3, for the made analyses there were necessary to define and use other important issues for the numerical simulation, as presented in Eq. 1 to Eq. 4 [4].

The optimization of the SLM process can be carried out efficiently using a computational approach based on a model that simulates the microstructure formation mechanisms in the material, in particular the phase transformations caused by the heat and mass transfer phenomena that take place during fabrication. The SLM process is characterized by the continuous addition of material on a layer-by-layer basis to produce a final component. In order to process the different layers into a consolidated part an energy source (laser beam) is used in order to heat up and melt the feedstock material before incorporation into the part. The interaction between the heat source and the material depends on the particular characteristics of the energy source being used such as its power. Assuming, for example, a Gaussian distribution of the laser beam power, the energy input into the material can be described by:

\[
q_{laser} = \frac{\alpha \cdot 2P}{\pi \cdot r_l^2} \cdot \exp(-\frac{2 \cdot r^2}{r_l^2})
\]

The phase transformations during SLM process are determined by the result of the energy absorption of the material, heat conduction within the metallic part being manufactured and heat losses by convection and radiation to the environment. Energy losses to the environment by convection and radiation can be described by:

\[
Q_{convection} = h \cdot [T(\vec{r}, t) - T_\infty]
\]
\[ Q_{\text{radiation}} = \varepsilon \cdot \sigma_s [T^4(\vec{r}, t) - T_{\infty}^4] \] (3)

where: where \( h, \varepsilon, \sigma_s, T_{\infty} \) and \( T(\vec{r}, t) = T_0(\vec{r}) \) are the convective heat transfer coefficient, emissivity, Stefan-Boltzmann constant, temperature of the surrounding environment (room temperature) and initial temperature distribution in the solid region \( \Omega \) of the part \( (\vec{r} \in \Omega) \), respectively. The balance between the heat lost to the environment by convection and radiation and the energy absorbed from the laser radiation on the part surface was determined using formula:

\[-k \nabla T_\Gamma = h \cdot [T(\vec{r}, t) - T_{\infty}] + \varepsilon \cdot \sigma_s [T^4(\vec{r}, t) - T_{\infty}^4] - q_{\text{laser}}, \vec{r} \in \Gamma \] (4)

where: \( k \) is the thermal conductivity, \( \Gamma \) represents the surface (or boundary) of the solid region and \( \vec{n} \) is the unitary vector normal to the surface \( \Gamma \).

With all these aspects determined, before running the analyses, it was necessary to specify the technological parameters that are used in the SLM process. Based on the studies and recommendations that are presented by the researchers in the specific literature, three parameters were considered as having the main influence on the accuracy of metallic parts made by SLM technology, such as laser power \([\text{W}]\), scanning speed \([\text{mm/s}]\) and powder bed temperature \([\text{°C}]\).

The MCP Realizer II SLM 250 that was used for manufacturing the metallic part presented in Fig. 1 is equipped with a fiber laser source that can be used with a maximum power up to 200 W. In concordance with the Stainless Steel 316L material granulation, it is not recommended to use a value lower than 175 W for producing the parts using this type of machine. The mechanical resistance of the metallic part that will be produced will be severely influenced in this case. The scanning speed to be used should be used in the limits 250 – 500 mm/s and the powder bed temperature should be taken into account for the made analyses in an interval from 80°C up to maximum 200°C [8]. Based on this it has been stated that the technological parameters to be considered for the analyses must be the ones presented in Table 1. The technological parameters were introduced within the finite element analyses through the APDL (Ansys Parametric Design Language) module that is compatible with Ansys FEA program. In order to simplify the number of analyses to be done using all possible combinations of technological parameters presented in Table 2, Design Expert 8 software was successfully used in order to estimate new limits that will lead to the minimum deformations, as it is possible to observe presented in Fig. 4.

The new limits according to Design Expert software were established as following: 190 – 200 W for the laser power, 400 – 450 mm/s for the scanning speed and 152 – 200 °C for powder bed temperature. With these new limits, 18 combinations of these parameters are still possible, so 18 finite element analyses were performed with the aim to determine the combination of parameters that leads to the minimum deformations of the two sides of the models presented in Fig. 2.
Table 1. Technological parameters considered for analyses in ANSYS FEA program

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power [W]</td>
<td>175  180  185  190  195  200</td>
</tr>
<tr>
<td>Scanning speed [mm/s]</td>
<td>250  300  350  400  450  500</td>
</tr>
<tr>
<td>Powder bed temperature [°C]</td>
<td>80   104  128  152  176  200</td>
</tr>
</tbody>
</table>

As can be observed in the images presented in Fig. 5, the deformations estimated within ANSYS FEA program are different in particular areas of the analyzed models. For instance, in the bottom area of the models there were recorded dilatations, as in the top area of the models there were recorder shrinkages. This aspect can be explained by the way the SLM process is running. Due to the fact that the building platform is maintained heated during the entire process contributes to the dilations resulted in that particular areas. In the top area of the parts, the tendency of the parts is to shrink in a significant way due to the stresses that are accumulated in the material structure. This is the main reason why in the SLM process is obligatory needed to use fixing supports.

![Fig. 5. Deformations as estimated within ANSYS FEA program](image_url)

The minimum dilatation that resulted in the ANSYS FEA has been 20.77 µm in the case of side with rectangular walls and 20.64 µm in the case of side with holes (see Fig. 5). The shrinkages resulted were higher, 58.29 µm in the case of side with rectangular walls and 82.29 µm in the case of side with holes. These values corresponded to the following set of technological parameters: laser power – 200 W, scanning speed – 400 mm/s and powder bed temperature – 176 °C.

**Experimental Results**

The results obtained with ANSYS FEA program (set of technological parameters) were successfully used in order to manufacture the test part illustrated in Fig. 6, using the MCP Realizer II SLM 250 equipment from the Technical University of Cluj-Napoca (TUC-N). The test part manufactured by Stainless Steel 316L material was measured afterwards by using the Werth Messtechnik VideoCheck IP 250 equipment that is available also at TUC-N. As it is possible to observe in Fig. 6, an original calculating program, called OptiScale has been developed at the end at TUC-N necessary in order to determine the optimum scale factors that are needed to be used for compensating the deformation of the metallic parts that occurs along X, Y and Z-axes, during the manufacturing process. The OptiScale program has been successfully used at TUC-N in order to improve the accuracy of the test part and other metallic parts that were made by Stainless Steel 316L at TUC-N. The minimum dilatation that was determined in the case of test part that has been manufactured by SLM was 25.5 µm in the case of side with rectangular walls and 28.5 µm in the case of side with holes. The shrinkages resulted were 66.5 µm in the case of side with rectangular walls and 79.5 µm in the case of side with holes, values that are close to the ones obtained within the ANSYS FEA program.
Conclusions

The finite element analyses that were performed using ANSYS FEA program has proved to be a useful tool for estimating the deformations of metallic parts made by Stainless Steel 316L material using the SLM technology. A set of technological parameters (laser power, scanning speed, powder bed temperature) that leads to minimum deformations in this case has been obtained in the end. A test part has been by SLM using the set of parameters obtained in ANSYS FEA program and an original program (called OptiScale) necessary for calculating the scale factors that are needed in order to compensate the deformations of metallic parts made by Stainless Steel 316L has been developed at the end at TUC-N. Further investigations still needs to be done in the future in order to improve the accuracy of metallic parts made by SLM, by taking into account the other two sides of the test part that has been used for the made analyses and experiment. There are also other issues that must be taken into account in the future, such as the roughness of the surface in close connection with the orientation of the part, porosity control in close connection with the size of the cells within lattice structures, etc.

References


Engineering Solutions and Technologies in Manufacturing
10.4028/www.scientific.net/AMM.657

Finite Element Analysis to Improve the Accuracy of Parts Made by Stainless Steel 316L Material Using Selective Laser Melting Technology
10.4028/www.scientific.net/AMM.657.236

DOI References
http://dx.doi.org/10.4028/www.scientific.net/AMM.404.754
http://dx.doi.org/10.4028/www.scientific.net/AMM.464.399
http://dx.doi.org/10.1023/A:1021153513925