A new approach for calculating inherent strain and distortion in additive manufacturing of metal parts

Hong-Seok Park · Hwa Seon Shin · Ngoc-Hien Tran

Received: 20 December 2021 / Accepted: 8 July 2022 / Published online: 19 July 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract

Additive manufacturing (AM) of metallic parts is widely utilized for industrial applications. However, quality issues of the printed parts, including part distortion and cracks caused by high temperature and fast cooling, result in high residual stress. This is a challenge that limits the industry acceptance of AM. To overcome this challenge, a numerical modeling method for predicting part distortion at the design stage plays an important role and enables design engineers to remove failures before printing as well as determine the optimal printing process parameters to minimize part deformation. This research proposes an inherent strain-based part deformation prediction method. To determine the inherent strain (IS) value, a micro-scale model for analyzing the temperature distribution is constructed. The IS value is calculated from the temperature gradient. Then, the IS value is used for determining the part deformation. The proposed methodology has been developed and evaluated using a 316L stainless steel cantilever beam in both simulations and experimental results.

Keywords Inherent strain · Heat source model · Heat treatment effect zone · Selective laser melting · Predicting distortion

1 Introduction

Additive manufacturing (AM), 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 AM process has been applied in the aerospace, automotive, biomedical, and energy fields. Currently, for manufacturing metallic parts, there are many AM processes that are presented in the literature as well as applied in the industry. The AM processes are classified into two groups: powder-bed-based and powder injection [1]. Selective laser melting (SLM) is a powder-bed-based AM process requiring full melting for manufacturing metallic parts. SLM is a complex process involving the interaction between a concentrated laser source and metallic powders [1, 2].

Figure 1 shows the mechanism of the 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. The optical system can contain additional elements that allow the melt pool shape and intensity to be monitored. The deposition system, such as a scraper or roller system, distributes the powder onto the build area. The build platform moves down with a distance of one-layer thickness. Then, a new powder layer is deposited on top. This procedure is repeated until the entire 3D part is completed. SLM has been applied widely for the manufacture of metallic parts. However, because of rapid heating and cooling, which generates residual stress, several defects usually exist in an SLM part, such as part distortion and cracks [3]. The surface tension and high viscosity at the melt pool area results in a very poor surface finish. In addition, un-melted powder and oxidized particles may also lead to porosity in the manufactured parts [4]. The powder properties, printing process parameters, and SLM machine characteristics are key factors affecting the quality of the printed parts [5].

Figure 2 shows an example of printing deformations of a name card part manufactured by an SLM process and tested by the Laboratory for Production Engineering, Ulsan University in Korea.
Results show that there are inaccuracies in shape caused by part deformation after cutting the printed name card from the base plate by using the electrical discharge machining (EDM) machine. To obtain the best quality in a printed part, key influence factors as mentioned above must be considered. However, during the SLM process, the residual stress caused by large thermal gradients and fast cooling exists, which will result in a loss of part shape, as well as other failures of the SLM part. Currently, the quality of parts manufactured by the AM process depends on the user’s experience with trial-and-error testing until all requirements are fulfilled, which requires larger manufacturing costs, as well as waste and scrap [6, 7]. Therefore, a quality prediction at the design stage is necessary, in that it enables the removal of failures and maintains the accuracy between the designed and printed parts. For predicting the printed part’s quality at the design stage, a computational simulation is the best choice to deal efficiently with the mentioned challenges.

According to a review from the reported research, current methods to reduce deformation include the following.

- **Experiment**: Carrying out printing experiments to determine the relationship between the printing parameters and deformation. This method requires many experiments.

- **Simulation**: Part-scale analysis to determine the residual stress and then predict the deformation.

The contribution of this research is to create an inherent strain-based part deformation prediction method during the SLM process. Part distortion in additive manufacturing is a major technical challenge to industry acceptance of this manufacturing technology. However, we can overcome this challenge at the design stage by predicting the part distortion based on simulation. According to the simulation results, we can optimize the printing process parameters in order to minimize the part deformation.

Many studies have successfully applied the inherent strain method to predict part deformation. This method consists of simulating the residual stress and deformation at the part scale by using the inherent strain tensor [8]. The original inherent strain method was used to predict weld deformation. This method reduces the analysis time compared to the thermal elastic–plastic analysis method [9, 10]. The inherent strain field can be identified from the experimental data at key points. Then, a model of the distribution of residual stresses can be constructed efficiently by using the obtained inherent strain field [11]. Saenz et al. used the elastic finite element method, based on the inherent strain theory, to predict the welding distortion on ship structures [12]. Thermal elastic–plastic analysis was performed to calculate residual plastic strain distribution, which is the input data for the elastic analysis of welding distortion [13]. The conventional inherent strain method can predict residual distortion of the regular metal welding problem. However, it is not applicable to a complicated layer-by-layer laser sintering deposition process, such as selective laser melting [14]. Therefore, it is necessary to adapt and modify this method for AM applications [8]. Many studies have proposed a modified inherent strain method for AM. One of the methods most often proposed is the extraction of inherent strain from micro-scale thermomechanical analysis. By applying this value to the part-scale model, the part deformation is determined [14]. It is challenging to predict the residual deformation in the part-scale model by performing detailed process simulation for a large part [15]. Thus, a multi-scale modeling approach is proposed.
Neugebauer et al. [16] and Schänzel et al. [17] proposed a multi-scale finite element model for calculating the part distortion during the SLM process. For rapid prediction of part distortion, Li et al. proposed a temperature-based multi-scale modeling approach to simulate the powder-liquid–solid material phase transition [18]. Liang et al. [15] and Chen et al. [19] proposed an inherent strain-based prediction of part distortion using the multi-scale process modeling framework for the direct metal laser sintering (DMLS) process. Li et al. [20] applied a temperature-thread multi-scale modeling approach to predict residual stress and part distortion of a twin cantilever during the SLM process. Some experimental research on AM processes has been carried out to determine the inherent strain values. These inherent strains are calculated considering layer lumping strategies [16].

Currently, commercial tools such as MSC Simufact, 3DSim, and Amphyon Works, which are based on the inherent strain method for predicting the residual stress and deformation in AM, are applied for industrial applications. MSC Simufact uses the inherent strain (IS) value as the input parameter for determining the residual stress and deformation. The IS values are obtained from an empirical method based on classical laminate theory [6]. 3DSim uses the IS value from micro-scale thermo-mechanical analysis. Compared to the results from simulation and experiment, the results obtained with these tools show the accuracy and efficiency of the inherent strain method. However, the algorithms for extracting the IS value, and the method of applying this IS value to the part-scale model to predict the residual stress and deformation, are not publicly available [19]. Therefore, it is necessary to research methods of extracting the IS value. In this research, we use the temperature gradient, in consideration of the temperature distribution from the thermal micro-scale simulation, in calculating the inherent strain value. Then, this inherent strain value is used to calculate the part deformation.

### 2 Characteristic of inherent strain

Inherent strain or Eigen strain is a general name for the expression of non-elastic strains. The term inherent strain was first used by Ueda in 1975 for analyzing the welding process. In 1982, Mura defined these strains with the name “Eigen strain.” These strains include the thermal strain $\varepsilon_{\text{thermal}}$, phase transfer strain $\varepsilon_{\text{phase}}$, plastic strain $\varepsilon_{\text{plastic}}$, and creep strain $\varepsilon_{\text{creep}}$ [6, 14, 21, 22].

During the heating and cooling cycles of the AM process, the total strain is the sum of the elastic strain $\varepsilon_{\text{elastic}}$ and inherent strain $\varepsilon^*$, as shown below:

$$\varepsilon_{\text{total}} = \varepsilon_{\text{elastic}} + \varepsilon^*$$  \hfill (1)

The inherent strain is calculated as follows:

$$\varepsilon^* = \varepsilon_{\text{thermal}} + \varepsilon_{\text{phase}} + \varepsilon_{\text{plastic}} + \varepsilon_{\text{creep}}$$  \hfill (2)

In practice, strain and stress are unknown variables. Currently, experiments are being performed to determine the value of one of these variables, such as the IS value or stress value. The commercial tools enable engineers to estimate the IS value. However, as mentioned earlier, the algorithms for calculating the IS value are not published.

### 3 Development of a system for calculating inherent strain

#### 3.1 Execution strategy for developing the system

Figure 3 describes a systematic procedure for executing the engineering design work. With the part requirements, material properties, and initial printing process parameters, we carry out four steps to obtain the research outcomes, including the inherent strain value, and the part deformation.

In the first step, a micro-scale model is developed to predict the inherent strain value for one layer. With thermal analysis, the temperature gradient due to the temperature distribution is determined. Then this temperature gradient is used to calculate the inherent strain value. In the second step, the part-scale modeling is carried out to predict the part deformation. Based on the inherent strain determined in the first step, we establish the formula for calculating the inherent strain for the whole part. Then, by applying this IS value, we can calculate the part deformation. In the third step, experimentation on the SLM machine is performed, with the same printing process parameters that were used in the simulation. A comparison between the experimental results and simulation results was performed to evaluate the accuracy of the inherent strain and deformation calculations.

#### 3.2 Calculation of the required heat source

Figure 4 shows the heat transfer mechanism in the SLM process. When the laser source scans on the powder surface, energy is transferred from the top layer to the lower layers through various physical changes, such as heat transfer, radiation, convection, conduction, fluid flow within the molten pool, melting, evaporation, and chemical reactions [23]. During the SLM process, thermal expansion occurs within the layers of the printed part, which can lead to deformation.

The heat source is calculated as follows:

$$Q_{\text{heat source}} = Q_{\text{arrived}} + Q_{\text{emitted}}$$  \hfill (3)

$$Q_{\text{arrived}} = Q_{\text{absorbed}} + Q_{\text{reflected}}$$  \hfill (4)
In consideration of printing process parameters, the volumetric energy density $E_v$ (J/mm$^3$) is calculated as follows [24]:

$$E_v = \frac{Q_{\text{melting energy}}}{u \cdot h \cdot h_a} \quad (6)$$

In which $u$ is the printing speed (mm/s), $h_a$ is the hatch distance (mm), and $h$ is the layer thickness (mm). If $E_v$ is very low, weak metallurgical bonding between the adjacent laser-melted tracks or layers will result in a low relative density. Conversely, if $E_v$ is too high, the evaporation of the powders will also decrease the relative density. For obtaining good quality printed parts, with a porosity less than 0.1%, the volumetric energy density $E_v$ for 316L material is selected as 40 (J/mm$^3$) [24]. Thus, the melting energy ($Q_{\text{melting energy}}$) is 163.8 (W) with the printing process parameters ($u$, $h$, and $h_a$), as shown in Table 1.

From the melting energy value, the laser heat source is calculated as follows:

$$Q_{\text{heat source}} = Q_{\text{melting energy}} + \Delta Q \quad (7)$$

$\Delta Q$ shows the laser energy loss which includes laser energy-consuming for conduction, convection, radiation, reflection, and emission. In consideration of the laser energy required for melting powder, the laser energy efficiency ($\eta$) is defined as follows:

Fig. 3 Systematic procedure for calculating inherent strain

Fig. 4 Heat model absorbed by a part
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]         |
| $Q_{\text{heat source}}$ | Laser power | 300 [W]        |
| $b$                | Length of the y-semi-axis of ellipsoid (mm) | 0.173 [mm] [32] |
| $c$                | Length of the z-semi-axis of ellipsoid (mm) | 0.230 [mm] [32] |
| $a_f$              | Length of the x-semi-axis of front ellipsoids (mm) | 0.173 [mm] [32, 43] |
| $a_r$              | Length of the x-semi-axis of rear ellipsoids (mm) | 0.347 [mm] [32] |
| $f_f$              | Coefficient of proportionality for a fraction of the heat deposited on the front quadrants of the source | $2/3$ [30] |
| $f_r$              | Coefficient of proportionality for a fraction of the heat deposited on the rear quadrants of the source | $4/3$ [30] |
| $u$                | Printing speed | 1300 [mm/s]    |
| $C$                | Thermal capacity | $500 \cdot 10^{-3}$ [J/(g K)] [43] |
| $\lambda$         | Thermal conductivity factor | $16.3 \cdot 10^{-3}$ [W/(mm K)] [43] |
| $T_a$              | Ambient temperature | 293 [K]        |
| $h$                | Layer thickness | 0.045 [mm]     |
| $h_m$              | Hatch distance | 0.07 [mm]      |

\[
\eta = \frac{Q_{\text{melting energy}}}{Q_{\text{heat source}}} \quad (8)
\]

with the reference values from the industry and experimental research for the SLM process [25], we selected $Q_{\text{heat source}}$ of 300 W and printing parameters for 316 L powder material. So, the laser energy efficiency is 0.546. The $\eta$ value shows that the main contribution of the laser energy in SLM is very low. The calculated $\eta$ value is in the allowed range that can be estimated to be 0.5–0.6 [26, 27]. The laser energy loss ($\Delta Q$) is 136.2 W.

The mathematical model of the heat transfer, which we used in determining the temperature distribution during the SLM process, is as follows [28, 29]:

\[
\rho C \frac{dT}{dt} + \rho C u \nabla T = \nabla (k \nabla T) + Q_G \quad (9)
\]

where $T$ is temperature, $\rho$, $C$, and $k$ are density, thermal capacity, and thermal conductivity factor, respectively, and $u$ is the printing speed. $Q_G$ is the power distribution given by the moving Goldak's double-ellipsoid heat source model, as shown in Fig. 5 [30]; this heat source model is from the welding process; however, it is also suitable for research on the SLM process [31].

The equations for calculating the $Q_G$ are as follows [32]:

\[
Q_G = \frac{6 \sqrt{3} Q_{\text{heat source}}}{\pi \sqrt{\pi a_f \cdot b \cdot c}} e^{-\frac{(x-u)^2}{a_f^2}} e^{-\frac{y^2}{b^2}} e^{-\frac{z^2}{c^2}} \quad (10)
\]

and for the rear heat source model:

\[
Q_G = \frac{6 \sqrt{3} Q_{\text{heat source}}}{\pi \sqrt{\pi a_r \cdot b \cdot c}} e^{-\frac{(x-u)^2}{a_r^2}} e^{-\frac{y^2}{b^2}} e^{-\frac{z^2}{c^2}} \quad (11)
\]

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 a fraction of the heat deposited on the front quadrants of the source, and $f_r$ is the coefficient of proportionality for a fraction of the heat deposited on the rear quadrants of the source.

The $a_f$, $a_r$, $b$, and $c$ values are dependent on experiment cases. However, these heat source dimensions parameters are determined by applying equations as follows [32]:

\[
\begin{align*}
 a_f &= \frac{b_m}{2}; & a_r &= 2a_f \\
 b &= \frac{b_m}{2}; & c &= h + D_m
\end{align*} \quad (12)
\]

In which $b_m$ is the melt pool width (mm), $h$ is the layer thickness (mm), and $D_m$ is the melt pool dilution (mm).

The summation of $f_f$ and $f_r$ is 2; and the $f_f$, $f_r$ values are calculated as follows [30, 33]:

\[
f_f = \frac{2a_f}{a_f + a_r}; f_r = \frac{2a_r}{a_f + a_r} \quad (13)
\]
3.3 Model of inherent strain

During the printing process, the material begins at the melting temperature via the heating stage and is changed to a lower temperature via the cooling stage at a high rate. The material of the printed part will receive a compressive force due to the thermal change. Thus, the three-dimensional inherent strains are compressive strains, and the equations can be defined as [34, 35]

\[ \varepsilon^* = -\frac{W_x}{F_x}, \quad \varepsilon^* = -\frac{W_y}{F_y}, \quad \varepsilon^* = -\frac{W_z}{F_z} \]  

(14)

in which \( F_x, F_y, \) and \( F_z \) are the zone areas where \( W_x, W_y, \) and \( W_z, \) respectively, are distributed. The total volume \( W_x \) of \( \varepsilon^*_x, \) the total volume \( W_y \) of \( \varepsilon^*_y, \) and the total volume \( W_z \) of \( \varepsilon^*_z \) in unit length are calculated as follows:

\[ W_x = \xi \cdot q_v, \quad W_y = W_z = K \cdot q_v \]  

(15)

in which \( q_v \) is the linear energy density (J/mm) [36]:

\[ q_v = \frac{Q_{\text{heat source}}}{u} \]  

(16)

\( \xi \) and \( K \) (mm/J) are longitudinal and transverse inherent strain coefficients, respectively. In this research, we utilized the \( \xi \) and \( K \) values from the welding process [35]. With a printing speed of 1300 (mm/s) and laser power of 300 (W), the calculated \( q_v \) is 0.2308 (J/mm).

The inherent strains in the \( x, y, \) and \( z \) directions for the first layer are calculated as follows:

\[ \varepsilon_{inh-x} = -\frac{\xi \cdot q_v}{F_x}, \quad \varepsilon_{inh-y} = -\frac{K \cdot q_v}{F_y}, \quad \varepsilon_{inh-z} = -\frac{K \cdot q_v}{F_z} \]  

(17)

Figure 6 shows the calculation of the inherent strain for \( n \) layers. After printing the first layer, the IS value is \( \varepsilon_{inh} \). If we add the second layer via the SLM process mechanism, the first layer is re-melted with the new heat treatment effect zone, so the remaining IS value for the first layer is

\[ \varepsilon'_1 = \varepsilon_{inh} - \frac{d}{h} e_{inh} \]  

(18)

Then, when the second layer is added, the IS value in this layer is

\[ \varepsilon_2 = \varepsilon'_1 + \varepsilon_{inh} = 2\varepsilon_{inh} - \frac{d}{h} e_{inh} \]  

(19)

If the third layer is added, the remaining IS value in the second layer is

\[ \varepsilon'_2 = \varepsilon_2 - \frac{d}{h} e_{inh} = 2\varepsilon_{inh} - \frac{2d}{h} e_{inh} \]  

(20)

and the IS value in the third layer is calculated as

\[ \varepsilon_3 = \varepsilon'_2 + \varepsilon_{inh} = 3\varepsilon_{inh} - \frac{2d}{h} e_{inh} \]  

(21)

Repeating this SLM process for \( n \) layers, we can calculate the IS value for the \( n \)th layer as follows:

\[ \varepsilon_n = \varepsilon'_{n-1} + \varepsilon_{inh} = n\varepsilon_{inh} - \frac{(n-1)d}{h} e_{inh} \]  

(22)

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

\[ \begin{cases} 
\varepsilon_x(n \text{ layer}) &= n\varepsilon_{inh-x} - \frac{(n-1)d}{h} e_{inh-x} \\
\varepsilon_y(n \text{ layer}) &= n\varepsilon_{inh-y} - \frac{(n-1)d}{h} e_{inh-y} \\
\varepsilon_z(n \text{ layer}) &= n\varepsilon_{inh-z} - \frac{(n-1)d}{h} e_{inh-z}
\end{cases} \]  

(23)
3.4 Calculation of heat treatment effect zone

Figure 7 shows the phase change with the temperature parameters of 316L steel. Currently, research on the welding process and 3D printing define the heat-affected zone (HAZ) as the zone from the melting pool to the region at environment temperature (20 °C). However, the temperature for 316L steel from 1173 to 293 K is only considered warm, e.g., that zone does not have phase change or effect on strain at 293 K. The melting pool also does not affect the strain in part; only the temperature zone, defined as the heat temperature effect zone (HTEZ), e.g., from 1173 to 1700 K is the plastic zone, affects the inherent strain. Therefore, we propose the concept of HTEZ for calculating the inherent strain.

Figure 8 shows the definition of the HTEZ surface for calculating the inherent strain. If the heat-affected zone (HAZ) surface is calculated with the $p$ length parameter including the melting pool, the HTEZ surface is calculated with the $x$ length parameter. The length of HTEZ, as shown in Fig. 8, is calculated as follows [37]:

$$x = 1.22 \sqrt{\gamma \cdot t}$$  \hspace{1cm} (24)

$\gamma$ is the heat diffusivity coefficient, and $t$ is the laser interaction time; $t = 7.7 \times 10^{-5}$ (s) [38]. The temperature value for describing the HTEZ is from 1173 K. Between the heat diffusivity coefficient and thermal conductivity coefficient, the following relation takes place [37]:

$$\gamma = \lambda \cdot \rho \cdot C$$  \hspace{1cm} (25)

in which $\lambda$ is the thermal conductivity coefficient (J/(m s K)), $\rho$ is the material density (kg/m$^3$), and $C$ is the specific heat (J/(kg K)).

Figure 9 explains how to apply the temperature gradient (TG) to an actual printing analysis model. The printing analysis model is divided into two regions, the first and second heat treatment effect zones, depending on the level of temperature variation. Then, the TG is determined by the average temperature gradient of each region.

The relationship between TG with the material properties is as follows [40]:

$$\Delta TG = |TG_{2nd \ HTEZ} - TG_{1st \ HTEZ}| = \frac{\rho \cdot m}{\alpha}$$  \hspace{1cm} (26)

in which $\rho$ is the density of the material, $m$ is the lattice parameter, and $\alpha$ is the thermal expansion coefficient. With $T = 1173$ K, the $m$ value is $3.63 \times 10^{-7}$ (mm) [41]. From that, we can generate the equation for calculating the material density based on the temperature gradient, lattice parameter, and thermal expansion coefficient:

$$\rho = \frac{\Delta TG \cdot \alpha}{m}$$  \hspace{1cm} (27)

As a result, we have the equation for calculating the $x$ value as follows:

$$x = 1.22 \sqrt{\gamma \cdot t} = 1.22 \sqrt{\lambda \cdot \rho \cdot C \cdot t} = 1.22 \sqrt{\frac{\Delta TG \cdot \alpha}{m} \cdot C \cdot t}$$  \hspace{1cm} (28)

For determining the temperature gradient and calculating the HTEZ, the 3D printing process parameters and material characteristics shown in Table 1 are used. From experimental research, we selected the printing process parameters including the laser power of 300 W, printing speed of 1300 mm/s, layer thickness of 0.045 mm, and hatch distance of 0.07 mm,
as shown in Table 1. With these printing parameters, the predicted melt-pool width is 0.346 mm [42]. From that, the parameters such as $a_p$, $a_r$, $b$, $c$, $f_p$, and $f_r$ are determined.

Applying the parameters in Table 1, we used the ComsolTM software for simulating the temperature distribution, as shown in Fig. 10. Figure 11 shows the temperature distribution and calculation of TG in the ZX plane. As a result, we have the $\Delta T_G$ in the $X$ direction as 0.1816. With $T = 16.3 \cdot 10^{-3}$ W/(mm K), $C = 500$ J/(kg K) [43], $m = 3.63 \cdot 10^{-7}$, $n = 16 \cdot 10^{-3}$, $\Delta T_G = 0.1816$, and $t = 7.7 \cdot 10^{-5}$, we have $x = 2.735$ mm.

The HTEZ surface in the ZX plane, as shown in Fig. 12, is calculated as follows:

$$F_x = (x + e) \cdot d - e \cdot c$$

(29)

where $d = 0.0896$ mm, $e = 0.056$ mm, and $x = 2.735$ mm, we have $F_x = 0.2859$ mm$^2$.

The HTEZ surface in the XY plane, as shown in Fig. 13, is calculated as follows:

$$F_y = 2(x + e) \cdot (a + b) - 2a \cdot e - f \cdot n$$

(30)

where $a = 0.1373$ mm, $b = 0.1681$ mm, $e = 1.2165$ mm, $f = 0.255$, $n = 3.25$, and $x = 2.735$ mm, we have $F_y = 1.262$ mm$^2$.

The HTEZ surface in the ZY plane, as shown in Fig. 14, is calculated as follows:

$$F_z = 2(a + b) \cdot d - a \cdot c$$

(31)

where $a = 0.1373$ mm, $b = 0.1681$ mm, $d = 0.0896$ mm, and $c = 0.056$ mm, we have $F_z = 0.0394$ mm$^2$.

### 3.5 Calculation of inherent strain

The inherent strains in the $x$, $y$, and $z$ directions for the first layer are calculated as follows: applying Eq. (17) with $\xi = 1.57 \cdot 10^{-3}$ mm$^3$/J, $K = 0.58 \cdot 10^{-3}$ mm$^3$/J [35], and $q_v = 0.2308$ (J/mm) for 316L stainless steel, $F_x = 0.2859$ mm$^2$, $F_y = 1.262$ mm$^2$, and $F_z = 0.0394$ mm$^2$, we have: $\varepsilon_{inh-x} = -0.00127$, $\varepsilon_{inh-y} = -0.00011$, and $\varepsilon_{inh-z} = -0.0034$, respectively.

Table 2 shows the comparison of the one-layer IS value of the proposed method with the IS calculated from the welding process; the highest IS value is in the Z direction. The IS value calculated by our method approximates the value calculated for the welding process. This is explained by the same use of the method of calculating the temperature gradient.

Thus, the IS value for the whole part after 67 layers printed (calculated with the layer thickness is 0.045 mm, the printed part height is 3 mm) is calculated as follows:

\[
\begin{align*}
F_x \text{ (whole part)} &= 67 F_x \text{ (one layer)} - \frac{67}{h} d \varepsilon_{inh-x} \\
F_y \text{ (whole part)} &= 67 F_y \text{ (one layer)} - \frac{67}{h} d \varepsilon_{inh-y} \\
F_z \text{ (whole part)} &= 67 F_z \text{ (one layer)} - \frac{67}{h} d \varepsilon_{inh-z}
\end{align*}
\]

(32)

Assuming that the dept ($d$) that affects the inherent strain distribution equals (1/3) the layer thickness ($h$), we have the inherent strain values as follows: $\varepsilon_{x\text{ (whole part)}} = -0.05715$, $\varepsilon_{y\text{ (whole part)}} = -0.00495$, $\varepsilon_{z\text{ (whole part)}} = -0.153$. 

![Def of TG thermal analysis model](image)
4 Proving the calculated results with experimental results

Experiments on printing a cantilever beam were carried out on an SLM machine at the Laboratory of Production Engineering, Ulsan University, Korea. The geometrical model of the cantilever beam and the printing direction (0°, 45°, and 90°) are shown in Fig. 15. The cantilever beam’s thickness, as shown in Fig. 15, on the right side is 3 mm, and the left side is 9 mm. For printing the part, we added 30 support bars. Due to during the printing process, we used the same material and printing process parameters for the support bars and the main part, so the total height (9 mm) was used for calculating the inherent strain value. Specimens were printed on the MetalSys 250 with the printing mechanism and printed parts shown in Figs. 16 and 17, respectively.

Table 3 shows the measured dimension at nine positions (as shown in Fig. 18). The highest deformation of the cantilever beam at position 1 in the Z direction with the printing direction 90° after cutting the part from the base plate by the EDM machine is 1.5976 mm, as shown in Table 3c. The inherent strain is calculated as follows:

$$\varepsilon = -\frac{l_t - l_0}{l_0}$$  \hspace{1cm} (33)

where $l_0$ is the part length before cutting by EDM and $l_t$ is the part length after cutting by EDM. Considering the Z direction, with the part height before cutting of 8.8909 (mm) and the part height after cutting is 10.4885 (mm), and we have $\varepsilon_z = -0.1797$, then the deformation in the Z direction is 1.5976 mm.
With our proposed method, the inherent strain value in the Z direction is $\varepsilon_z = -0.153$. From this inherent strain value, with a total part height of $H = 9$ mm, the deformation ($\delta$) of the printed part in the Z direction is $1.377$ mm, which is calculated as follows:

$$\delta = \varepsilon_z(\text{whole part}) \cdot H \quad (34)$$

| Table 2 | Comparison of the proposed method with the welding process |
|---------|-----------------------------------------------------------|
| Our proposed method | Welding process [39] |
| $\varepsilon_{\text{ind-x}} = -0.00127$ | $\varepsilon_{\text{ind-x}} = -0.00085$ |
| $\varepsilon_{\text{ind-y}} = -0.00011$ | $\varepsilon_{\text{ind-y}} = -0.00085$ |
| $\varepsilon_{\text{ind-z}} = -0.0034$ | $\varepsilon_{\text{ind-z}} = -0.0017$ |
Fig. 16  Experiments on the SLM machine

Fig. 17  Specimens printed by SLM
Table 3  Measured dimension at nine positions on the samples

|                | 0°     | 45°    | 90°     |
|----------------|--------|--------|---------|
| **Length**     | 70.5714| 70.3836| 70.3076 |
| **Width**      | 11.9409| 11.9122| 11.9828 |
| **Height at positions** | | | |
| 1               | 8.9954 | 8.9478 | 8.8909  |
| 2               | 8.9665 | 8.9453 | 8.8476  |
| 3               | 8.9903 | 8.9217 | 8.8425  |
| 4               | 8.9479 | 8.9087 | 8.8422  |
| 5               | 9.0063 | 8.9198 | 8.8223  |
| 6               | 8.9727 | 8.9231 | 8.7642  |
| 7               | 8.9505 | 8.9431 | 8.8523  |
| 8               | 9.0060 | 8.9444 | 8.8887  |
| 9               | 8.9698 | 8.9644 | 8.8328  |

b) After cutting

|                | 0°     | 45°    | 90°     |
|----------------|--------|--------|---------|
| **Length**     | 70.4991| 70.4208| 70.2975 |
| **Width**      | 11.9620| 11.9122| 11.9788 |
| **Height at positions** | | | |
| 1               | 10.5611| 10.4808| 10.4885 |
| 2               | 9.8849 | 9.8629 | 9.7993  |
| 3               | 9.4045 | 9.3788 | 9.3121  |
| 4               | 9.0718 | 9.0631 | 9.0217  |
| 5               | 8.9597 | 8.9171 | 8.8249  |
| 6               | 8.9336 | 8.9309 | 8.7682  |
| 7               | 8.8759 | 8.9342 | 8.8598  |
| 8               | 10.5713| 10.4047| 10.4335 |
| 9               | 10.5321| 10.4254| 10.3818 |

c) Deviation

|                | 0°     | 45°    | 90°     |
|----------------|--------|--------|---------|
| **Length**     | −0.0723| 0.0372 | −0.0101 |
| **Width**      | 0.0211 | 0      | −0.004  |
| **Height at positions** | | | |
| 1               | 1.5657 | 1.5330 | 1.5976  |
| 2               | 0.9184 | 0.9176 | 0.9518  |
| 3               | 0.4142 | 0.4571 | 0.4696  |
| 4               | 0.1239 | 0.1544 | 0.1795  |
| 5               | −0.0466| −0.0027| 0.0026  |
| 6               | −0.0391| 0.0078 | 0.0040  |
| 7               | −0.0746| −0.0089| 0.0075  |
| 8               | 1.5653 | 1.4603 | 1.5448  |
| 9               | 1.5623 | 1.4610 | 1.5490  |
Comparing this to the experimental results, the deviation is 0.2206 mm. Therefore, the approach of calculating the inherent strain based on the temperature gradient is reliable for predicting part deformation.

5 Conclusions

The contribution of this research is to propose an inherent strain-based part deformation prediction model. This method enables:

- predicting the deformation of the part before actual printing, thereby enabling cost reduction,
- determining the appropriate printing process parameters to improve the quality of the printed part, and
- fixing 3D printing failures in an efficient and effective way by understanding printing process behaviors.

To determine the inherent strain (IS) value, a micro-scale model for analyzing the temperature distribution is created. The IS value is calculated from the temperature gradient. Then, the IS value is used to determine the part deformation. The proposed methodology has been developed and evaluated using 316L stainless steel cantilever beams, and both simulated and experimental results have been obtained. The difference between the two results is 0.2206 mm. This shows that the developed method is reliable and applicable for predicting the deformation of a 3D printing part.

Further research on optimizing the printing process in order to minimize part deformation would be beneficial in the future. In addition, to apply the proposed method in the industry, other factors affecting product quality, as well as the different weightings of the additive manufacturing criteria, should be considered.

Author contribution All authors contributed to the study’s conception and design. Material preparation, data collection, and analysis were performed by Ngoc-Hien Tran and Hwa Seon Shin. The first draft of the manuscript was written by Hong-Seok Park, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the ICT R&D program of MSIP/IITP. [B0101-19-1081, Development of PBF 3D printing analysis SW Technology for manufacturing simulation of metal parts in power generation or shipping].

Declarations

Competing interests The authors declare no competing interests.

References

1. Schoinochoritis B, Chantzis D, Salonitis K (2015) Simulation of metallic powder bed additive manufacturing processes with the finite element method: a critical review. Proc Inst Mech Eng Part B J Eng Manuf 231:96–117. https://doi.org/10.1177/0954405414567522
2. Mahesh M, Brandon ML, Donmez MA, Feng SC, Moylan SP (2017) A review on measurement science needs for real-time control of additive manufacturing metal powder bed fusion processes. Int J Prod Res 55:1400–1418. https://doi.org/10.1080/00207543.2016.1223378
3. Kundacioglu E, Lazoglu I, Rawal S (2016) Transient thermal modeling of laser-based additive manufacturing for 3D freeform structures. Int J Adv Manuf Technol 85:493–501. https://doi.org/10.1007/s00170-015-7932-2
4. Li C, Fu CH, Guo YB (2016) A multiscale modeling approach for fast prediction of part distortion in selective laser melting. J Mater Process Technol 229:703–712. https://doi.org/10.1016/j.jmatprotec.2015.10.022
5. Vrancken B, Wauthle R, Kruth JP, Humbeeck JV (2013) Study of the influence of material properties on residual stress in selective laser melting. Proc Solid Freeform Fabr Symp 393–407. https://doi.org/10.26153/tsw/15559
6. Setien I, Chiumenti M, Veen S, Sebastian MS, Garcïa Ñá, Echeverría A (2019) Empirical methodology to determine
10. Huang H, Wang J, Li L, Ma N (2016) Prediction of laser welding induced deformation in thin sheets by efficient numerical modeling. J Mater Process Technol 227:117–128. https://doi.org/10.1016/j.jmatprotec.2015.08.002

11. Cao YP, Hu N, Lu J, Fukunaga H, Yao ZH (2002) An inverse approach for constructing the residual stress field induced by welding. J Strain Anal Eng Des 37:345–359. https://doi.org/10.1243/030932402760074562

12. Saenz AV, Plazaola C, Banfeld I, Rashed S, Murakawa H (2012) Analysis and prediction of welding distortion in complex structures using elastic finite element method. Ship Sci Technol 6:35–42. https://doi.org/10.25043/19098642.67

13. Mochizuki M, Mikami Y, Yamasaki H, Toyoda M (2009) Analytical study on effects of strain distribution in welding start/end on welding distortion. Weld Int 23:654–661. https://doi.org/10.1080/09507110902482844

14. Liang X, Chen Q, Cheng L, Yang Q, To AC (2017) A modified inherent strain method for fast prediction of residual deformation in additive manufacturing of metal parts. Proc Ann Int Solid Freeform Fabr Symp 2539–2545. https://doi.org/10.26153/sw/16972

15. Liang X, Chen Q, Cheng L, Haydke D, To AC (2019) Modified inherent strain method for efficient prediction of residual deformation in direct metal laser sintered components. Comput Mech 64:1719–1733. https://doi.org/10.1007/s00446-019-01748-6

16. Neugebauer F, Keller N, Ploshikhin V, Köhler H (2014) Multi scale FEM simulation for distortion calculation in additive manufacturing of hardening stainless steel. Int Workshop Therm Form Weld Distortion, Bremen

17. Schänzel M, Ilar T, Brueckner F, Kaplan A (2018) Energy efficiency contributions and losses during selective laser melting. J Laser Appl 30:032304. https://doi.org/10.1080/13699197.2018.1504060

19. Chen Q, Liang X, Haydke D, Jikai Liu J, Cheng L, Oskin J, Whitmore R, To AC (2019) An inherent strain based multiscale modeling framework for simulating part-scale residual deformation for direct metal laser sintering. Addit Manuf 28:406–418. https://doi.org/10.1016/j.addma.2019.05.021

21. Shokrieh MM, Jalili SM, Kamangar MA (2018) An Eigen-strain approach on the estimation of non-uniform residual stress distribution using incremental hole-drilling and slitting techniques. Int J Mech Sci. https://doi.org/10.1016/j.ijmecsci.2018.08.035

22. Wang J, Ma N, Murakawa H (2015) An efficient FE computation for predicting welding induced buckling in production of ship panel structure. Mar Struct 41:20–52. https://doi.org/10.1016/j.marstruct.2014.12.007

23. Fu CH, Guo YB (2014) 3-Dimensional finite element modeling of selective laser melting Ti-6Al-4V alloy. Proc Ann Int Solid Freeform Fabr Symp 1129–1144. https://hdl.handle.net/2152/89257

24. Leicht A, Fischer M, Klement U, Nyborg L, Hryha E (2021) Increasing the productivity of laser powder bed fusion for stainless steel 316L through increased layer thickness. J Mater Eng Perform 30:575–584. https://doi.org/10.1007/s11665-020-05533-4

25. Deng Y, Mao Z, Yang N, Niu X, Lu X (2020) Collaborative optimization of density and surface roughness of 316L stainless steel in selective laser melting. Materials 13:1601. https://doi.org/10.3390/ma13071601

26. Mishra P, Ilar T, Brueckner F, Kaplan A (2018) Energy efficiency method in simulating powder bed fusion processes. Addit Manuf 17:157–168. https://doi.org/10.1016/j.addma.2017.06.037

27. Papazoglou EL, Karkalos NE, Markopoulos AP (2020) A comprehensive study on thermal modeling of SLM process under conductive mode using FEM. Int J Adv Manuf Technol 111:2939–2955. https://doi.org/10.1007/s00170-020-06294-7

28. Saryykin AA, Ibragimov EA, Babakova EV (2016) Modeling the temperature fields of copper powder melting in the process of selective laser melting. IOP Conf Ser Mater Sci Eng 42:012061. https://doi.org/10.1088/1757-899X/42/1/012061

29. Roberts IA (2012) Investigation of residual stresses in the laser melting of metal powders in additive layer manufacturing. Dissertation, University of Wolverhampton

30. Samad Z, Nor NM, Fauzi ERI (2019) thermo-mechanical simulation of temperature distribution and prediction of heat-affected zone size in MIG welding process on aluminum alloy EN AW 6082–T6. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/530/1/012061

31. Papazoglou EL, Karkalos NE, Karmiris OP, Markopoulos AP (2021) On the modeling and simulation of SLM and SLS for metal and polymer powders: a review. Arch Comput Methods Eng. https://doi.org/10.1007/s11831-021-09601-x

32. Nain V, Engel T, Carin M, Boisselier D, Seguy L (2021) Development of an elongated ellipsoidal heat Source model to reduce computation time for directed energy deposition process. Front Mater 8:474389. https://doi.org/10.3389/fmats.2021.474389

33. Pyo C, Kim J, Kim J (2020) Estimation of heat source model’s parameters for GMAW with non-linear global optimization-Part I: Application of multi-island genetic algorithm. Metals 10:885. https://doi.org/10.3390/met10080885

34. Chen J, Lu H, Wang J, Chen W, Hao D (2000) Prediction of welding deformation with inherent strain method based on FEM. Shanghai Huizhong Automotive Manufacturing Co. LTD report

35. Yazhi L (2014) Research on inherent strain distribution in welded low-alloy components. Proc Int Conf Meas Technol Mechatron Autom 512–515. https://doi.org/10.1109/ICMTMA.2014.125

36. Donik C, Kramer J, Paulin I, Godec M (2020) Influence of the energy density for selective laser melting on the microstructure and mechanical properties of stainless steel. Metals 10:919. https://doi.org/10.3390/met10070919

37. Śloderbach Z, Pająk J (2015) Numerical investigation and an effective modeling framework for simulating part-scale residual deformation in MIG welding process on aluminium alloy 6061. Int J Heat Mass Tran 80:288–300. https://doi.org/10.1016/j.ijheatmasstransfer.2014.09.014

38. Ville PM, Heidi P, Antti S, Olli N (2015) Preliminary investigation of keyhole phenomena during single layer fabrication in laser additive manufacturing of stainless steel. Phys Procedia 78:377–387. https://doi.org/10.1016/j.phpro.2015.11.052

39. Kim TJ, Jang BS, Kang SW (2015) Welding deformation analysis based on improved equivalent strain method considering the effect of temperature gradients. Int J Naval Arch Ocean Eng 7:157–173. https://doi.org/10.1015/iijnaoe-2015-0012
40. Barabash OM, Horton JA, Babu SS, Vitek JM, David SA, Park JW, Ice GE, Barabash RI (2004) Evolution of dislocation structure in the heat affected zone of a nickel-based single crystal. J Appl Phys 96:3673–3679. https://doi.org/10.1063/1.1777393

41. Hussain A, Choudhry MA, Hayat SS (2009) Effects of ordering on the thermal properties of an Ni3Al intermetallic alloy system: a molecular dynamics approach. Chinese J Phys 47:344–354

42. Kwon O, Kim HG, Ham MJ, Kim W, Kim GH, Cho JH, Kim NI, Kim K (2020) A deep neural network for classification of melt-pool images in metal additive manufacturing. J Intell Manuf 31:375–386. https://doi.org/10.1007/s10845-018-1451-6

43. Ametek: Alloy 316L. https://www.finetubes.co.uk/products/materials/stainless-steel-tubes/alloy-316-uns-s31600-wnr-14401. Accessed 30 Apr 2022

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.