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## Original Research Article

# Simulation of Residual Stress in Additive Manufacturing Process Using Finite Element Analysis

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## ABSTRACT

Selective laser melting (SLM) has emerged as a powerful additive manufacturing technique for creating complex metal parts. However, the high thermal gradients and rapid solidification rates inherent in this technique trigger significant residual stresses within the produced components. These stresses can potentially cause some defects such as cracks and deformation, threatening the structural integrity and performance of the parts. To overcome this challenge, this study employed a new Finite Element Analysis (FEA) feature in Abaqus software was employed in this study. This feature facilitates a more accurate prediction of residual stresses in the SLM-produced Ti-6Al-4V alloy samples under various laser power settings and real-world machine conditions. Simulating the SLM process and capturing the complex thermal and mechanical interactions would enable the researchers to identify the optimal laser power that minimizes the residual stress formation. The findings of this study brought about significant implications for the optimization of SLM processes. Once the factors that contribute to residual stress are identified, manufacturers can adjust process parameters to produce parts with improved mechanical properties and reduced risk of failure. In this regard, this research work is a significant step forward in using simulation to optimize additive manufacturing techniques in various industries.



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## 1. INTRODUCTION

Selective Laser Melting (SLM) offers a unique capability to produce complex titanium components with intricate internal structures. However, rapid heating and cooling cycles in SLM intensifies the residual stresses within the fabricated parts (Song et al., 2020). These stresses result in deformation and cracking, potentially threatening the structural integrity and performance of the components (Kruth et al., 2012; X. Li et al., 2022). To mitigate these risks, it is essential to optimize the SLM process parameters and gain a thorough understanding of the factors that affect the formation of residual stress (Salem et al., 2020). Several factors contribute to the formation of the residual stress in the SLM-produced

components, including the material properties, sample geometry, support structure design, process parameters (such as energy input, powder layer thickness, scanning technique, and preheating), and building direction (Xiao et al., 2020). By carefully considering and controlling these factors, it is possible to minimize the residual stresses and produce high-quality SLM components.

Thermal gradients are known as the primary driver of residual stress. These gradients, caused by temperature variation across the material, can result in uneven expansion and contraction of the material, hence the formation of residual stresses (Ahmed et al., 2023). Laser power is the primary factor that affects the temperature variations within a material during laser-based processes.

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A higher laser power setting provides more significant temperature differences, thereby significantly contributing to the formation of residual stresses. While both scanning speed and hatch spacing play a key role in temperature distribution, laser power is generally considered the most influential parameter (He et al., 2023). Increased laser power results in higher peak temperatures in the molten pool (C. Li et al., 2024), accelerating the cooling rate and potentially causing uneven material expansion. However, by carefully adjusting the distribution of laser power, it is possible to mitigate these effects and create a more uniform temperature field within the material, thereby improving the overall temperature management (Murzin et al., 2016).

Finite Element Analysis (FEA) proved to be a valuable tool for simulating the SLM process and predicting residual stress distribution. However, traditional FEA methods often require expertise in Fortran programming and thermodynamics theory, limiting their accessibility to a specialized group of researchers and engineers. To address this challenge, the AM Modeler plugin was developed as a user-friendly interface for Abaqus software (An et al., 2021).

In this study, the AM Modeler plugin was utilized to quantify residual stress in the SLM-fabricated Ti-6Al-4V components. To investigate the effect of laser power on the residual stress, simulations were conducted across a range of laser power settings. The obtained results from these simulations were in good agreement with the experimental data reported in the previous studies, thus validating the accuracy and effectiveness of the AM Modeler plugin for predicting residual stress in SLM-produced parts. This tool represents a significant advancement in the field of additive manufacturing, enabling researchers and engineers to optimize SLM processes, particularly with respect to laser power, and ensure the production of high-quality components with minimal residual stress.

## 2. MATERIALS AND METHODS

The material used in this study was Ti-6Al-4V alloy, a titanium alloy in additive manufacturing, which is commonly used owing to its excellent mechanical properties and biocompatibility. Given the significant differences in the thermal properties of the powder and solid forms, the properties of the material were assumed to vary with temperature. These temperature-dependent properties (Lu et al., 2019) were incorporated into the simulation based on the data provided in Table 1.

To accurately model the heat source introduced during the laser melting process, Goldak heat source model (Homami & Ojo, 2023) was employed to carry out residual stress analysis through the numerical simulation in powder bed additive manufacturing based on the representative volume approach. The model was defined based on the mesh size of the simulation domain.

AM Modeler, a specialized plugin for Abaqus software, was used to simulate the SLM process. This plugin provides dedicated tools for AM process simulation, thus eliminating the need for users to develop custom user subroutines.

A rectangular sample with the dimensions of  $5 \times 5 \times 4$  mm was fabricated in the z direction. The residual stress simulations were conducted under varying laser power settings, ranging from 100 to 250 W in 50W increments, while keeping all other process parameters constant. To simulate the support provided by the substrate, the XY plane of the component was constrained. As shown in Figure 1, the thermal simulation was completed for different laser power levels at a constant scanning speed of 10 mm/s.

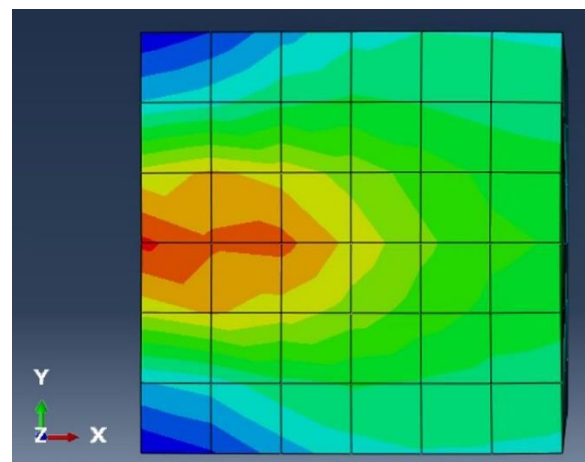


Figure 1. Thermal Simulation of Ti-6Al-4V Component

Following the completion of thermal simulations under various laser power settings, the mechanical simulations were conducted for each thermal history. To evaluate the residual stress distribution within the component, a vertical path was defined from the bottom to the top of the sample, as illustrated in Figure 2. This path facilitates the analysis of residual stress variation along the z-direction.

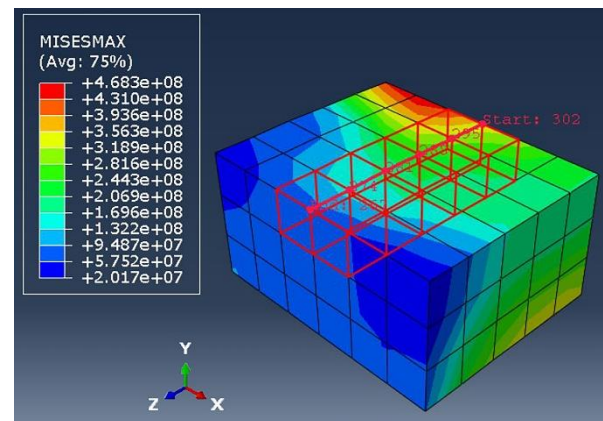


Figure 2. The defined path for residual stress analysis in a Ti-6Al-4V component

**TABLE 1.** Temperature-Dependent properties of Ti-6Al-4V(Lu et al., 2019)

Temperature (°C)	Density (kg/m <sup>3</sup> )	Thermal Conductivity (W/m°C)	Heat Capacity (J/kg°C)	Poisson's Ratio	Thermal Expansion Coefficient (µm/m°C)	Young's Modulus (GPa)	Elastic Limit (MPa)
20	4420	7	546	0.345	8.78	110	850
205	4395	8.75	584	0.35	10	100	630
500	4350	12.6	651	0.37	11.2	76	470
995	4282	22.7	753	0.43	12.3	15	13
1100	4267	19.3	641	0.43	12.4	5	5
1200	4252	21	660	0.43	12.42	4	1
1600	4198	25.8	732	0.43	12.5	1	0.5
1650	3886	83.5	831	0.43	12.5	0.1	0.1
2000	3818	83.5	831	0.43	12.5	0.01	0.01

### 3. RESULTS AND DISCUSSION

Figure 3 illustrates the predicted residual stress distribution on the bottom plane of an SLM-produced component. The analysis reveals a non-uniform stress distribution, with a pronounced stress concentration in a specific region. Such stress concentrations are often identified as potential failure sites.

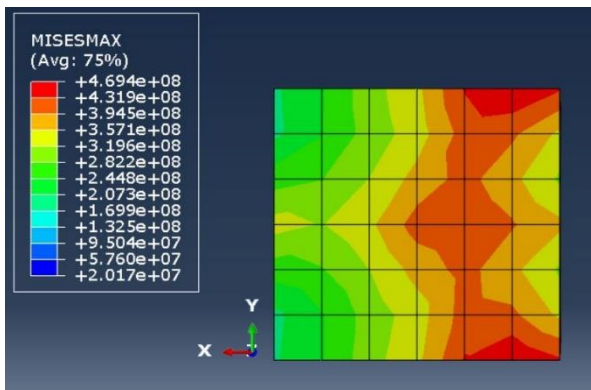
**Figure 3.** Stress distribution on the bottom plane

Figure 4 illustrates the distribution of the residual stress within the component after a two-second cooling period, considering various laser power settings. The results reveal that the most significant residual stresses are concentrated at the base of the component, which is fixed to mimic the substrate. As the depth increases, the residual stress gradually diminishes. The middle layers of the conducted part is characterized by higher stress than the top layer. Due to its ability to deform freely, the top layer has significantly lower stress levels than the interface layer (Fang et al., 2020).

It should be noted that laser power also plays a crucial role in determining residual stress levels. Lower laser power settings generally result in lower residual stress values (Ali et al., 2018). On the contrary, higher laser power settings cause more rapid heating and cooling rates

within the material. This rapid temperature change creates steeper thermal gradients which, in turn, contributes to higher residual stresses. The increased thermal gradients cause uneven expansion and contraction of the material, resulting in localized stress concentrations.

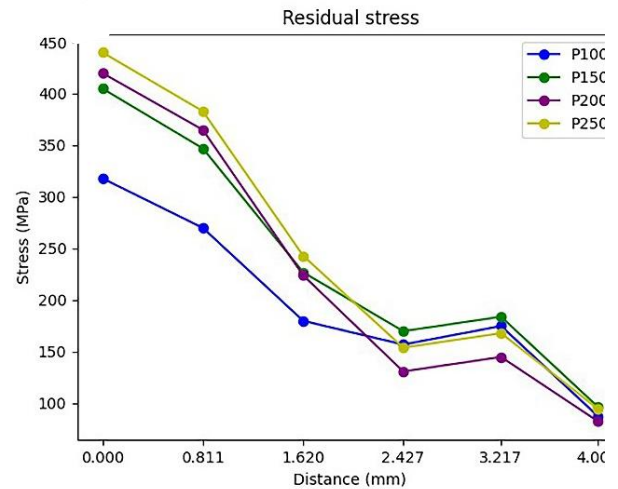
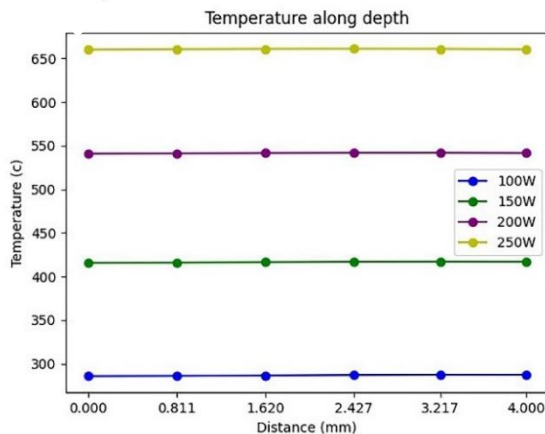
**Figure 4.** Comparison of residual stresses distribution along depth for different laser powers in SLM-produced component

Figure 5 presents the temperature distribution within the component following the same cooling period. At this point, the temperature seems to be relatively uniform throughout the component. This phenomenon occurs due to heat conduction, which facilitates the heat transfer from warmer to cooler regions. Over time, this heat diffusion process results in a state of thermal equilibrium where the temperature is evenly distributed across the component (Marques et al., 2020). Additionally, according to the data presented in the graph, there is a positive relationship between laser power and final temperature after a consistent processing time.



**Figure 5.** Temperature distribution along depth after 2 seconds of cooling for different specimens

#### 4. CONCLUSION

The AM plugin employed in this study effectively simulated residual stress in additive manufacturing processes, demonstrating comparable accuracy to the traditional methods. This validation highlights the plugin value as a multipurpose tool for researchers and engineers studying thermomechanical phenomena. The plugin's user-friendly interface, which eliminates the need for extensive technical knowledge, makes it accessible to a wide range of users.

A particular strength of the AM plugin is its ability to accurately simulate the effects of different laser power settings on the residual stress. This is crucial for optimizing additive manufacturing processes since the laser power is a key factor affecting the thermal gradients and, consequently, residual stress. By accurately predicting the impact of the laser power on the residual stress, the AM plugin can help engineers design and control additive manufacturing processes to minimize unwanted deformations and ensure the production of high-quality components.

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