Calculating the Inherent Strain in 3D Printed Part Based on the Heat Affected Zone

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Abstract Today, 3D printing technology has been applied in industrial applications. However, improving the quality of printed products is still an issue that needs to be studied for this technology to be used more widely. This research proposes the calculation of the inherent strain (IS) value based on the heat affected zone (HAZ). Then, the IS values are used for calculating the deformation of the printed part. HAZ depends on the printing process parameters and material properties. This paper presents method to calculate the HAZ in different plans according to the printing process parameters for printing Ti6Al4V with selective laser melting (SLM) printing method.

1 Introduction

3D printing is used widely in the manufacturing industry because of its advantage. It is applied in aerospace, biomedical, automotive, etc. The 3D printing process can be divided into two groups such as powder spreading and powder spraying method. Selective laser melting (SLM) is a powder spreading method using a laser source to melt a thin powder layer. SLM is developed in 1995 by German scientists [1].

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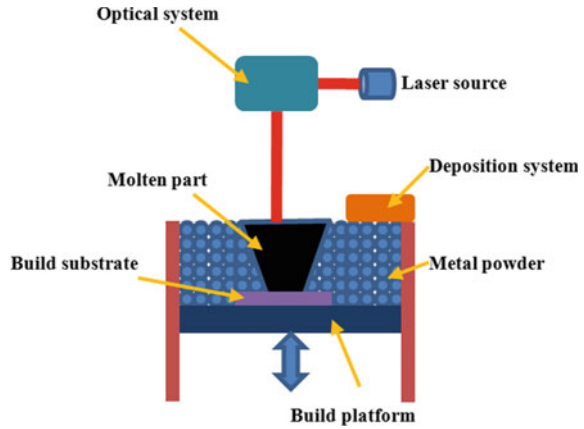**Fig. 1** Model of SLM
printing process

Figure 1 shows the SLM process. During the SLM process, a product is formed
by selectively melting layers of powder using a laser beam. The powder is heated
and melted to form a liquid pool. Then the molten pool solidifies and cools down
and starts to form the product. The building platform is lowered by the amount
of layer thickness and a new layer is deposited. The process is repeated until the
product is made. Because of its ability to heat and cool rapidly, the SLM is used
commonly. However, several defects usually exist in an SLM part, such as part
distortion and cracks. The printed parts are affected by key influence factors such as
powder properties, printing process parameters, and machine characteristics.

To obtain the best quality in a printed part, key influence factors must be consid-
ered. However, during the SLM process, large thermal gradients and fast cooling
exist that cause residual stress, which leads to a loss of part shape and other failures
of the SLM part. The failure quality of parts results in manufacturing costs, as well
as waste and scrap [2]. Therefore, all requirements and predictions for the process
need to be fulfilled at the design stage to reduce failure and increase accuracy. To
predict the quality at the design stage, a computational simulation is the best choice.

According to the previous research on this, the current methods to reduce
deformation include [1, 2]:

- Experiment: Achieve printing experiments to resolve the relationship between the
  printing parameters and deformation.
- Simulation: Analysis to complete the residual stress and then predict the
  deformation.

The contribution of this research is to suggest the deformation calculation based
on the inherent strain (IS) value. The IS values in x, y, z directions are determined by
the heat-affected zone (HAZ). HAZ depends on the printing process parameters and
material properties. This paper presents a method to calculate the HAZ in different
plans according to various printing process parameters using Ti6Al4V alloy material
with selective laser melting (SLM) printing method.

2 Calculation of Inherent Strain

Inherent strain resulting from welding is a combination of thermal strains $\varepsilon_{thermal}$, phase transfer strain ε_{phase}, plastic strains $\varepsilon_{plastic}$ and creep strain ε_{creep} [3, 4].

In SLM printing process, the total strain is calculated as follows:

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon^* \tag{1}$$

in which $\varepsilon_{elastic}$ is the elastic strain; ε^* is the inherent strain.

The ε^* value is calculated by considering other strains as follows:

$$\varepsilon^* = \varepsilon_{thermal} + \varepsilon_{plastic} + \varepsilon_{phase} + \varepsilon_{creep} \tag{2}$$

During heating and cooling process, at the plastic stage the IS value in x, y, z directions can be defined as follows [5]:

$$\varepsilon_x^* = \frac{W_x}{F_x};\ \varepsilon_y^* = \frac{W_y}{F_y};\ \varepsilon_z^* = \frac{W_z}{F_z} \tag{3}$$

In which F_x, F_y, and F_z are the heat effected zone (HAZ) areas where W_x, W_y, and W_z, respectively, are distributed. W_x, W_y, and W_z are calculated as follows:

$$W_x = \xi.\,q_v;\ W_y = W_z = K.\,q_v \tag{4}$$

In which q_v is the linear energy density (J/mm) [6]:

$$q_v = \frac{Q_{heatsource}}{u} \tag{5}$$

ξ and K (mm/J) values are used from the welding process due to the same heating and cooling process.

3 Numerical Model for SLM Process

For determining the temperature distribution during SLM process, the mathematical model of the heat transfer is as follows [7]:

$$\rho C \frac{\partial T}{\partial t} + \rho C u\, \nabla T = \nabla(k \nabla T) + Q_{heatsource} \tag{6}$$

in which T is temperature; ρ, C, k, and u are density, thermal capacity, thermal conductivity factor and laser velocity, respectively. Q is defined as follows:

Fig. 2 The Goldak's heat
source model
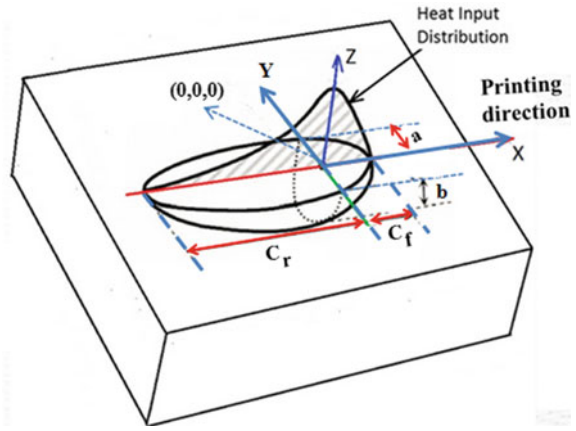
$$Q_{heatsource} = Q_{requiredpower} + Q_{conduction} \tag{7}$$

$$Q_{requiredpower} = Q_{deliveredlaser} - Q_{convection} - Q_{radiation} - Q_{conduction}$$

$$Q_{deliveredlaser} = Q \frac{6\sqrt{3}}{ab\pi\sqrt{\pi}} e^{\left[\frac{-3z^2}{a^2} + \frac{-3y^2}{b^2}\right]} \left[\frac{f_f}{C_f} e^{\frac{-3x^2}{C_f^2}} + \frac{f_r}{C_r} e^{\frac{-3x^2}{C_r^2}} \right]$$

The power distribution is given by the moving Goldak's double-ellipsoid heat
source model as shown in Fig. 2 [8]. The model parameters are explained in Table 1.

4   Results and Discussion

To determine the HAZ during the SLM process, we use the data from Table 1 as the
input data using Comsol tool. Figures 3, 4 and 5 show the method to calculate the
HAZ in Fx, Fy, Fz plans.

$$F_x = (x + e).d - e.c] \tag{8}$$

With $d = 0.153$ mm; $c = 0.09$ mm; $e = 1.97$ mm; and $x = 2.34$ mm, we have F_x
$= 0.482$ mm^2. With $\xi = 1.57 \ 10^{-3}$ mm^3/J; $q_v/h^2 = 104.52$ J/mm^3 for Ti6Al4V and
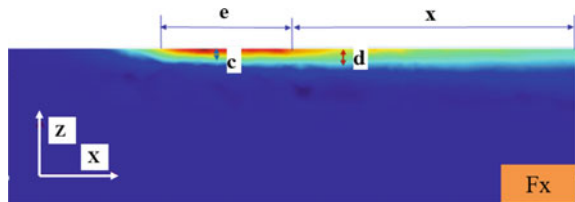$h = 0.045$ mm, we have:

$$\varepsilon_{inh-x} = -0.000937$$

$$F_y = 2(x + e).(a + b) - 2a.e] \tag{9}$$

Table 1 SLM process parameters for Ti6Al4V material

Name	Description	Value
x_0	X-start coordinate	0 (mm)
y_0	Y-start coordinate	0 (mm)
Q	Laser power from machine	140 (W)
a	Ellipsoid length in y axis	0.4205 (mm)
b	Ellipsoid length in z axis	0.1682 (mm)
C_f	Front ellipsoid length in x axis	0.4205 (mm)
C_r	Rear ellipsoid length in x axis	0.84 (mm)
f_f	Coefficient of heat source in the front ellipsoid	2/3
f_r	Coefficient of heat source in the rear ellipsoid	4/3
u	Printing speed	1300 (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	0.045 (mm)
Ha	Hatch distance	0.07 (mm)

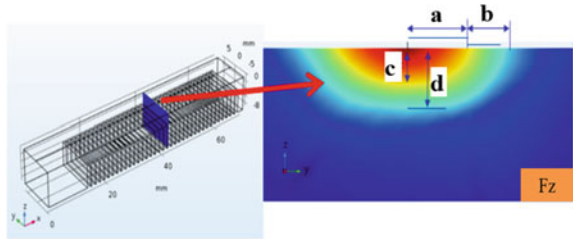**Fig. 3** Calculation of the HAZ in Fx plane

Fig. 4 Calculation of the HAZ in Fy plane
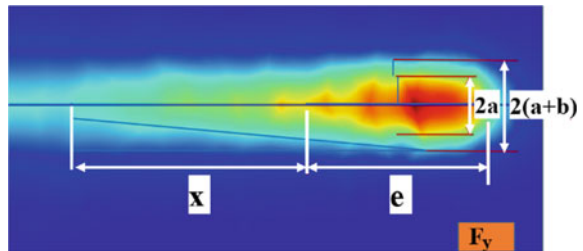
With a = 0.19 mm; b = 0.102 mm; e = 1.97 mm; and x = 2.34 mm, we have F_y = 1.275 mm^2.

With K = 0.58 10^{-3} mm^3/J; q_v/h^2 = 104.52 J/mm^3 for Ti6Al4V and h = 0.045 mm, we have:

Fig. 5 Calculation of the
HAZ in Fz plane

$$\varepsilon_{inh-y} = -0.0000963$$

$$F_z = 2[(a + b).d - a.c] \tag{10}$$

a = 0.19 mm; b = 0.106 mm; d = 0.153 mm; and c = 0.09 mm, we have F_Z = 0.0564 mm^2. With K = 0.58 10^{-3} mm^3/J; q_v/h^2 = 104.52 J/mm^3 for Ti6Al4V and h = 0.045 mm, we have:

$$\varepsilon_{inh-z} = -0.00217$$

With the same processing parameters such as the beam width, velocity, power, and material, we used Simufact^{TM} tool for predicting the inherent strain. The predicted results are shown in Fig. 6. In comparison with the proposed method, the biggest IS value is in the Z direction, this is correct for both simulation and experiment [2, 7].

Fig. 6 Calculation of the
inherent strain by using
Simufact
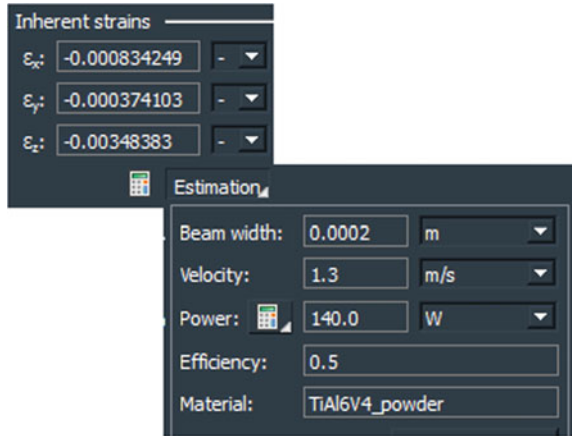
5   Conclusions

In this study, we propose to calculate IS value based on printing process parameters and HAZ area. To calculate the HAZ area during SLM printing process, the heat transfer equation was established. Then, Comsol™ was used to determine the temperature distribution in the printed part. From the temperature distribution, the HAZ surfaces were calculated. The IS values are used to calculate the deformation of the printed part in all directions. From that, the reasonable printing process parameters are determined to reduce distortion when carrying out the actual printing process. The proposed IS calculation results are reliable when compared with the IS values calculated by Simufact™ software under the same conditions and printing method.

References

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