

CALCULATION OF THE HEAT AFFECTED ZONE BASED INHERENT STRAIN IN 3D METAL PRINTING

TÍNH TOÁN BIẾN DẠNG DƯ TỪ VÙNG ẢNH HƯỞNG NHIỆT
KHI IN 3D KIM LOẠI

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ABSTRACT

Heat affected zone (HAZ) depends on the printing process parameters and material properties. Calculation of the HAZ enables to determine the inherent strain (IS) caused by the fast change of material phases from solid - liquid - solid during 3D printing. IS based deformation of the printed part after removing from the base plate by using electrical discharge machining (EDM) is determined. This paper presents method to calculate the HAZ in different plans according to the printing process parameters for printing 316L stainless steel with SLM printing method. From that, calculation of the IS values in x, y, z directions. Then, we propose the equation for calculating the IS value for whole part.

Keywords: Heat affected zone; Inherent strain; 3D printing; SLM.

TÓM TẮT

Vùng ảnh hưởng nhiệt (HAZ) phụ thuộc vào thông số chế độ in và thuộc tính vật liệu. Tính được vùng ảnh hưởng nhiệt cho phép xác định được biến dạng dư do quá trình thay đổi pha nhanh của vật liệu từ rắn - lỏng - rắn khi in 3D. Biến dạng của chi tiết in 3D sau khi cắt bỏ khỏi tấm nền (bởi phương pháp gia công EDM) xác định được trên cơ sở giá trị của biến dạng dư. Bài báo trình bày cách xác định diện tích vùng ảnh hưởng nhiệt trong các mặt phẳng khác nhau trên cơ sở thiết lập chế độ in với thép 316L theo phương pháp in thiêu kết laser - SLM. Từ đó tính toán giá trị biến dạng dư cho lớp in đầu tiên theo các phương x, y, z. Đồng thời đề xuất công thức xác định biến dạng dư cho toàn bộ chi tiết.

Từ khóa: Vùng ảnh hưởng nhiệt; Biến dạng dư; In 3D; SLM.

1. INTRODUCTION

3D printing or layer-by-layer manufacturing, enables the manufacture of three-dimensional products from plastic to metal in a layer-by-layer sequence, starting from a digital model. The 3D printing of metallic parts is widely applied for industrial applications. Currently, for manufacturing metallic parts, there are many 3D printing methods which are presented in the literature as well as applied in industry. This research focuses on the selective laser printing (SLM) method.

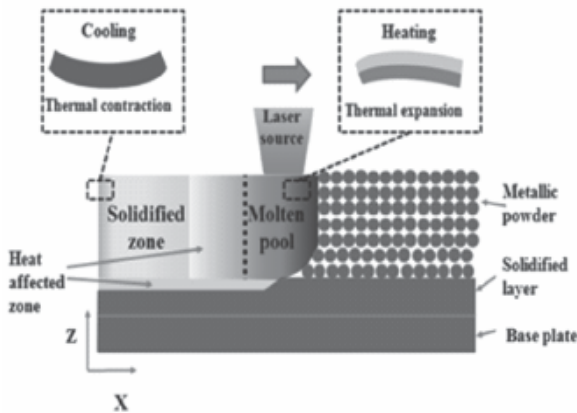


Figure 1. Mechanism of the selective laser melting process.

Figure 1 shows the mechanism of SLM process. In SLM, the laser source melts a thin powder layer distributed by the deposition system. An optical system with a set of optical mirrors enables the laser source to be directed onto the powder bed surface. Because of rapid heating and cooling which generates residual stress, several defects usually exist in a SLM part such as part distortion and cracks [1]. The contribution of this research is to propose the method for calculating the HAZ based inherent strain for the first layer and for whole part of the SLM printed part.

2. MATHEMATICAL MODEL OF THE HEAT TRANSFER

The mathematical model of the heat transfer, which we used in determining the temperature distribution during the SLM process, is as follows [2]:

$$\rho C \frac{\partial T}{\partial t} + \rho C u \nabla T = \nabla(k \nabla T) + Q_G \quad (1)$$

where: T is temperature; ρ , C , and k are density, thermal capacity, and thermal conductivity factor, respectively; u is the printing speed. Q_G is the power distribution given by the moving Goldak's double-ellipsoid heat source model as shown in Figure 2 [3], this heat source model from the welding process, however, it is also suitable for research on the SLM process [4].

The equations for calculating the Q_G are as follows [5]:

For the front heat source model:

$$Q_{G(1)} = \frac{6\sqrt{3}Q_{\text{heat source}}f_f}{\pi\sqrt{\pi}a_fbc} e^{-3\left(\frac{(x-ut)^2}{a_f^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}\right)} \quad (2)$$

and for the rear heat source model:

$$Q_{G(2)} = \frac{6\sqrt{3}Q_{\text{heat source}}f_r}{\pi\sqrt{\pi}a_rbc} e^{-3\left(\frac{(x-ut)^2}{a_r^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}\right)} \quad (3)$$

where: $Q_{\text{heat source}}$ is the generated laser power from the SLM machine (W); b is the length of the y-semi-axis of the ellipsoid (mm); c is the length of the z-semi-axis of the ellipsoid (mm); a_f is the length of the x-semi-axis of the front ellipsoids (mm); a_r is the length of the x-semi-axis of the rear ellipsoids (mm); f_f is the coefficient of proportionality for the fraction of the heat deposited on the front quadrants of the source; f_r is the coefficient of proportionality for the fraction of the heat deposited on the rear quadrants of the source; and x , y , and z are the

local coordinates of a point with respect to the moving heat source.

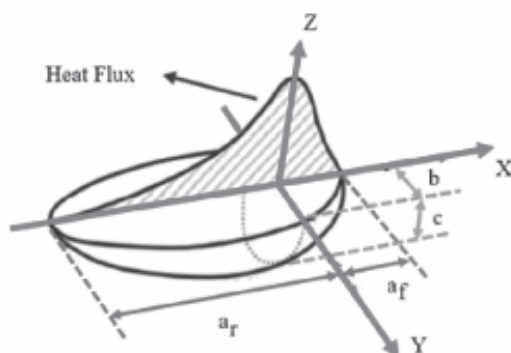


Figure 2. Goldak heat source in the SLM process.

3. CALCULATION OF THE HAZ

For determining the temperature distribution and calculating the HAZ, the 3D printing process parameters and material characteristics of the 316L steel shown in Table 1 are used. We use Comsol tool for analyzing the temperature distribution.

Table 1. 3D printing process parameters and material characteristics.

Name	Description	Value
x_0	Path center X-Coordinate	0 [mm]
y_0	Path center Y-Coordinate	0 [mm]
Q	Laser power	250 [W]
b	Length of the y-semi-axis of ellipsoid (mm)	0.173 [mm]
c	Length of the z-semi-axis of ellipsoid (mm)	0.230 [mm]
a_f	Length of the x-semi-axis of front ellipsoids (mm)	0.173 [mm]
a_r	Length of the x-semi-axis of rear ellipsoids (mm)	0.347 [mm]

f_f	Coefficient of proportionality for the fraction of the heat deposited on the front quadrants of the source	2/3
f_r	Coefficient of proportionality for the fraction of the heat deposited on the rear quadrants of the source	4/3
u	Laser velocity	1100 [mm/s]
C	Thermal capacity	500×10^{-3} [J/(g.K)]
λ	Thermal conductivity factor	19.4×10^{-3} [W/(mm.K)]
T_a	Ambient temperature	293 [K]
h_c	Convective and (W/mm ² .K)	186.3 [W/(mm ² .K)]
h_r	Radiant heat transfer coefficient	4.4 [W/(mm ² .K)]
h	Layer thickness	0.05 [mm]
h_a	Hatch distance	0.07 [mm]

Figures 3, 5, and 7 show the temperature distribution in ZOX, XOY, and ZOY plans respectively. The temperature for 316L steel from 1173 K to 293 K is only considered warm, e.g. that zone does not have phase change or effect to strain at 293 K. The melting pool also does not affect the strain in the part; only the temperature zone from 1173 K to 1700 K is the plastic zone, effects the inherent strain.

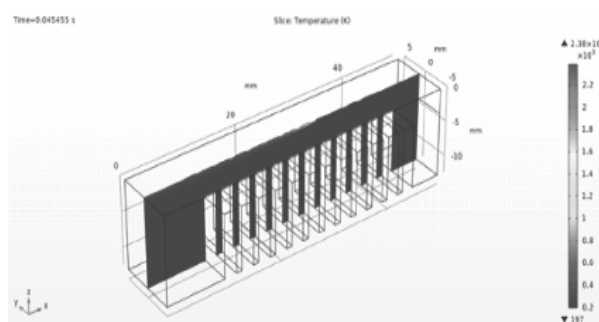


Figure 3. Temperature distribution in ZOX plan.

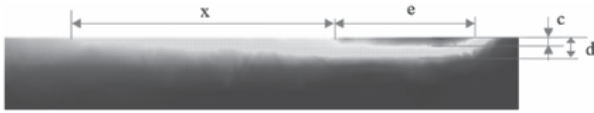


Figure 4. Calculation of the HAZ surface in ZOX plan.

The HAZ surface in ZOX plan is calculated as follows:

$$F_x = (x+e).d - e.c \quad (4)$$

With $d = 0.112$ mm; $c = 0.0522$ mm; $e = 0.5255$ mm; and $x = 2.429$ mm, we have $F_x = 0.3035$ mm².

The HAZ surface in XOY plan is calculated as follows:

$$F_y = 2(x+e).(a+b) - 2a.e - f.n \quad (5)$$

With $a = 0.089$ mm; $b = 0.137$ mm; $f = 0.258$; $n = 3.166$, $e = 0.5255$ mm; and $x = 2.429$ mm, we have $F_y = 0.425$ mm².

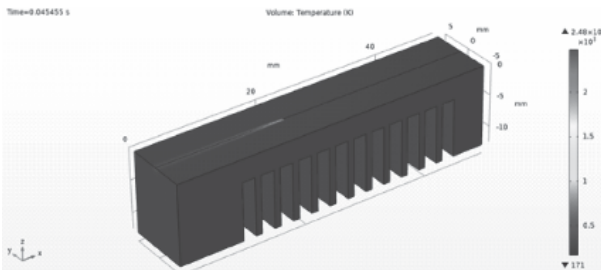


Figure 5. Temperature distribution in XOY plan.

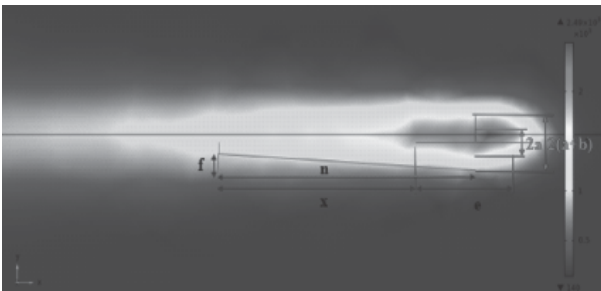


Figure 6. Calculation of the HAZ surface in XOY plan.

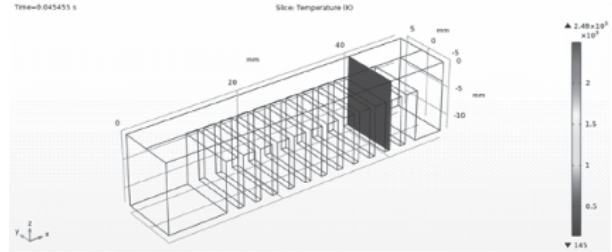


Figure 7. Temperature distribution in ZOY plan.

The HAZ surface in ZOY plan is calculated as follows:

$$F_z = 2[(a+b).d - a.c] \quad (6)$$

$a = 0.089$ mm; $b = 0.137$ mm; $d = 0.112$ mm; and $c = 0.0522$ mm, we have $F_z = 0.0627$ mm².

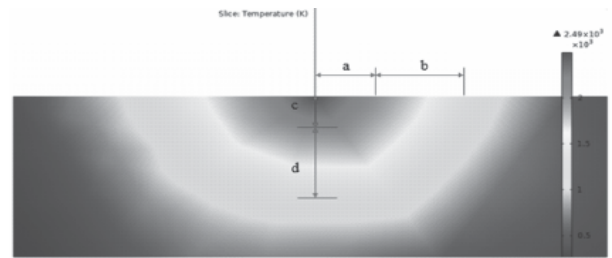


Figure 8. Calculation of the HAZ surface in ZOY plan.

4. CALCULATION OF THE INHERENT STRAIN VALUE

The equation for calculating the IS value in the first layer is as follows:

$$\varepsilon_{inh-x} = -\frac{\xi.q_v}{F_x} \cdot \varepsilon_{inh-y} = -\frac{K.q_v}{F_y}, \quad \varepsilon_{inh-z} = -\frac{K.q_v}{F_z} \quad (7)$$

in which q_v is the linear energy density (J/mm); F_x , F_y , and F_z are the HAZ areas; ξ and K (mm/J) are longitudinal and transverse inherent strain coefficients, respectively.

With $\xi = 1.57 \times 10^{-3}$ mm³/J, $K = 0.58 \times 10^{-3}$ mm³/J, and $q_v = 0.2308$ (J/mm) for 316L stainless steel

steel, $F_x = 0.3035 \text{ mm}^2$, $F_y = 0.425 \text{ mm}^2$, and $F_z = 0.0627 \text{ mm}^2$, we have: $\varepsilon_{inh-x} = -0.00117$, $\varepsilon_{inh-y} = -0.00031$, and $\varepsilon_{inh-z} = -0.0021$, respectively.

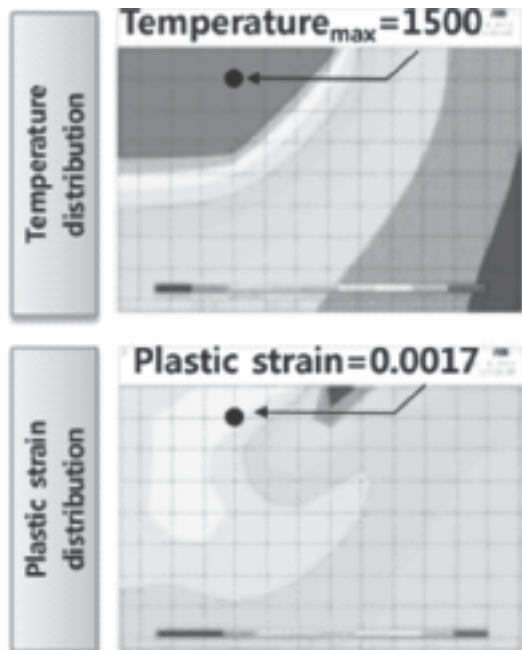


Figure 9. Temperature and residual plastic strain distributions [8]

In comparison with the reported IS value for the first layer in the welding process which also considering the influences of the temperature distribution to IS value, the calculated IS is acceptable. In Z direction, with the highest temperature is 1500 °C (or 1773 K) the inherent strain value in Z direction is 0.0017.

For whole part, in x, y, and z directions, we have the IS value in x, y, z directions as follows:

$$\begin{cases} \varepsilon_x(n \text{ layer}) = n\varepsilon_{inh-x} - \frac{(n-1)d}{h} \varepsilon_{inh-x} \\ \varepsilon_y(n \text{ layer}) = n\varepsilon_{inh-y} - \frac{(n-1)d}{h} \varepsilon_{inh-y} \\ \varepsilon_z(n \text{ layer}) = n\varepsilon_{inh-z} - \frac{(n-1)d}{h} \varepsilon_{inh-z} \end{cases} \quad (8)$$

5. CONCLUSIONS

In this research, we introduce a method to calculate the inherent strain for the first layer in the selective laser melting process based on the heat affected zone areas. To have the HAZ areas, we define the mathematical model for the heat transfer, printing process parameters, and material properties. Then, these data are input to Comsol tool for analyzing the temperature distribution. The proposed method has been evaluated through simulation with 316L stainless steel cantilever beams.

Acknowledgements:

This research is funded by University of Transport and Communications (UTC) under grant number T2022-CK-12.

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