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**Abstract.** Selective laser melting (SLM) is a well-established Additive Manufacturing technique for the fabrication of end-use metal components. Process reliability and maximum product quality are ensured by 20 years of technology development. Nevertheless, depending on the complexity of the part geometry and on the operator experience, different trials are often needed before getting a part first time right. To reduce the number of failed jobs, simulation software packages predict residual stresses and related distortions in SLM parts and propose a compensated geometry for the "right first time" production of the product. In this works, the simulation routines of Amphyon software by Additive Works are experimentally calibrated and validated for the fabrication of a reference geometry by means of an EOSINT M270 machine and Ti6Al4V powder. The calibration of Amphyon is performed using three cantilever specimens and the calibrated SLM simulation is then used to compute the compensated shape of the reference part. The validation of the compensated shape by comparison to the real part geometry shows that Amphyon routines have good prediction capability and dimensional accuracy.

**Keywords:** Additive Manufacturing, Laser powder bed fusion, process simulation and Ti6Al4V

## 1. Introduction

Selective laser melting (SLM) is one of the most widespread Additive Manufacturing (AM) techniques for the fabrication of end-use components directly from the CAD model with no need for specific moulds or tools [1]. SLM, also named laser powder bed fusion (L-PBF), exploits the thermal energy of a laser beam to selectively melt the metal particles of a powder bed layer by layer until the height of the part in the building direction is reached [2].

Unlike conventional manufacturing technologies, the absence of specific tools or dies together with higher freedom of design for SLM products enables mass customization at a reduced cost. For this reason, the "right first time" principle is extremely important in additive manufacturing [3, 4], especially in the case of unique parts as those of the racing or biomedical sectors[5]. Thus, the optimization of the laser powder bed fusion process is a fundamental step to maximize the part quality and economic profit.

Numerical methods for SLM process simulation can be used to reduce the defect rate and improve material sustainability if compared to a more resource-demanding trial and error approach. In the literature, different approaches have been proposed for SLM simulation [6-14]. For the melting process layer after layer, these simulation approaches consider the interaction of the laser source with

the metal powder. The high energy density of the laser beam locally melts the metal particles that then solidify during subsequent fast cooling. Virtual simulations are aimed at predicting the effect of the physics of the SLM process over the material properties and their influence on the geometrical accuracy and quality of the as-built AM part.

As an optimization tool, computational methods should consider different aspects of SLM such as the orientation of the part on the build platform, the support structures for overhangs, and the operating parameters of the machine. The main goal of the optimization is to help the user in manufacturing the part "first time right" with fewer efforts and reduced resource consumption when compared to the traditional trial and error approach. The aim is pursued through minimization of the residual stresses and consequent distortions of part geometry [15, 16].

Residual stresses are induced by thermal gradients that are caused by the local action of the laser over the powder bed. The area that is invested by the energy density of the laser beam is named heat influence zone (HIZ). In the HIZ the temperature of the metal particles will be close to the melting point of the material whereas the surrounding bed zone will be much colder[17,18]. The material in the HIZ expands because of the higher temperature and forces the adjacent cold area to accommodate and deform. After a fraction of a second, when the action of the laser beam is over, the molten metal in the HIZ cools and shrinks. The volumetric shrinkage causes residual tensile stress of the underlying layers. Since the stress levels are high, permanent plastic deformation is caused during the SLM process.

During SLM, the build plate is constantly heated for preventing layer distortion through minimization of the thermal gradients in the powder bed. In addition to this, heat can be removed from the hottest areas of the bed by using support structures connected to the build platform. Therefore, supports have a double role in SLM. They support undercuts and overhangs of the part geometry with respect to the build direction, but they also prevent part distortion and warping. Additional post-processing steps and increased manufacturing times and costs are required to remove the supports that are made of the same material as the SLM product. Therefore, the use of numerical simulations in SLM allows considering different orientation alternatives and supporting strategies as important aspects of the process optimization along with the definition of process parameters for minimum part distortions. However, to compensate for inevitable part deformations, the simulation software can compute a compensated or pre-distorted geometry to be fabricated for meeting the desired part shape. Figure 1 summarizes the main steps and operations in the fabrication route of a metal SLM part.
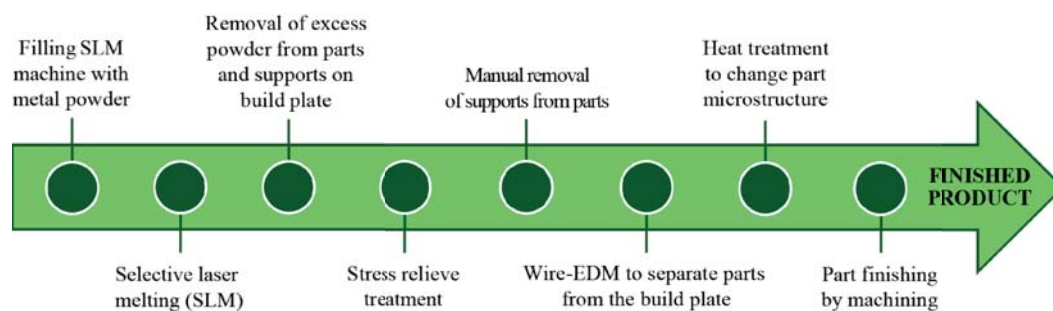


**Figure 1.** Fabrication route of a metal component starting from SLM.

Thermal treatment for stress relieving can be applied to the as-built part connected to the build platform before removal of the support structures. By reduction of the residual stresses, the distortion of the parts is minimized at the separation from the supports and build plate.

The thermal stress relief and the compensation of the deformations of the part geometry are two important features that are integrated into most complete software packages for SLM simulation. The

production of the pre-distorted shape using the same process parameters of the SLM simulation should result in a real deformed geometry of the component that is ideally identical to the nominal CAD model.

Different software solutions for the simulation of laser powder bed fusion are offered in the market [19]. In this work, Amphyon software by Additive Works is experimentally calibrated and tested for the simulation of SLM of Ti6Al4V powder in an EOSINT M270 Dual Mode machine by the German company Electro Optical Systems (EOS GmbH). The next section of this paper describes the methodology and equipment, while the experimental results of the calibration and validation phases are presented in the third section. The last section is about conclusions and proposals for future works.

## 2. Materials and methods

Amphyon software is a product of the German company Additive Works GmbH, a partner of the Altair Partner Alliance (APA) program. The first beta release of Amphyon dates back to 2016, while the fifth version of 2020 is tested in this work. Amphyon proposed five modules within its user-friendly framework. The modules cover different steps of the SLM manufacturing route starting from the CAD model to the compensation of geometric distortions, including the preparation of the build job with part orientation, support structures, and post-processing by the stress-relieving treatment.

The parameters for processing 30 $\mu$m layers of EOS Ti6Al4V powder in the EOSINT M270 system are assumed from a previous work of the authors [20]. The machine comes with a Ytterbium (Yb) fiber laser source that has a maximum power of 200 Wand a size of 100 $\mu$m for the laser spot.

**Table 1.** SLM parameters for Ti6Al4V powders in an EOSINI 270 systems

| Parameter | Skin | Contour | Core |
|---|---|---|---|
| Laser power (W) | 150 | 120 | 170 |
| Scan speed (mm/s) | 1000 | 1250 | 1250 |
| Hatching distance (mm) | 0.10 | 0.10 | 0.10 |

However, Amphyon considers only one parameter set for the simulation of SLM without distinguishing between the different portions of the part cross-sectional area in the layer of the powder bed. However, most of the cross section usually corresponds to the core region, so the laser parameters in the right column of table 1 mainly influence the thermal history of the metal powder. Hence, the parameters of the core region were considered as input for Amphyon simulations, while the temperature of the build platform was set at 100 °C. The material characteristics for Ti6Al4V powder were assumed from the datasheet of EOS company that declares values of 110 GPa for the Young Modulus, 1060 MPa for the Yield stress, and 0.3 for the Poisson coefficient.

Additive Works has developed an experimental approach for the calibration of Amphyon computational routines to account for the specific material and SLM machine. This approach requires the production of a cantilever geometry. The cantilever has overall dimensions of 180 mm x 7.2 mm x 8 mm and a T-shape with two pillars at the opposite ends and support structures below the overhangs of the long arms of the "T". Three replicas of the cantilever should be produced with a different strategy of laser hatching for precise calibration considering the material anisotropy (figure 2).
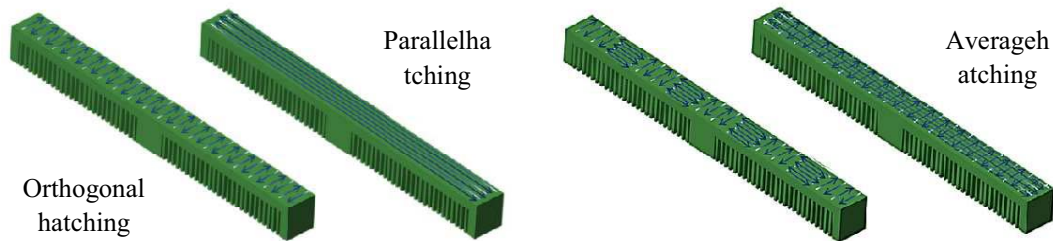
**Figure 2.** Different strategies for laser hatching to account for material anisotropy in SLM.

The different laser scanning strategies of figure 2 generate a distinct thermal history within the layer of the powder bed. Therefore, resulting residual stresses and related deformation of each specimen will be different. To consider the direct effect of the SLM process only, the stress relief treatment must not be applied to the as-built parts. For the same reason, the separation of the specimens from the build platform is carried out by Wire-Electro Discharge Machining (W-EDM) because a mechanical cutting action will add additional stresses to the material that could alter the resulting distortion of the cantilevers because of the residual SLM stresses.

After calibration, the ability of Amphyon to predict part deformation was tested and validated on the "AW Box" component designed by Additive Works. The AW Box has the geometry of a hollow thin square tube. Its faces are oriented at 45 degrees to the build direction (figure 3) so that the part can be fabricated without the need for support structures for the tilted surfaces. A vertical 6.35 mm edge serves as a support and connects the AW Box to the build platform. The square tube has a length of 100 mm and a uniform wall thickness of 1.67 mm.

The adaptive mesh structure used in Amphyon for the simulation of the laser powder bed fusion of the AW Box is shown in figure 4. The software differentiates between the mesh parameters for the mechanical simulation and the thermal one. A mesh resolution of 2 over a scale from 0 (coarse) to 10 (fine) was selected for both simulations. The solver accuracy was set to 0.5 for the mechanical simulation and 0.2 for the thermal simulation over a scale from 0.0 (fast) to 1.0 (accurate). These parameters were chosen to have each type of simulation completed in about 1 hour and a half when run on a standard notebook.
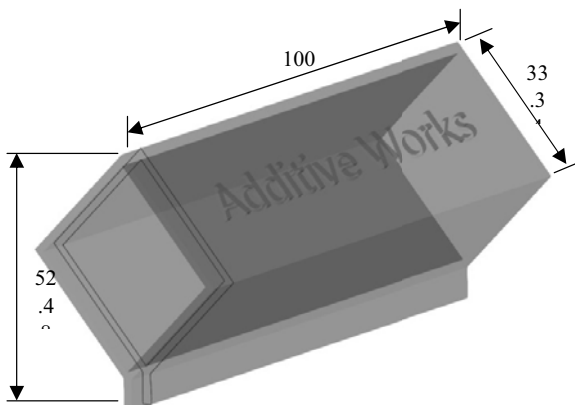


**Figure 3.** Nominal geometry of the AW Box with overall dimensions and outline of its cross section.



**Figure 4.** Geometry of the as-built AW Box with mesh structure for SLM simulation.

## 3. Experimental results

SLM simulations and calibration calculation of Amphyon release 2020 were run on a standard notebook with Windows 10 64-bit operative system. The PC has an Intel®Core™i7-6700HQ CPU @ 2.60 GHz, 16 GB RAM, and a SATA SSD for data storage.

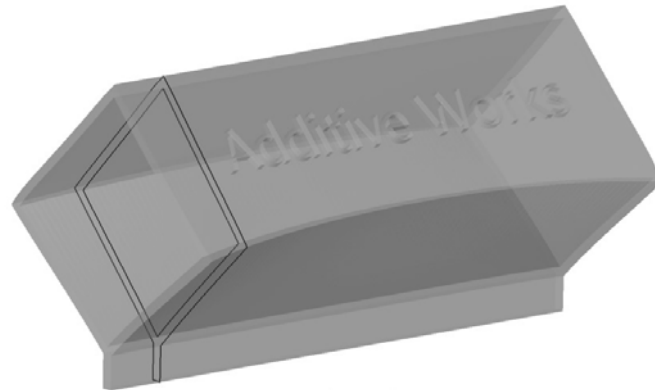**Figure 5.**Inspection of a cantilever using the Atos Compact Scan 2M.



**Figure 6.**Pre-distorted geometry of the AW Box computed by Amphyon for compensation of the SLM distortions.

After SLM fabrication of the three cantilever specimens of Ti6Al4V using the EOSINT M270 system, their real geometry was measured by 3D scanning. For this activity, a structured light Atos Compact Scan 2M by GOM GbmH was used. The Atos Compact Scan exploits stereoscopic vision and blue LED light for fringe projection (figure 5) over the surface of the measured object. Moreover, it is very accurate because its length measurement error is smaller than 0.02 mm as defined by the acceptance test of VDI/VDE 2634 guideline part 3. To capture the real deformed geometries of the three cantilevers, the scanning phase was also repeated after the separation of the parts from the build platform by W-EDM.

The maximum deflection (table 2) of the three cantilevers was measured from the scan data using GOM Inspect software and the value was used for the calibration of Amphyon software.

**Table 2.** Maximum deflection of the three cantilevers for Amphyon calibration.

| Type of laser hatching | Average | Parallel | Orthogonal |
|---|---|---|---|
| Maximum deflection of the cantilever | 2.28 mm | 2.74 mm | 2.09 mm |

After calibration of the Amphyon software for Ti6Al4V powder and the EOSINT M270 machine, the laser powder bed fusion of the AW Box was simulated. The simulation predicted the deformed shape (figure 4) caused by the SLM residual stress. Based on this result, Amphyon calculated the compensated geometry (figure 6) of the AW Box with pre-distortion. Since the deformation mainly affects the longitudinal edge of the square tube that bows down (figure 4), the opposite change in shape was applied to the pre-distorted geometry whose edge bows up (figure 6). This pre-distorted shape was then exported into the STL format and a replica of Ti6Al4V (figure 7) was manufactured using the EOSINT M270 machine.

The real geometry of the fabricated replica was digitized using the Atos Compact Scan. The nominal CAD model (figure 3) of the AW Box was then aligned and compared to the scan data (about 121,000 points) of the real part (figure 7) using GOM Inspect software for the validation of the capability of Amphyon to predict and compensate the distortions induced by the SLM process.
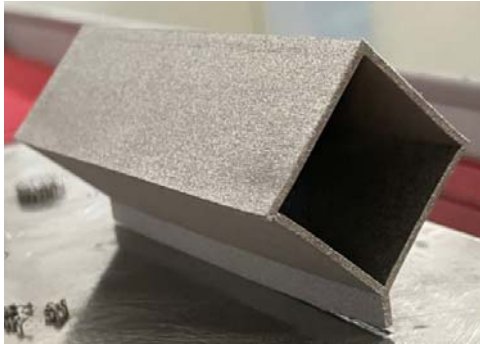
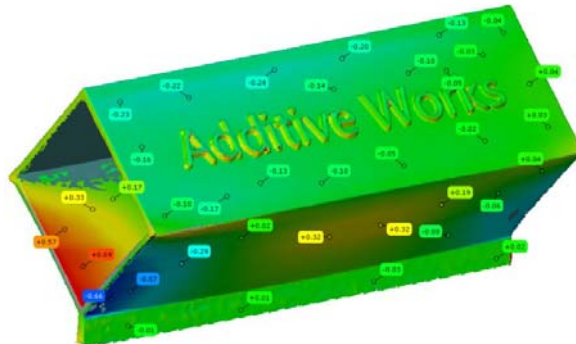**Figure 7.** Pre-distorted replica of the AW Box of Ti6Al4V.



**Figure 8.** Deviations between the real geometry of the pre-distorted replica and the CAD model.

The results of the validation are shown in figure 8 by means of a coloured map representing the deviations between the compared geometries. The labels in figure 8 show the local deviations between the desired ideal shape of the AW Box and the real shape of the as-built pre-distorted model proposed by Amphyon. The distribution of the signed deviations has an average value of 0.00 mm and a standard deviation of 0.22 mm. However, the majority of the deviations are included in the symmetric range -/+ 0.40 mm. The maximum absolute difference between the compared geometries is smaller than 0.80 mm and is limited to the extremes of the down-facing surfaces of the square cube. The results of the experimental validation show that using the cantilever calibration procedure, Amphyon simulation can predict the SLM distortion of the as-built part and compensate it by pre-distortion of the AW Box geometry with good dimensional accuracy.

## 4. Conclusions

This paper aimed to test and validate the simulation modules of Amphyon software by Additive Works for the Additive Manufacturing process of laser powder bed fusion. Amphyon performance was evaluated for EOS Ti6Al4V powder in an EOSINT M270 Dual Mode machine.

The experiment-based calibration developed by Additive Works was effective in accounting for the anisotropy of the specific combination of material, process parameters, and machine. After calibration, the simulation of Amphyon software was validated for the production of the AW Box as reference geometry for thin hollow shapes with sharp edges.

The pre-deformation module of Additive Works was specifically tested in this study. The pre-distorted shape of the AW Box was computed by Amphyon software for the compensation of the deformations of the as-built part. After the production of a replica of the pre-distorted geometry, the real shape of the SLM part was digitized using 3D scanning and then compared to the nominal CAD model. The results of the comparison assess Amphyon capability of correctly predicting and compensating the geometrical distortions generated by the thermal gradient during SLM of Ti6Al4V material. For the AW Box, the statistical distribution of the signed difference between the compared geometries had an average of 0.00 mm and a standard deviation of 0.22 mm, while the maximum difference was smaller than one millimeter. Over these first results for the AW Box, further investigation is needed to assess Amphyon performance for more complex geometries.

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