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Distortion Prediction of Ti6Al4V Parts in Selective Laser Melting: An Industrial Case Study

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Rapid heating and cooling in the Selective Laser Melting (SLM) additive manufacturing process generates large amounts of tensile residual stresses in the component. These stresses lead to part distortions and poor product performance. In most cases, distortions become more significant after cutting the part from the build tray and removing support structures. In this study, a complex topology optimized Gimbal Mount was considered for physical printing and finite element analysis of the print process. Th component was printed using Ti6Al4V material on an SLM machine and measurement points were taken on its outer profile. This data was compared with original geometry and simulation results. A good agreement was found between simulation and experimental results which was helpful in part development and establishing the technology.

I. Nomenclature

σ^0 = static yield stress
ϵ^{-pl} = equivalent plastic strain
θ = current temperature
$\hat{\theta}$ = non-dimensional temperature
θ_{melt} = melting temperature
$\theta_{transition}$ = transition temperature

II. Introduction

Additive Manufacturing (AM) has become an established manufacturing technique and interest to industries due to its capability of manufacturing fully functional complex geometries from a digital model [1]. Additive

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Manufacturing is a process that fabricates parts layer by layer directly from a CAD representation. AM has experienced massive development in the last decade and as a result of this, aerospace, defense, automotive and medical industries have started using this technique beyond just prototyping. In 2012, ASTM has classified additive manufacturing technologies into seven categories depending on the raw material and energy used in the process. They are, i) Vat Photopolymerisation ii) Powder Bed Fusion iii) Binder Jetting iv) Material Jetting v) Sheet Metal Lamination vi) Material Extrusion vii) Direct Energy Deposition. The Powder Bed Fusion (PBF) family consists of many specific methods like Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) and others.

Selective Laser Melting (SLM) is a layer-by-layer additive manufacturing technique where parts are built from powder. A thin powder layer is mechanically deposited on a built tray and then selectively bound by a scanning laser beam. In this process material is heated locally and rapidly above melting temperature and then allowed to solidify and cool to form a dense geometry. Extremely high heating and cooling rates are obtained due to the highly concentrated nature of heat source [2]. This involves large thermal gradients. Thereby, residual stresses and distortions are generated due to the local inherent nature of the process. Moreover, post-print processes such as support structure removal or part cutting from build plate result into redistribution of internal stresses and strain modifying asbuild-distortions. Parts can fail during an SLM build or later in service due to these high internal residual stresses [3]. Thus, the prediction of residual stresses and distortion is very important and various literature has been published on this topic which is described in the next section.

III. Literature review

Distortions due to residual stresses can result in failure of a component during SLM build or later in service, particularly when subjected to alternating loadings or in corrosive environments [3-6]. Researchers have studied various approaches like experimental, Finite Element Analysis (FEA), combination of experimental and FEA, and multi-scale to mitigate the distortion or residual stresses. Haider Ali et al. [7] experimentally examined the effect of scanning strategy and rescanning strategy on residual stress formation and mechanical properties of SLM Ti6Al4V parts. They also proposed re-scanning with 150% energy density to reduce residual stresses. C. E. Protasov et al. [8] proposed a method to cut SLM parts in thin plates and reconstruct the residual stresses from the measured deformation of the plates. The measured stress profile was validated with results from other sources. L. Mugwagwa et al. [9] investigated influence of laser power and scanning speed on thermal stress-related warping distortion and porosity. They found that laser power has strong effect on part density and cantilever distortion increases with the increase in scanning speed.

While in simulation or FEA method, Samer M. Tawfik et al. [10] used Abaqus code to model the SLM process for a cube and validated that with experimental results for temperature and displacement. The effect of laser scan speed on part distortion was also studied. Few authors have used both FEA method and validated the code through experimental tests. In such cases, Shukri Afazov et al. [11] presented a novel approach to use a calibrated analytical thermal model to derive a structural finite element analysis (FEA). This reduced the computation time to less than 3 hours. Developed FEA methodology was then applied to power heat shield and a tubular structure. Turbine blade geometry was compensated based on FEA results and final results were validated. Deqiao Xie et al. [12] proposed a new method of constraining force for predicting distortions in SLM. This method was compared with FEA and experimental results. The constraining force was found primarily related to the material properties, temperature, and cross-sectional area of the added layer. H S Park et al. [13] focused on quality of SLM printed parts by considering optimal printing process parameters with temperature distribution. The authors developed a system for predicting the quality of the printed part by simulation and performed the experimental works in consideration of the temperature distribution. L.A. Parry et al. [14] investigated the geometrical effect of scan strategy on residual stress development. They found that the arrangement of scan vectors due to geometry heavily influenced the thermal history within a part, which in turn significantly affected residual stress generation.

C. Li et al. [15] and few other authors used a multiscale approach for predicting residual stress and distortion . They developed a temperature-thread multiscale modeling approach to predict part distortion of a twin cantilever. Simulation results were further validated with experimental data for upward distortion of the cantilever beam.

Due to the complexity of this process, efficient and accurate prediction of residual stress or distortion in large components remains a challenge. After closely observing the literature it appears that most of the research has been conducted with small cubes, thin walls, single/double cantilever beams or other simple geometries. To have a fundamental understanding of the distortion mechanisms for SLM processed parts, numerical modeling is a powerful tool.In this study, a complex topology optimized gimbal mount component as shown in figure 1 from an Unmanned Aerial System is considered for physical printing and finite element analysis of the print process. Ti6Al4V has been widely used in aerospace, automotive and medical sectors because of its low density and high strength at low to moderate temperatures [16]. This material was selected for printing the gimbal mount plate.

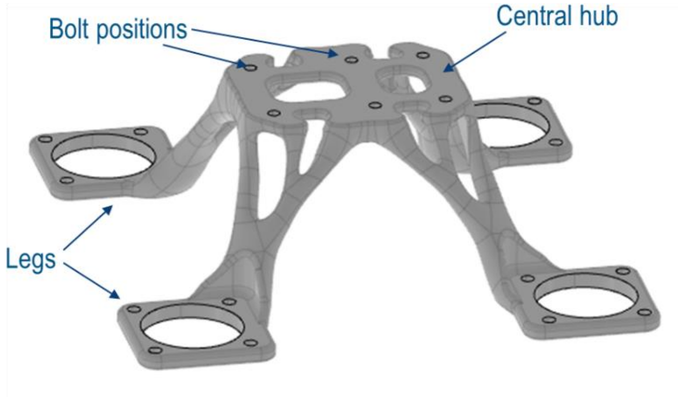


Fig. 1 Gimbal mount plate

IV. Experimental Work

A Gimbal Mount Plate geometry was built experimentally as shown in Figure 1 at Morf3D Aerospace using an EOS M290 machine having a 400W Yb-fibre laser with a spot size diameter of 100 μm. The EOS M290 system has a standard build volume of 250 x 250 x 325 mm.The chemical composition of material Ti6Al4V is shown in Table 1 [17].

Table 1 Chemical composition of Ti6Al4V(wt.%)

Al	V	O	N	C	H	Fe	Other	Ti
5.5-6.74	3.5-4.5	≤0.20	≤0.05	≤0.08	≤0.015	≤0.30	≤0.40	Bal.

Build planning was performed using Magics software where a part is imported in *.stl file format. Build preparation stages like model positioning and alignment, orientation selection to ease support removal, and support structures generation were carried out. Shell support structure with perforations were generated with a grid gap of 2mm. After completing these operations, data was sent to the machine with its readable format allowing manufacture using laser energy to melt fine metal powder. The substrate was heated to 40°C and process parameters are set as defined in Table 2.

Table 2 Process Parameters

No.	Parameter	Values
1	Laser power	300 W
2	Layer thickness	30 μm
3	The angle of rotation between hatches	67°
4	Scan speed	877 mm/s
5	Hatching distance	190 μm
6	Laser spot diameter	80 μm

Build plate of Ti6Al4V material with dimensions 250 x 250 x 40mm is used. Inert gas flow of 1 mbar was supplied to achieve clean processing conditions. Figure 2 shows the build set up with perforated supports, and a physical print image.

Fig. 2 Build setup and physical print

Once the build was complete and cooled down to room temperature, the part was removed from the build plate using wire EDM and the supports were removed with hand tools. CMM measurements were taken for more than 0.3M points around the outer profile of the part after support removal, without any heat treatment.

V. Distortion Prediction Methodology

The additive manufacturing framework on the **3D**EXPERIENCE platform was used to perform SLM process simulations using finite element analysis. Before performing the simulation, build preparation operations were performed on the **3D**EXPERIENCE platform to emulate the physical print. This included creating the build tray, part orientation, wired support generation and scan path generation using the Powder Bed Fabrication application on the platform. For this study, the process parameters were defined which were same as that of the physical print (laser power, scan speed, recoater timing, layer thickness and a few others), the scan path was generated and passed on to the simulation framework for driving the analysis. The Additive Manufacturing Scenario application on platform was used to simulate additive manufacturing processes This app represents material and energy addition events separately in space and time. This was mainly done by two modules in the solver: the mesh-intersection module and the moving heat flux module. The mesh-intersection module allows the solver to take information of machine tool path in the form of time, location and field data and intersect this tool path data with any arbitrary mesh [18]. With this framework, finite elements were activated in a progressive fashion during the analysis, simulating the recoating process. The moving heat flux module allows single or multiple moving heat sources of different shapes to be applied to a mesh as a loading condition. In this analysis, the part and supports were meshed using solid tetrahedron and shell elements respectively. Tie connections were created between the build plate and the supports and between the supports and part geometries.

Material properties are important in achieving accurate result prediction. In the simulation model, all relevant temperature-dependent thermal properties, such as conductivity, latent heat, and specific heat were defined for the heat transfer analysis. For structural analysis, mechanical properties of Ti6Al4V were referred from manufacturer's datasheet. Johnson-Cook hardening plasticity model was used which is a particular type of isotropic hardening where the static yield stress, σ^0 is assumed to be of the form [19]

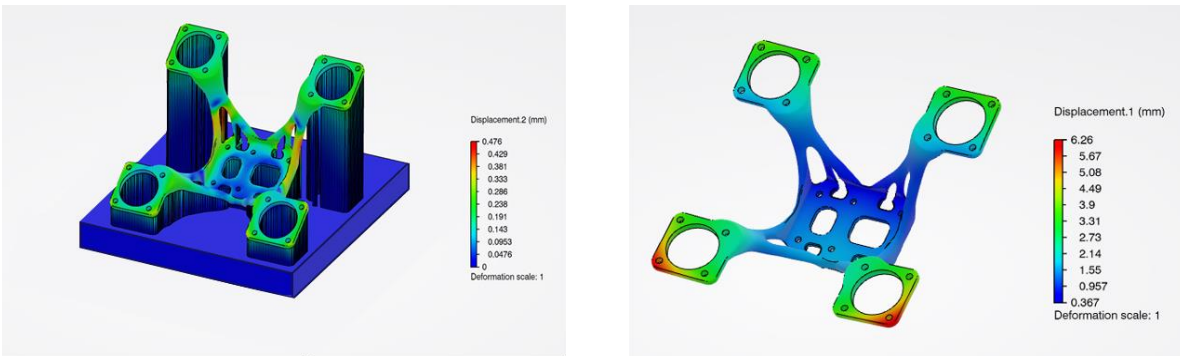
$$\sigma^0 = [A + B(\epsilon^{-pl})^n](1 - \hat{\theta}^m)$$

Where ϵ^{-pl} is the equivalent plastic strain and A, B, n, and m are material parameters measured at or below the transition temperature, $\theta_{transition}$. $\hat{\theta}$ is the non-dimensional temperature defined as:

$$\hat{\theta} = \begin{cases} 0 & \text{for } \theta < \theta_{transition} \\ (\theta - \theta_{transition}) \, / \, (\theta_{melt} - \theta_{transition}) & \text{for } \theta_{transition} \leq \theta \leq \theta_{melt} \\ 1 & \text{for } \theta > \theta_{melt} \end{cases}$$

Where θ is the current temperature, θ_{melt} is the melting temperature, and $\theta_{transition}$ is the transition temperature defined as the one at or below which there is no temperature dependence of the yield stress.

Radiation and convection were modeled on a continuously evolving surface that reflects the current free-surface shape of the part at any given point in the build. The sequentially coupled thermal mechanical analysis was performed to predict temperatures, distortions, and residual stresses. In the heat transfer analysis, initial temperatures for build tray and powder were defined as per the physical build. The initial temperature defined in the structural analysis represents a relaxation temperature, above which thermal straining induces negligible thermal stresses. This temperature is material dependent and it is no higher than the melting temperature of the material. In this study, it was observed that this temperature had a significant effect on distortion results. The martensitic decomposition temperature for Ti6Al4V is 600–650ºC [20] so this was set as relaxation temperature. The heat transfer analysis provided the temperature history of the process, which then drove the subsequent structural analysis to compute the distortions and stresses. In both thermal and structural analyses, additional steps were added after the build analysis that included cooling the part to room temperature, removing the part from the build plate, and finallys removing the support structures from the part. Part removal was done using the Model Change technique in the solver. The distortions observed at the end of the cooling step and after removing the supports are as shown in figure 3.



a) b)

Fig. 3 a) Displacement after cooling b) Displacement afterremoval of build plate and supports

VI. Deviation Analysis

CMM measurement point cloud data of the final build part was imported into the **3D**EXPERIENCE platform in ASCII format using Digitized Shape Preparation application. While importing the data, scale factor and file unit was correctly selected. Using the 3D Mesher functionality on this application a 3D mesh was created from previously imported cloud points as shown in figure 4.

a) b)

Fig. 4 a) Point cloud data b) Converted mesh

This mesh was then oriented with the original CAD geometry by referencing the bolt positions from the central hub region of the original geometry as shown in figure 1 for comparison. Figure 5 shows the resulting mesh superimposed on the original CAD. In this figure, circle 1 shows how both mesh and geometry is aligned using bolt positions and flat surface of central hub. Circle 2and 3 shows that two legs out of four are distorted severely.

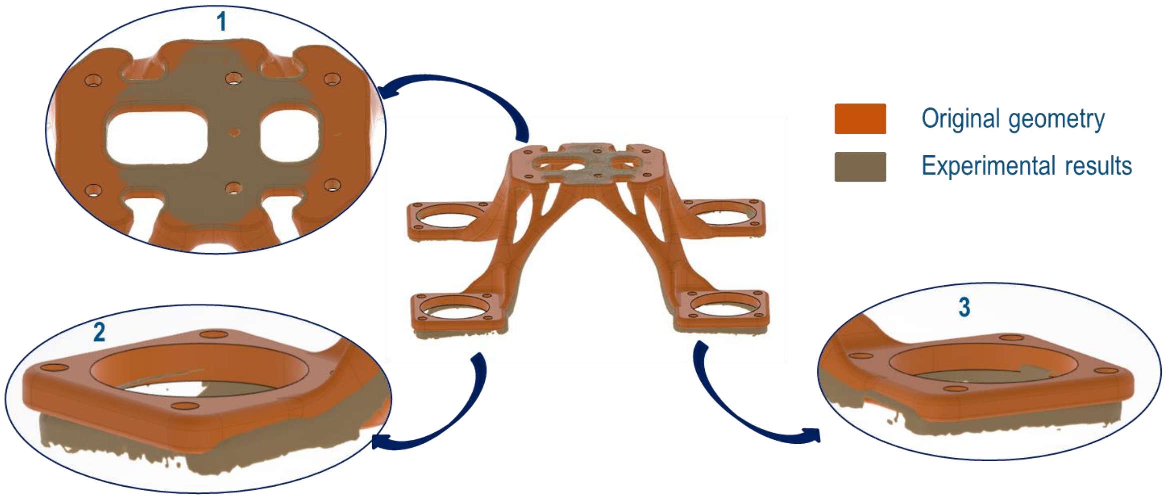


Fig. 5 Original CAD and Experimental results mesh alignment

A. Original Design Vs. Printed Component Comparison

Using the same application, deviation analysis was performed between the original CAD and the experimental measurements to quantify the deformation trends. Figure 6 shows the result of deviation analysis. It clearly shows that two legs out of four are distorted and can be seen through red contour.

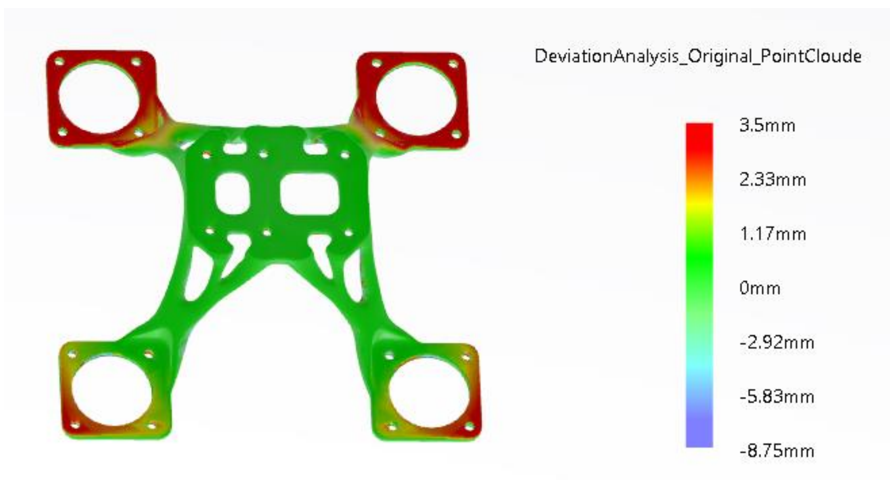


Fig. 6 Deviation analysis of experimental results w.r.t. original CAD

B. Printed Part Vs. Simulation Results Comparison

For this step, a CAD representation of the deformed build part, as predicted by simulation was required. The displacement outputs for exterior nodes of the part were extracted from the simulation results into a tabulated vector field. The vector field was then transformed to map the predicted displacement results onto the original geometry location. Digital morphing was then performed on the original CAD object using this displacement vector field to generate deformed geometry representing the predicted as-built part. Deviation analysis was then performed to quantify the correlation between simulation results and experimental measurements. Figure 7 shows that simulation results match with experimental results to a good extent and deviation analysis mostly shows green contour. Tolerance legend on the right shows that more than 80% points are within ±2.5mm tolerance.

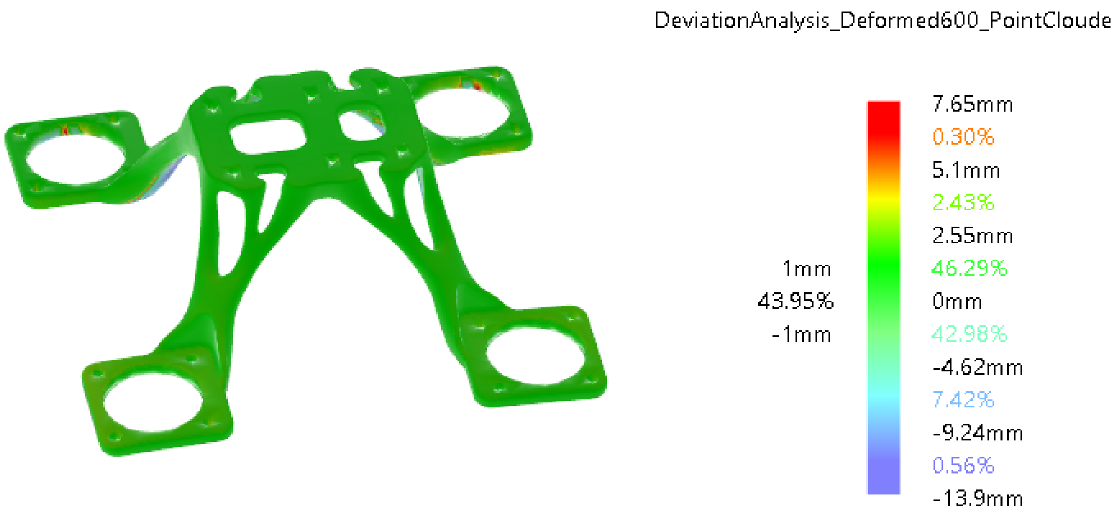


Fig. 7 Deviation Analysis of simulation results w.r.t experimental results

VII. Conclusion

Selective Laser Melting is a complex additive manufacturing process where a material undergoes rapid heating and cooling which in turn generates residual stresses and distortion. Effects like part distortion get amplified after removing the part from the buid plate and support removal. Therefore, accurate prediction of distortion through finite element analysis and its fidelity, plays a critical role in part development and establishing the technology. Material properties used in the analysis played a very important role in accurately predicting part distortions, assuming all other process parameters were correctly defined.

Reverse engineering functionalities on **3D**EXPERIENCE platform like importing cloud point data, converting the data into 3D mesh effectively helped in comparing simulation results with experimental data for a complex industrial component. Future work includes compensating the original CAD geometry based on experimental results and then iterating the process simulation to get results as close to original geometry. This compensated geometry can then be sent to a printer for getting better results.

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