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FINITE ELEMENT ANALYSIS OF TEMPERATURE FIELD IN SELECTIVE LASER MELTING PROCESS

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ABSTRACT: The quality of the parts manufactured by selective laser melting is significantly influenced by the transient temperature distribution, which is associated with the process parameters such as laser power, scan speed, hatch distance and powder layer thickness. In this paper, a three-dimensional finite element model is developed to investigate the transient temperature distribution and analyze the effect of the laser power and scan speed on the depth of the melt pool. The modelling results show that the temperature becomes higher when the power increases and the higher scan speed leads to larger temperature gradient. In addition, the increasing trend of the depth becomes slow gradually with the ascending of the power and the depth decreases almost linearly after the laser scan speed is raised.

KEYWORDS: Selective Laser Melting; Finite Element Method; ANSYS; Temperature Field; Heat Transfer

INTRODUCTION

Selective laser melting (SLM) is a typical Additive Manufacturing (AM) that uses high intensity laser to melt the metal powder to fabricate the objects on a layer-by-layer basis from the three-dimensional computer aided design (CAD) models. The laser melting process of the metal powder includes considerably complex physical process, such as absorption and scatter of laser radiation, heat and mass transfer, Marangoni flow in the melt pool and phase change of the powder particles (Antony et al., 2014). The high temperature gradient is a distinguishing feature in the SLM, which may lead to undesired shrinkage, cracks, residual strains and stresses (Hussein et al., 2013).

The temperature distribution is associated with the melting process parameters, such as laser power, laser scan speed, laser beam diameter, hatch distance, powder layer thickness and scanning strategy. Many scholars focus on the research of understanding the SLM process through experiments and simulations (Gusarov et al., 2009; Foroozmehr et al, 2016; Loh et al., 2015; Yadroitsev et al., 2010). In this paper, we will mainly investigate the effect of laser power and scan speed on the transient temperature field and the depth of melt pool.

MODELLING APPROACH

In the SLM, the fusion of metal powder occurs when the temperature exceeds the melting point. After the laser moves away, the molten metal will be solidified gradually. The heat provided by the laser beam mainly diffuses through conduction, air convection and radiation to the ambient environment. Since the heat conduction is the most main way of heat diffusion and affects directly the melting and solidifying process, the modelling is based on the heat conduction equation. The
The three-dimensional transient heat transfer equation with internal heat source is written by:

\[
\rho c(T) \frac{dT}{dt} = \frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + Q, \ t > 0
\]

\[T(t) = T_0, \ t = 0\]  

(1)

Where, \( T \) is the temperature (°C); \( \rho \) is the material density (kg/m³); \( c \) is the specific heat capacity (J/(kg·°C)); \( k \) is the thermal conductivity (W/(m·°C)) and \( Q \) is the internal heat generation rate per unit volume (W/m³). The initial temperature \( T_0 \) is 25 °C.

The air natural convection and radiation to the ambient environment on the top surface of the powder layer (\( z=0 \)) can be described together by:

\[
k \frac{\partial T}{\partial z} = \sigma \epsilon ((T + 273)^4 - (T_\infty + 273)^4) + h(T - T_\infty)
\]

\[= (\lambda + h)(T - T_\infty)\]  

(2)

Where, \( \sigma \) is the Stefan-Boltzmann constant and its value is \( 5.67 \times 10^{-8} \); \( \epsilon \) is the emissivity; \( T_\infty \) is the environment temperature (°C), which is assumed to be 25 °C; \( h \) is the heat transfer coefficient (W/(m²·°C)); \( \lambda \) is given by:

\[
\lambda = \sigma \epsilon ((T + 273)^4 + (T_\infty + 273)^4)((T + 273) + (T_\infty + 273))
\]

(3)

And the other surfaces are assumed to be thermal insulating boundary condition:

\[-k \nabla T \cdot \hat{n} = 0\]  

(4)

The energy intensity distribution of the laser heat source can be described as Gauss distribution. The Gauss distribution of the heat source can be defined as:

\[
Q = \frac{3\alpha q}{\pi r_0^2} \exp \left(-\frac{3r^2}{r_0^2}\right)
\]

(5)

Where, \( \alpha \) is the powder absorptivity, which is taken as 0.52 (Badrossamay and Childs, 2007); \( q \) is the power of the laser; \( r_0 \) is the radius of the laser beam; \( r \) is the radial distance from the powder to the center of the laser beam projection spot.

The thermal conductivity and density of the powder is a function of the porosity of the powder. They can be calculated according to the following equation:
Where, $\rho_{\text{solid}}$ and $k_{\text{solid}}$ are respectively the density and heat conductivity of the solid; $\rho_{\text{powder}}$ and $k_{\text{powder}}$ are respectively the density and heat conductivity of the powder; $\varphi$ is the porosity of the powder and its value is taken as 0.4 (Hussein et al., 2013).

In order to consider the latent heat during the melting and solidifying process, the enthalpy is used as the input parameter of the material property instead of specific heat capacity in the ANSYS. The enthalpy can be written as:

$$H = \int_{25^\circ C}^{T} \rho(T) \cdot c(T) dT$$

The temperature dependent material properties (Mills, 2002) of the powder and solid are depicted in the Figure 1.
RESULTS AND DISCUSSION

The simulation is performed by using the ANSYS software. The material and modelling parameters are shown in Table 1. The computation domain of substrate in the model is 4 mm×2 mm×1 mm and the thickness of the powder layer is 30 μm.

<table>
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<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>Powder material</td>
<td>AISI 316L</td>
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<tr>
<td>Melting point, $T_{\text{melt}}$</td>
<td>1385 °C</td>
</tr>
<tr>
<td>Powder layer thickness, $t$</td>
<td>30 μm</td>
</tr>
<tr>
<td>Laser beam diameter, $d$</td>
<td>200 μm</td>
</tr>
<tr>
<td>Laser power, $q$</td>
<td>50, 100, 150, 200, 250 W</td>
</tr>
<tr>
<td>Laser scan speed, $V$</td>
<td>100, 150, 200, 250, 300 mm/s</td>
</tr>
<tr>
<td>Environment temperature, $T_\infty$</td>
<td>25 °C</td>
</tr>
<tr>
<td>The size of the model (length × width × height ), $l \times w \times h$</td>
<td>4 × 2 × 1 mm³</td>
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Figure 2 shows the temperature distribution result ($q=100$ W, $V=150$ mm/s). The highest temperature is around 2438 °C, occurring on the surface of the powder layer. When the temperature exceeds the melting temperature ($T_{\text{melt}}=1385$ °C), the powder and solid will be melted to form melt pool. From the Figure 2 (a), the depth of the melt pool is just over the thickness of the powder layer. Hence, the powder can be melted fully and then solidified after the laser beam leaves.

Figure 3(a) and 3(b) show the change of temperature with time on the top surface of the powder layer for different powder and laser scan speed respectively. All the curves have the same variation trend. When the laser beam reaches the point of the surface, the temperature grows quickly. After the laser moves away, the temperature decreases rapidly first and then reduces slowly. In the Figure 3(a), the laser scan speed is fixed at 150 mm/s and the power is from 50 W to
we can see that the temperature becomes higher during the whole period of the temperature change when the laser power increases. In the Figure 3(b), the laser power is fixed to 150 W and the scan speed is from 100 mm/s to 300 mm/s. The peak temperature of the curves reduces and the time of peak point occurs earlier with the increasing of the scan speed. Furthermore, high speed leads to large temperature gradient.

Figure 3. Effect of (a) power and (b) scan speed on the change of temperature with time

Figure 4(a) and 4(b) give the depth variation of the melt pool with change of the power and laser scan speed respectively. The melted depth is measured from the powder surface to the bottom of the melt pool. The depth can be acquired through the temperature distribution on the x-z cross section (see Figure 2(b)). From the Figure 4(a), the depth of the melt pool ascends quickly with the increasing of the power before the power is less than 150 W. After the power is larger than 150 W, the increasing trend of the depth becomes slow. Since the thickness of the powder layer in the model is 30 μm, the melt pool can penetrate to the powder bed when power is more than around 100 W. Figure 4(b) shows that the depth of the melt pool decreases linearly when the scan speed becomes faster.

Figure 4. Effect of (a) power and (b) scan speed on the depth of the melt pool
CONCLUSIONS

In this paper, a finite element method for simulating the temperature distribution of the laser melting process is developed. Based on the model, the effect of the laser power and scan speed on the temperature distribution and the depth of melt pool is investigated. The conclusions can be drawn from the analysis of the modeling results. The temperature becomes higher when the power increases and higher scan speed leads to larger temperature gradient. In addition, the increasing trend of the melting depth becomes slow with the ascending of the power. The depth of the melting pool decreases almost linearly after the laser scan speed is raised.

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REFERENCES


