Thermal Behavior and Molten Pool Morphology during Laser 3D Printing Process of Alloy Steel Powder

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Abstract. In this paper, a finite element analysis (FEA) model is proposed to systematically study the thermal behavior of metal material in Selective Laser Melting (SLM) 3D printing process. It is found that the material undergoes a fast and complex thermal cycle process. Laser beam can re-heat the adjacent formed scanning track and layer, and also produce a certain preheating effect on the unformed powder bed of the adjacent scanning track when laser beam scans a track, which is conductive to improve metallurgical bonding performance of SLM-fabricated parts. With the increase of scanning tracks or scanning layers, the peak temperature and molten pool lifetime increase owing to the thermal accumulation effect, but the increasing trend gradually slows down. The peak temperature and lifetime of each scanning track center in the second layer are larger than those of the corresponding scanning tracks in the first layer, respectively. Furthermore, SLM experiments are carried out to study complicated molten pool morphology in SLM process. The results obtained in this study have certain guiding significance for understanding thermal mechanisms of SLM process.

1. Introduction

3D printing, also known as additive manufacturing, is an advanced rapid prototyping technology. With the rapid development of this technology, its application scope has been gradually broadened, covering many fields such as aviation, aerospace, military industry, automobile, etc. [1, 2]. The materials that can be manufactured also range from various non-metals, titanium alloys, aluminium alloys, and stainless steel to superalloys and composites [3, 4]. Selective Laser Melting (SLM) technology is one of 3D printing technologies that can manufacture metal parts with complex geometries, and uses high-energy laser beam to scan metal powder, so that metal powder is melted and then solidified. The technology has the advantages of high degree of freedom, no need of dies and rapid response, etc. [5, 6].

Foroozmehr et al. [7] established a three-dimensional FEA model to simulate and analyze the size change of molten pool in SLM process of 316L stainless steel, and predicted the influence of scanning speed on the molten pool behavior. Li et al. [8] established a FEA model to efficiently study the multi-physical phenomena related to the optimization of SLM process parameters of 316L stainless steel and alumina composites. Yuan et al. [9] simulated the temperature evolution of molten pool in SLM.
process of TiC/AlSi10Mg nanocomposites, taking into account the transition from powder to solid and temperature-related material properties.

Nowadays, although there have been many studies on the FEA of temperature field in SLM process, it is still necessary to further improve the finite element analysis model to study the thermal behavior of SLM process, which is of great significance to understand the thermal mechanisms of SLM process. In this paper, a FEA model is proposed to systematically study the thermal behavior of H13 tool steel materials in SLM process by using ABAQUS software. Meanwhile, SLM experiments are carried out to study complicated molten pool morphology in SLM process.

2. FEA model

2.1. Analysis model

Fig. 1 shows the three-dimensional FEA model of the SLM process established by ABAQUS software. The materials of the powder bed and substrate are H13 alloy steel and 45 steel, respectively. The mesh size of powder bed is 0.01 mm × 0.01 mm × 0.005 mm. The parameters used in the simulation are listed in Table 1.

![FEA model for SLM process.](image)

**Table 1. Laser processing parameters.**

| Parameter     | Laser power $P$ (W) | Scanning speed $v$ (mm/s) | Powder layer thickness $d$ (μm) | Hatch spacing $h$ (μm) |
|---------------|---------------------|---------------------------|---------------------------------|-----------------------|
| Value         | 200                 | 1000                      | 20                              | 90                    |

2.2. Key issues

2.2.1. Heat source model. The double ellipsoidal heat source is used to simulate the spatial input of the laser energy of the SLM process, and the DFLUX user subroutine of the ABAQUS software is applied to realize the scanning of the laser heat source according to the predetermined scanning strategy. The expression for the heat source model is:

$$q(x, y, z) = \frac{6\sqrt{3}P\eta}{\pi \sqrt{abc}} e^{-\frac{x^2}{a^2} - \frac{y^2}{b^2} - \frac{z^2}{c^2}}$$  \hspace{1cm} (1)

Where $P$ is the laser power, $\eta$ is the laser absorptivity, $a$, $b$ and $c$ are the shape parameters of the heat source, $x$, $y$ and $z$ are the local coordinates.
2.2.2. Phase change latent heat. The phase change latent heat in SLM process is treated by equivalent specific heat capacity method, expressing as:

\[ C'_P = C_P + \frac{L}{T_L - T_s} \]  

Where \( L \) is the phase change latent heat, \( T_L \) the liquidus of material, \( T_s \) the solidus of material, \( C_P \) is the actual specific heat capacity of material, \( C'_P \) is the modified specific heat capacity.

2.2.3. Material properties. In the finite element thermal simulation process, the thermal conductivity, specific heat capacity and density of the material vary with temperature changing, which are need to be defined.

3. Experiment investigation

The experiment was carried out using the SLM apparatus of EOS M280. The laser beam wavelength was 1064 nm and the laser beam diameter was 90 μm. The processing parameters and the laser scanning strategy were the same as those used in the simulation (see Fig. 1 and Table 1). After SLM, the molten pool morphology was characterized by a SEM of JSM-IT300 (JEOL, Japan) in secondary electron mode of 20 kV.

4. Results and discussion

4.1. Thermal cycle process

Figure 2 shows the thermal cycling process at the center of different scanning tracks (P1-P6). Similar temperature fluctuations are observed at all points. The horizontal dashed line shows the melting temperature of H13 alloy steel material (1454 °C). When the laser heat source scans to various points, the powder temperature increases sharply to extremely high temperature and melts, and then decreases sharply to a lower level as the laser heat source moves away, and then the material is solidified and formed. The slope of the curve represents the rate of temperature change. The steeper curve means the faster the temperature changing. It can be seen that the heating rate and cooling rate in SLM process are very fast. At the same time, there are lower temperature peaks at the adjacent points, which indicates that laser beam can re-heat the adjacent formed scanning track and layer, and also produce a certain preheating effect on the unformed powder bed of the adjacent scanning track when laser beam scans a track. The thermal conduction of materials makes the heat diffuse gradually, affecting adjacent points.

In addition, when the second layer is scanned, the center temperature of the corresponding track in the first layer is also higher than the melting temperature of the material. It can be seen that the adjacent layer is reheated, re-melted and solidified under the action of laser (Fig. 2(b)), ensuring a good metallurgical bonding between the adjacent layers, which contributes to obtaining SLM-fabricated parts with high density and excellent performance. At the same time, it also can be clearly seen that with the increase of scanning tracks or layers, the peak temperature of P1-P6 shows an increasing trend, and the temperature of each point in the upper layer is also higher than that of the corresponding points in the next layer. This is mainly due to the effect of thermal accumulation on the next scanning track and scanning layer, but this effect is gradually weakened.
4.2. Prediction of molten pool lifetime

Figure 3 shows the variation of the peak temperature and lifetime of the molten pool at the center of different scanning tracks (P1-P6). It can be found that the peak temperature and the lifetime of molten pool increase in turn with the increase of the scanning tracks or scanning layers, but this effect is gradually weakened. As shown in Fig. 3(a), in the first layer, the peak temperature at the center of the 1st scanning track (P1) to the center of the 3rd scanning track (P3) gradually increases from 2138 °C to 2327 °C by 8.84 %, and in the second layer, the peak temperature at the center of the 4th scanning track (P4) to the 6th scanning track (P6) gradually increases from 2202 °C to 2365 °C by 7.40 %. Meanwhile, the peak temperature of each scanning track center in the second layer is higher than the corresponding center of each scanning tracks in the first layer (P4: 2202 °C > P1: 2138 °C; P5: 2312 °C > P2: 2265 °C; P6: 2365 °C > P3: 2327 °C, with an increase rate of 2.99 %, 2.08 % and 1.63 %, respectively). This is mainly due to the heat accumulation effect, and with the increase of scanning tracks or scanning layers, the heat conduction capacity of the whole part is weakened.
In addition, as shown in Fig. 3(b), with the increase of scanning tracks, the lifetime of the molten pool increases from 0.170 ms to 0.204 ms by 20.0 % in the first layer, and from 0.192 ms to 0.235 ms by 22.4 % in the second layer. The lifetime of the molten pool in the second layer is longer than that in the corresponding first layer (P4: 0.192 ms > P1: 0.170 ms; P5: 0.224 ms > P2: 0.193 ms; P6: 0.235 ms > P3: 0.204 ms, with an increase rate of 12.9 %, 16.1 % and 15.2 %, respectively). This is because the size of the molten pool increases as the temperature of the molten pool increases. It universally acknowledged that a larger size of the molten pool means more liquid phase in the molten pool, which implies longer molten pool lifetime. It should be specified that the molten pool at high temperature has lower liquid phase viscosity and better fluidity, which is conducive to improving the spreading and wetting process of liquid metal between adjacent scanning tracks and adjacent scanning layers, and then the melted power could fully fill the pores and SLM-fabricated parts with excellent metallurgical bonding and high density are obtained.

4.3. Characteristic of molten pool morphology
Figure 4 shows typical molten pool morphology on the cross-section of H13 alloy steel specimen processed by SLM under $P=200$ W and $v=1000$ mm/s. The contour of the molten pool can be clearly observed, which reflects the characteristics of SLM process stacking and forming track by track and layer by layer. The cross-section of the molten pool is arc structure, which is mainly attributed to the gradual attenuation of laser energy with non-uniform distribution in space as the distance increases from the center of laser spot. However, the molten pool is not regularly arranged track by track and layer by layer, which may be related to the complex dynamic behavior of molten pool caused by the strong Marangoni convective heat and mass transfer effect [10] in SLM process, or the oxidation phenomenon caused by oxygen inclusion in powder disturbs the dynamic behavior of molten pool [11]. Moreover, it is demonstrated that there is a certain overlap rate between adjacent molten tracks due to laser re-melting between adjacent scanning tracks and adjacent layers, ensuring to achieve a sound metallurgical bonding in SLM process, which is conducive to obtaining SLM-fabricated parts with high density and excellent performance.
Figure 4. SEM images at (a) low and (b) high magnification showing the characteristic molten pool morphology on the cross-section of SLM-fabricated specimen under $P=200$ W and $v=1000$ mm/s.

5. Conclusion
In this paper, a three-dimensional FEA model is proposed to systematically study the thermal behavior in SLM process of metal materials on the basis of considering the phase change latent heat, multiple heat transfer mechanisms, thermos-physical properties varying with temperature, and the difference between material powder state and solid state. The following conclusions can be drawn:

(1) The center of each scanning tracks undergoes a similar temperature iteration process. This fast and complex thermal cycling process would lead to a rapid and complex stress cycling and microstructure evolution of the material. Laser beam can re-heat the adjacent formed scanning track and layer, and also produce a certain preheating effect on the unformed powder bed of the adjacent scanning track when laser beam scans a track, which is conductive to improve metallurgical bonding performance of SLM-fabricated parts.

(2) With the increase of scanning tracks or scanning layers, the peak temperature and molten pool lifetime increase owing to the thermal accumulation effect, but the increasing trend gradually slows down. For the first layer, from the 1st scanning track to the 3rd scanning track, the peak temperature of the molten pool increases from 2138 °C to 2327 °C by 8.84 %, and the lifetime of the molten pool increases from 0.170 ms to 0.204 ms by 20.0 %. For the second layer, from the 4th scanning track to the 6th scanning track, the peak temperature of the molten pool increases from 2202 °C to 2365 °C by 7.40 % and the lifetime of the molten pool increases from 0.192 ms to 0.235 ms by 22.4 %.

(3) There is a certain overlap rate between adjacent molten tracks due to re-melting between adjacent scanning tracks and adjacent layers, ensuring to achieve a sound metallurgical bonding in SLM process, which is conducive to obtaining SLM-fabricated parts with high density and excellent performance.

Furthermore, the study on thermal behavior of SLM process is of great significance for understanding the thermal mechanism of SLM process. The numerical method proposed in this work can systematically and quantitatively study the thermal behavior in SLM process, which has certain engineering significance.

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