Computational Modeling of Residual Stress Formation during the Electron Beam Melting Process for Inconel 718

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Abstract

A computational modeling approach to simulate residual stress formation during the Electron Beam Melting (EBM) process within the Additive Manufacturing (AM) technologies for Inconel 718 is presented in this paper. The EBM process has demonstrated a high potential to fabricate components with complex geometries, but the resulting components are influenced by the thermal cycles observed during the manufacturing process. When processing nickel based superalloys, very high temperatures (approx. 1000 C) are observed in the powder bed, base plate, and build. These high temperatures, when combined with substrate adherence, can result in warping of the base plate and affect the final component by causing defects. It is important to have an understanding of the thermo-mechanical response of the entire system, that is, its mechanical behavior towards thermal loading occurring during the EBM process prior to manufacturing a component. Therefore, computational models to predict the response of the system during the EBM process will aid in eliminating the undesired process conditions, a-priori, in order to fabricate the optimum component. Such a comprehensive computational modeling approach demonstrated to analyze the warping of the base plate, stress and plastic strain accumulation within the material, and thermal cycles in the system during different stages of the EBM process.
1. Introduction

Powder Bed Fusion is a specific category of Additive Manufacturing (AM) that forms parts layer-by-layer using a bed of metal powder and a heat source. Laser Melting (LM) uses a laser beam as the heat source and Electron Beam Melting (EBM) uses an electron beam. Recent research efforts have focused on developing Inconel 718, a nickel-based superalloy attractive material for aerospace and energy applications involving high-temperature applications, for production using LM [1, 2, 3, 4] and EBM [5, 2, 6, 7]. The cost associated with machining and shaping Ni-based alloys can be reduced in some cases by using the EBM process [8].

Extensive work has been conducted by researchers for model development and material property characterization for laser AM process [9, 10, 11, 12, 13, 14, 1, 15, 16]. Previous work on EBM Inconel 718 has focused on characterizing the as-fabricated and post-processed microstructure. Parts produced in these studies are typically removed from the build substrate, or base plate, for testing and analysis by metal saws or wire electro-discharge machining. The EBM build substrate is traditionally stainless steel, which forms a brittle interface with the commonly processed Ti-6Al-4V alloy [17]. The stainless steel interface with Inconel 718 is not brittle, which leads to interesting residual stress as well as the additional step of substrate removal.

The origin of residual stress in AM processes is due to either (1) differential heating of solid forming large thermal gradients or (2) differential cooling. Previous work [18] to experimentally quantify residual stress has shown that residual stress is compressive near the center of parts and tensile at the edge. Additionally, measurements of parts adhered to the build plate showed concentration near the substrate interface [19]. Laser free formed material showed residual stress of 50-80 % of the yield stress [20], whereas EBM material shows only 5-10 % of UTS [21]. Substrate warping, or deformation during the AM build process, and its physical relationship to residual stress has been noted in LM [22].
There has been limited work to model substrate deformation [23], and no work has been published to study the impact on EBM processed material. Previous work has confirmed residual stress concentration near the substrate interface. [14] Other work has calculated geometric deformation in LM parts, demonstrating the usefulness of using FEA tools for studying AM processes [24]. Due to the higher operating temperature of the EBM process (approximately 1000°C for Inconel 718), modeling work is important to better understand this phenomenon.

**Motivation**

Using an Arcam EBM system, Inconel builds were fabricated at the Manufacturing Demonstration Facility (MDF) at the Oak Ridge National Laboratory (ORNL), TN. Warping in the base plate was observed in some cases, causing the build to have irregular layers near the base plate. In a few cases, difficulties to proceed to the next layers were faced due to excessive deformation of the base plate. In order to avoid such setbacks during the EBM process, computational models that are able to predict such mechanical behavior a priori are useful to developing and implementing solutions.

### 2. Computational Model

The computational model considered for this study is a build with tensile test coupons as shown in Fig. 1. The build consists of a Inconel 718 powder bed (red region), a stainless steel base plate (blue region) and six Inconel 718 coupons (green region). The base plate is sintered into the powder bed, as shown in Fig. 1(a). The coupon dimensions are 8 cm x 1.8 cm x 2 cm, and the dimension of the base plate are 15 cm x 15 cm x 1 cm. For clarity, Fig. 1(b) displays only the tensile test coupons and the base plate.

A layer by layer model for the coupon build with 50 layers is constructed using commercially available finite element analysis (FEA) software (ABAQUS 6.12) to simulate the EBM process. A thermal analysis is conducted first to determine the temperature distribution within the model, followed by a structural analysis to determine the stress,
Figure 1: Tensile Test Coupon Build Model (a) with Powder Bed and (b) without Powder Bed

stain and deformation caused due to the heat imparted to the model during the EBM process. Details of the material properties used, the thermal and the stress analyses conducted are given in the following sections.

3. Material System

The properties of Inconel 718, stainless steel and the sintered powder is given in this section. The heat transfer analysis requires the variation of properties like, density, thermal conductivity and specific heat capacity of the three materials with temperature. Further, for the structural analysis an elastic-plastic behavior for the the build and the base plate is assumed. Therefore, the properties required are the elastic modulus, Poisson’s ratio, yield stress, hardening behavior and the coefficient of thermal expansion variation with temperature.

<table>
<thead>
<tr>
<th>Table 1: Thermo-Physical Properties</th>
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<tr>
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<tr>
<td><strong>Temperature</strong></td>
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<tr>
<td><strong>Density</strong></td>
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<tr>
<td><strong>Thermal Conductivity</strong></td>
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<tr>
<td><strong>Specific Heat Capacity</strong></td>
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</table>
The thermal-physical and mechanical properties used in the model are given in Table 1 and Table 2, respectively.

<table>
<thead>
<tr>
<th></th>
<th>Inconel 718 [26, 27]</th>
<th>Stainless Steel [26, 27]</th>
<th>Powder Bed (Assumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>93 °C 760 °C</td>
<td>20 °C 500 °C</td>
<td>25 °C 500 °C</td>
</tr>
<tr>
<td><strong>Elastic Modulus</strong></td>
<td>205 162</td>
<td>200 165</td>
<td>20 12</td>
</tr>
<tr>
<td><strong>Poisson’s Ratio</strong></td>
<td>0.3 0.3</td>
<td>0.28 0.28</td>
<td>0.1 0.1</td>
</tr>
<tr>
<td><strong>Yield Stress</strong></td>
<td>1172 758</td>
<td>215 122</td>
<td>- -</td>
</tr>
<tr>
<td><strong>Hardening Coefficient</strong></td>
<td>0.637 0.637</td>
<td>0.206 0.206</td>
<td>- -</td>
</tr>
<tr>
<td><strong>Coeff. of Thermal Expansion</strong></td>
<td>12.8e-6 16e-6</td>
<td>16e-6 18e-6</td>
<td>6e-6 8e-6</td>
</tr>
</tbody>
</table>

4. Thermal Analysis

The thermal analysis consists of a heat transfer problem to be solved to determine the spatial and temporal distribution of temperature during the EBM process. Towards that, layer-by-layer heat transfer is conducted in this paper. A temperature profile shown in Fig. 2 is imparted on each layer of the build, followed by a cool down process after all the layers are built. The maximum temperature applied on each layer of the build is 1500°C. Since the model does not account for radiation effects from the surface, a lower temperature than that expected during the EBM process is assumed to be applied on each of the layers.

![Figure 2: Temperature Profile applied to the Model during the EBM Process](image-url)
From the first law of thermodynamics, the heat equation accounting for the heat generated and conducted is given by,

\[ \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( K \frac{\partial T}{\partial x} \right) \] (1)

The spatial and temporal distribution of temperature in the entire system for the complete period of the EBM process is determined.

The temperature distribution in the model corresponding to the completion of different number of layers is shown in Fig. 3. It is observed that the influence of temperature applied on the layers to the base plate reduces as the layers are built up. This implies that the thermal impact on the base plate reduces as the number of layer of the build increases, and is restricted to only a few build layers beneath them, as shown in Fig. 3.
5. Stress Analysis

The temperature distribution in the model for the entire process obtained from the thermal analysis is then applied to the model in order to conduct the stress analysis. Again, a layer-by-layer analysis is conducted to investigate the influence of the heat applied during the EBM process on the stress, strain and deformation in the model.

The equilibrium equation shown below is solved numerically within the FEM framework to determine the displacement field in the model for the temperature field and mechanical boundary conditions applied.

\[
\frac{\partial \sigma}{\partial x} + f = 0
\]

\[
u_1 = 0 \ @ \ x_1 = 0; \ u_1 = 0 \ @ \ x_1 = L
\]

\[
u_2 = 0 \ @ \ x_2 = 0; \ u_2 = 0 \ @ \ x_2 = W
\]

\[
u_3 = 0 \ @ \ x_3 = 0
\]

(2)

where, \( u_i, \) \( i = 1, 2, 3 \) are the displacements in the x, y and z-directions, \( L \) and \( W \) are the dimensions of the powder bed in the x and y-directions, respectively. The bottom of the powder bed \( (x_3 = 0) \) is fixed \( (u_3 = 0) \) in the z-direction. The fixed boundary conditions applied are on the faces of the powder bed, and and not on the base plate or the build. Therefore, the base plate and build are sitting on a bed of the Inconel 718 powder.

The maximum principal strain and stress on the top and bottom faces of the base plate are plotted in Fig. 4. Stresses and plastic strain accumulation in the base plate appear to be high after the end of the EBM process, which indicate that the coupons obtained will be deformed. Therefore, the quality of the coupons are affected by the warping of the base plate during the EBM process.

The deformation of the base plate along with the build is shown in Fig. 5 at different times that correspond to different number of layers built on the base plate. It is
observed that the top face of the base plate bulges upward during the build process. The red regions around the build represent higher extent of the bulge compared to the builds, which implies that there is a warping in the plate that causes the coupons to be deformed. The bulge in the base plate reduces with increasing number of layers of
the build, hinting that the layers built later are less deformed than the initial layers of the build. After cool down there is a permanent upward warp in the base plate, but the top of the build is fairly flat. Therefore, the bottom layers in the build are warped more than the upper layers. Similar behavior is observed during the EBM process with stainless steel base plate.

6. Qualitative Comparison of Deformation

A qualitative comparison of the deformation of the base plate and the coupon build is conducted in this section. The plate deflection observed in the computational model is qualitatively similar to the one observed in the experiments. The side views of the plate deformation in the out of plane direction is shown in Fig. 6.

![Image of deformation comparison]

Figure 6: Comparison of the Model Deformation with Experiments

The deformation in the plate and the build are shown in Fig. 7. An overall warping of the base plate is observed (Fig. 7(a)). A closer view of the build, shown in Fig. 7(b), indicates that the build layers in the vicinity of the base plate are warped, but they tend to become more even away from the base plate.

It is hypothesized that the warping of the base plate occurs during the building of the initial few layers, due to the intensity of the electron beam. The influence of the beam on the base plate reduces as the build progresses away from the baseplate. It is observed in the computational model (Fig. 5) that the edges surrounding the build appear to warp causing the bottom layers to warp as well. Therefore, measures should
be taken during the initial stages of the EBM process to avoid any such warping in the baseplate from occurring.

7. Conclusion

In this paper, a computational modeling approach to simulate the EBM process within an Arcam machine is developed. A layer-by-layer model is constructed, and thermal and stress analyses are conducted within the FEA framework to determine the deformation and stresses in the build and the base plate. Warping in the baseplate and the initial layers of the build was observed post the EBM process. It was observed that the warping in the base plate and the build occurred during the construction of the first few layers using the computational model. The model predictions were qualitatively comparable to the deformations observed in the base plate and the build manufactured using EBM.

Such a modeling approach has a potential to aid in understanding the behavior of the manufactured components during the EBM process. Undesired process conditions can be eliminated if the deformation observed during the simulation of the process is excessive that could potentially result in bad build or process. Therefore, the modeling approach presented in this paper can be used as a design tool to minimize the trial and error associated with the EBM process.
8. Acknowledgements

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References


[25] COMSOL materials library [Inconel 718 (UNS N07718); Stainless Steel 304 (UNS S30400 solid polished)].
