The Residual Stress Distribution of Ti-6Al-4V Thin Wall in the Selective Laser Melting

Changpeng Chen, Haihong Zhu*, Zhongxu Xiao, Shiwen Liu, Jie Yin, Xiaoyan Zeng
Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, Hubei, 430074, PR China

*Corresponding author: zhuhh@mail.hust.edu.cn; 86-27-87544774

Abstract. High residual stress caused by the high temperature gradient brings undesired effects such as shrinkage and cracking in the SLM process. This study developed a layer-by-layer 3D FE model based on sequentially coupled thermal-structural method to predict the residual stress distribution and the stress variations of Ti-6Al-4V thin wall. The X-component of stress has the greatest impact on the residual stress distribution of the thin wall, followed by the Z-component of stress, and the smallest is the Y-component of stress. The maximum residual stress is observed at the corner of the interface between the part and substrate, the secondary stress is near the top center region of the part. The findings of this study will provide a better understanding of residual stress distribution in the SLM and constructive guidance for process parameter optimization.

1. Introduction
Selective laser melting (SLM), well known as a type of additive manufacturing (AM), is a promising technology for the rapid manufacturing of three-dimensional (3D) parts with complex structures[1, 2]. However, in the SLM process, the local heat input caused by the high-energy laser beam leads to a high temperature gradient, which causes large residual stresses and undesired thermal deformation, and even fails to shape the part [3, 4].

The investigation of the residual stress in the SLM has attracted much attention in the past years. Mercelis and Kruth [4] found that the parts connected to the substrate contained very high levels stress while contained low stress levels when parts removing from the substrate. Hussein et al.[5] predicted high equivalent stress within a layer and alternating compressive and tensile residual stress within each track. Yadroitsev and Yadroitsava[6] found that the maximum stress was at the point where the sample joins with the substrate, the similar results also reported by Gu and He[7]. Ghasri-Khouzani et al.[8] measured a large tensile in-plane stress (up to ≈ 400 MPa) near the as-built disk top surfaces and found a marked breakdown of self-similarity in the residual stress distribution using Neutron diffraction method. Anderson et al.[9] used the neutron diffraction to determine the distribution of residual stress in a set of SLMed block. Wang and Chou[10] observed that there was a sharp variation in the average residual stress magnitude at the interface corner between the solid and the overhang. However, the residual stress distribution of Ti-6Al-4V thin wall in the SLM is not clear yet.

In the study, a layer-by-layer 3D FE model based on sequentially coupled thermal-structural method is developed to predict the residual stress distribution and the stress variations of Ti-6Al-4V thin wall.
The findings of this study will provide a better understanding of residual stress distribution in the SLM and constructive guidance for process parameter optimization.

2. The 3D FE Model for the SLM Process

2.1. Basic Equations in the Thermal and Structural Analysis

2.1.1. Governing Equations of Heat Transfer. The governing equations of thermal analysis for three-dimensional heat transfer can be expressed as follows:

\[ \rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + q \]

where, \( \rho \) is material density (kg/m\(^3\)); \( c \) is specific heat capacity (J/kg \(^\circ\)C); \( T \) is temperature (\(^\circ\)C); \( t \) is interaction time of powder and heat source (s); \( k_x, k_y \) and \( k_z \) are the thermal conductivities (W/m \(^\circ\)C) of x, y and z directions; \( q \) is heat generation per unit volume (W/m\(^3\) s).

The initial temperature of finite models is set to ambient temperature, which is 25 \(^\circ\)C. In order to obtain more accurate simulation results, the combined radiative and convective heat transfer coefficient are considered to calculate heat transfer between powder bed and the environment, it can be described as [11]:

\[ h = h_{\text{conv}} + \varepsilon \sigma (T^2 + T_{\text{amb}}^2)(T + T_{\text{amb}}) \]

where \( h \) is the combined radiative and convective heat transfer coefficient; \( h_{\text{conv}} \) is the convection heat transfer coefficient; \( \varepsilon \) is the emissivity of the powder bed; \( \sigma \) is the Stefan Boltzmann constant.

2.1.2. The Basic Equations of Structural Analysis. During SLM, a large temperature gradient is generated due to high energy input concentrated a small region, which can lead to large thermal stresses and strain. The relationship between stress and strain is defined as:

\[ \{\sigma\} = [D]\{\varepsilon\} \]

where \( \{\sigma\} \) is the stress vector; \([D]\) is the elasticity matrix; \( \{\varepsilon\} \) is the elastic strain vector. Meanwhile, the simplified ideal elastic-plastic model is used in this model, therefore, \( \{\varepsilon\} \) can be expressed as follows:

\[ \{\varepsilon\} = \{\varepsilon\} - \{\varepsilon^p\} - \{\varepsilon^t\} \]

where \( \{\varepsilon\}, \{\varepsilon^p\} \) and \( \{\varepsilon^t\} \) are the total strain vector, the plastic strain vector, and the thermal strain vector, respectively.

The Von Mises yield criterion is used in this model and equivalent stress, \( \sigma_e \) is computed as:

\[ \sigma_e = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} \]

where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the three principal stresses.
2.2. Layer-by-layer Model

2.2.1. Methodology. In the SLM, the three-dimensional size of the components reaches tens or even hundreds of millimeters. However, the laser beam spot diameter is only sub-millimeter, which indicates that tens of thousands or even millions of scanning tracks are needed for fabricating the parts. At the same time, the forming process will take dozens of hours. Therefore, the current computing power is difficult to simulate this process, and develop a model that fully reflect the process is also not practical. A reasonable predicting model must be developed to quickly obtain the residual stress distribution of large-scale parts.

In the study, a layer-by-layer 3D FE model that ignores intra-layer scanning strategies is developed. In the model, the part is divided into multiple layers along the deposition height direction. Each layer has equal thickness and consists of one or multiple powder layer for improving the computing efficiency. The process that laser scanning the powder layer is simplified into a process that heating the segmentation layer using a volume heat resource ($Q$). The volume heat source is calculated based on process parameters:

$$Q = m \frac{AP}{DHk}$$  \hspace{1cm} (6)

where $m$ is the heat source coefficient, $A$ is the laser absorption coefficient, $P$ is the laser powder, $D$ is the laser beam spot diameter, $H$ is hatch spacing, $k$ is the powder layer thickness.

After the heating phase of the current layer is completed, there is a cooling phase with a powder recoating time (20 s). This process is repeated until the part is completed and the residual stress distribution is obtained after the parts is cooled down to room temperature.

Several assumptions have been applied in the layer-by-layer model for simplifying simulation:

- The whole powder bed is considered to be homogeneous and continuous media.
- The heat transfer at the bottom of the model can be assumed to be negligible due to the fact that the substrate is much larger than the manufacturing zone.
- The effect of scanning strategies in the layers is ignored for improving calculating efficiency.

2.2.2. 3D FEM Model Meshing. Figure 1 depicts the 3D FE model and meshing, the Ti-6Al-4V thin wall has a length of 50 mm, a width 5 mm and a height of 20 mm, the metal substrate of Ti-6Al-4V alloy with dimensions of 100×20×30 mm$^3$. The the laser scanning region is fine meshed with hexahedral element (0.5×0.5×0.8 mm$^3$), the coarser mesh is adopted for the surrounding substrate. The process parameters used in the study are listed in Table 1.

![Figure 1. 3D finite element model and meshing](image)
2.2.3. Ti-6Al-4V material properties in residual stress analysis. In order to ensure the prediction accuracy of the residual stress model, the authoritative structural properties of material are obtained, the temperature-dependent material properties in structural analysis are shown in Table 2.

Table 2. The temperature-dependent structural properties for bulk Ti-6Al-4V

| Temperature (°C) | Elastic modulus, $E_t$ (GPa) | Thermal expansion coefficient, $a \times 10^{-6}/(1/°C)$ | Yield strength, $\sigma_{0.2}$ (MPa) | Poisson’s ratio, $\nu$ | Temperature (°C) | Elastic modulus, $E_p$(GPa) |
|------------------|------------------------------|--------------------------------------------------|---------------------------------|-----------------|------------------|------------------|
| 23               | 125                          | 8.78                                            | 1000                            | 0.34            | 25               | 2.87             |
| 260              | 110                          | 9.83                                            | 630                             | 0.35            | 300              | 2.88             |
| 316              | 100                          | 10.14                                           | 630                             | 0.35            | 427              | 1.62             |
| 427              | 100                          | 10.71                                           | 525                             | 0.36            | 482              | 0.41             |
| 538              | 80                           | 10.97                                           | 446                             | 0.37            | 650              | 0.40             |
| 600              | 74                           | 11.22                                           | 300                             | 0.38            | 800              | 0.45             |
| 825              | 55                           | 11.68                                           | 45                              | 0.39            | 805              | 0.44             |
| 850              | 27                           | 12.21                                           | 25                              | 0.42            | 900              | 0.43             |
| 1650             | 20                           | 12.5                                            | 5                               | 0.45            | 950              | 0.43             |

3. Results and Discussions

3.1. The Residual Stress Distribution of Thin Wall

Figure 2 depicts the residual stress distribution in the three direction after the part is cooled down to room temperature. As shown in Figure 2 (a), it is found that the maximum X-component of stress is observed at the corner of the interface between the part and substrate, and a large tensile X-component of stress is also found near the top region of the thin wall. For compressive stress, the values on both the sides of the thin wall is small while the substrate region under the thin wall is large ($\approx$-500 MPa). Other regions and the bottom region of the substrate are small. The distribution of the Y-component of stress is depicted in Figure 2 (b), the residual stress is small except for the corner of the interface between the part and substrate. For the Z-component of stress, as shown in Figure 2 (c), there is a large compressive stress region inside the thin wall and still a large tensile stress is found the corner of the interface between the part and substrate.

Comparing the residual stress in the X, Y and Z direction, the maximum residual stress is the X-component of stress, followed by the Z-component of stress, the Y-component of stress is the minimum. This is caused by the largest temperature gradient existing in the scanning direction, and Y-component of stress is easily released by deformation due to small size in the thin wall in the Y direction. As shown in Figure 2 (c), a large equivalent stress is found in the top region of the thin wall and it is similar to the X-component of stress as shown in Figure 2 (d). Moreover, the maximum stress is observed at the corner of the interface between the part and substrate due to all three stress components have a maximum at this position. This can be contributed to the high cooling rates and solidification at the bottom of part while the large constrain is imposed by the substrate.
3.2. The Residual Stress Distribution of Thin Wall

The stress variations along the deposition height of the thin wall is shown in Figure 3. It can be seen that both X and Y-component of stress show a transition from compressive stress to tensile stress as the deposition height increases, but the Z-component of stress is always compressive stress. The position of the tensile-compressive transformation is near the junction of the substrate and the thin wall, and a large stress fluctuation is also found at this location.

Furthermore, the maximum tensile stress in the X direction is found at the top surface of the thin wall and the value is 971.60 MPa, the maximum compressive stress is observed at $Z = -2.81$ mm which is -493.72 MPa. For the values of the Y-component of stress, the maxima of tensile and compressive stress are 310.70 and -307.94 MPa, respectively. The maximum compressive stress in the Z direction is -583.47 MPa and located at the junction of the substrate and the thin wall while the tensile stress can be ignored. As can be seen from the above, the maximum tensile stress is observed in the X direction while maximum compressive stress is found in Z direction. Therefore, the equivalent stresses at the bottom and top of the thin wall are close and the values are 1000.87 and 991.40 MPa respectively. Meanwhile, it is found that the X-component of stress has the greatest impact on equivalent stress in the thin wall, followed by the Z-component of stress, and the smallest is the Y-component of stress.
4. Conclusions
A layer-by-layer 3D FE model based on sequentially coupled thermal-structural method is developed to predict the residual stress distribution and the stress variations of Ti-6Al-4V thin wall. The residual stress in the three direction has different distribution along the deposition height. The X-component of stress has the greatest impact on residual stress distribution of the thin wall, followed by the Z-component of stress, and the smallest is the Y-component of stress. The maximum of residual stress is observed at the corner of the interface between the part and substrate, the secondary stress is near the top center region of the part. The findings of this study will provide a better understanding of residual stress distribution in the SLM and constructive guidance for process parameter optimization.

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