A New Approach For Calculating Inherent Strain and Distortion in Additive Manufacturing of Metal Parts

Hong-Seok Park

Ulsan University

Hwa Seon Shin

Korea Electronics Technology Institute

Ngoc-Hien TRAN (✉ tranhien.tkm@utc.edu.vn)

University of Transport and Communications

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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.

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 industry. The AM processes 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 a 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 a SLM process and tested by the Laboratory for Production Engineering, Ulsan University in Korea.

Results show that there are inaccuracies in the 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 require 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 review from the reported research, current methods to reduce deformation include:

- 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 then predicting 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 thermo-mechanical 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 with 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 $\epsilon_{thermal}$, phase transfer strain ϵ_{phase} , plastic strain $\epsilon_{plastic}$ and creep strain ϵ_{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 $\epsilon_{elastic}$ and inherent strain ϵ^* , as shown below:

$$\epsilon_{total} = \epsilon_{elastic} + \epsilon^*$$

1

The inherent strain is calculated as follows:

$$\epsilon^* = \epsilon_{thermal} + \epsilon_{plastic} + \epsilon_{phase} + \epsilon_{creep}$$

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. 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 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:

$$Q_{heatsource} = Q_{arrived} + Q_{emitted}$$

3

$$Q_{arrived} = Q_{absorbed} + Q_{reflected}$$

4

$$Q_{absorbed} = Q_{meltingenergy} + Q_{convection} + Q_{radiation} + Q_{conduction}$$

5

In consideration of printing process parameters, the volumetric energy density E_v (J/mm^3) is calculated as follows [24]:

$$E_v = \frac{Q_{\text{meltingenergy}}}{u \cdot h \cdot h_a}$$

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 ($Q_{\text{meltingenergy}}$) 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:

$$Q_{\text{heatsource}} = Q_{\text{meltingenergy}} + \Delta Q$$

7

which ΔQ 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 is 0.546 [25, 26] and we selected $Q_{\text{heat source}}$ of 300 W.

The mathematical model of the heat transfer, which we used in determining the temperature distribution during the SLM process, is as follows [27,28]:

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

8

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 Fig. 5 [29], this heat source model from the welding process, however, it is also suitable for research on the SLM process [30].

The equations for calculating the Q_G are as follows [31]:

For the front heat source model:

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

9

and for the rear heat source model:

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

10

where $Q_{heat\ source}$ 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.

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 [32,33]:

$$\epsilon_x^* = -\frac{W_x}{F_x}; \epsilon_y^* = -\frac{W_y}{F_y}; \epsilon_z^* = -\frac{W_z}{F_z} \quad (11)$$

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 ϵ_x^* , the total volume W_y of ϵ_y^* , and the total volume W_z of ϵ_z^* in unit length are calculated as follows:

$$W_x = \xi \cdot q_v; W_y = W_z = K \cdot q_v \quad (12)$$

in which q_v is the linear energy density (J/mm) [34]:

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

13

ξ and K (mm/J) are longitudinal and transverse inherent strain coefficients, respectively. In this research, we utilized the ξ and K values from the welding process [33]. 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:

$$\epsilon_{inh-x} = -\frac{\xi \cdot q_v}{F_x}; \epsilon_{inh-y} = -\frac{K \cdot q_v}{F_y}; \epsilon_{inh-z} = -\frac{K \cdot q_v}{F_z} \quad (14)$$

Figure 6 shows the calculation of the inherent strain for n layers. After printing the first layer, the IS value is ϵ_{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:

$$\epsilon_1' = \epsilon_{inh} - \frac{d}{h} \epsilon_{inh}$$

15

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

$$\epsilon_2 = \epsilon_1' + \epsilon_{inh} = 2\epsilon_{inh} - \frac{d}{h} \epsilon_{inh}$$

16

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

$$\epsilon_2' = \epsilon_2 - \frac{d}{h} \epsilon_{inh} = 2\epsilon_{inh} - \frac{2d}{h} \epsilon_{inh} \quad (17)$$

and the IS value in the third layer is calculated as:

$$\epsilon_3 = \epsilon_2' + \epsilon_{inh} = 3\epsilon_{inh} - \frac{2d}{h} \epsilon_{inh}$$

18

Repeating this SLM process for n layers, we can calculate the IS value for the nth layer as follows:

$$\epsilon_n = \epsilon_{n-1}' + \epsilon_{inh} = n\epsilon_{inh} - \frac{(n-1)d}{h} \epsilon_{inh}$$

19

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

$$\begin{cases} \epsilon_{x(nlayer)} = n\epsilon_{inh-x} - \frac{(n-1)d}{h} \epsilon_{inh-x} \\ \epsilon_{y(nlayer)} = n\epsilon_{inh-y} - \frac{(n-1)d}{h} \epsilon_{inh-y} \\ \epsilon_{z(nlayer)} = n\epsilon_{inh-z} - \frac{(n-1)d}{h} \epsilon_{inh-z} \end{cases}$$

20

3.4. Calculation of heat treatment effect zone (HTEZ)

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 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 defined as the heat temperature effect zone (HTEZ), e.g., from 1173 K to 1700 K is the plastic zone, effects 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 Figure 8 is calculated as follows [35]:

$$x = 1.22 \sqrt{\gamma \cdot t}$$

21

γ is the heat diffusivity coefficient and t is the laser interaction time; $t = 7.7 \cdot 10^{-5}$ (s) [36]. 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 [35]:

$$\gamma = \lambda \cdot \rho \cdot C$$

22

in which λ is the thermal conductivity coefficient (J/ (m.s.K)), ρ is the material density (kg/m³), 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 [38]:

$$\Delta TG = \left| TG_{2ndHTEZ} - TG_{1stHTEZ} \right| = \frac{\rho \cdot m}{\alpha}$$

23

in which ρ is the density of material, m is the lattice parameter, and α is the thermal expansion coefficient. With $T = 1173$ K, the m value is $3.63 \cdot 10^{-7}$ (mm) [39]. From that we can generate the equation for calculating the material density based on the temperature gradient, lattice parameter, and thermal expansion coefficient:

$$\rho = \frac{\Delta TG. \alpha}{m}$$

24

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

$$x = 1.22 \sqrt{\gamma. t} = 1.22 \sqrt{\lambda. \rho. C. t} = 1.22 \sqrt{\lambda. \frac{\Delta TG. \alpha}{m}. C. t}$$

25

For determining the temperature gradient and calculating the HTEZ, the 3D printing process parameters and material characteristics shown in Table 1 are used.

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]
$Q_{heat\ source}$	Laser power	300 [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	Printing speed	1300 [mm/s]
C	Thermal capacity	$500 \cdot 10^{-3}$ [J/(g.K)]
λ	Thermal conductivity factor	$19.4 \cdot 10^{-3}$ [W/(mm.K)]
T_a	Ambient temperature	293 [K]
h	Layer thickness	0.045 [mm]
h_a	Hatch distance	0.07 [mm]

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

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

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

26

where $d = 0.0896$ mm, $c = 0.056$ mm, $e = 1.2165$ mm, and $x = 2.735$ mm, we have $F_x = 0.2859$ mm².

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

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

27

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 $F_y = 1.262$ mm².

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

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

28

where $a=0.1373$ mm, $b=0.1681$ mm, $d=0.0896$ mm, and $c=0.056$ mm, we have $F_z = 0.0394$ mm².

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 the equation (14) with $\xi = 1.57 \cdot 10^{-3}$ mm³/J, $K = 0.58 \cdot 10^{-3}$ mm³/J [33], and $q_v = 0.2308$ (J/mm) for 316L stainless steel, $F_x = 0.2859$ mm², $F_y = 1.262$ mm², and $F_z = 0.0394$ mm², we have: $\epsilon_{inh-x} = -0.00127$, $\epsilon_{inh-y} = -0.00011$, and $\epsilon_{inh-z} = -0.0034$, respectively.

Table 2
Comparison of the proposed method with the welding process

Our proposed method	Welding process [37]
$\epsilon_{inh-x} = -0.00127$	$\epsilon_{inh-x} = -0.00085$
$\epsilon_{inh-y} = -0.00011$	$\epsilon_{inh-y} = -0.00085$
$\epsilon_{inh-z} = -0.0034$	$\epsilon_{inh-z} = -0.0017$

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 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:

$$\left\{ \begin{array}{l} \epsilon_{x(wholepart)} = 67\epsilon_{inh-x} - \frac{(67-1)d}{h}\epsilon_{inh-x} \\ \epsilon_{y(wholepart)} = 67\epsilon_{inh-y} - \frac{(67-1)d}{h}\epsilon_{inh-y} \\ \epsilon_{z(wholepart)} = 67\epsilon_{inh-z} - \frac{(67-1)d}{h}\epsilon_{inh-z} \end{array} \right.$$

29

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: $\epsilon_{x(wholepart)} = -0.05715$, $\epsilon_{y(wholepart)} = -0.00495$, $\epsilon_{z(wholepart)} = -0.153$.

4. Proving The Calculated Results With Experimental Results

Experiments on printing a cantilever beam were carried out on a 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. Specimens were printed on the MetalSys 250 with the printing mechanism and printed parts shown in Figures 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 the 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 3 (c). The inherent strain is calculated as follows:

$$\epsilon = - \frac{l_t - l_0}{l_0}$$

30

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 $\epsilon_z = -0.1797$, then the deformation in the Z direction is 1.5976 mm.

With our proposed method, the inherent strain value in the Z direction is $\epsilon_z = -0.153$. From this inherent strain value, with a total part height of $H = 9$ mm, the deformation (δ) of the printed part in the Z direction is 1.377 mm, which is calculated as follows:

$$\delta = \epsilon_{z(wholepart)} \cdot H \quad (31)$$

Table 3. Measured dimension at nine positions on the samples.

a) Before cutting

	0°	45°	90°
Length	70.5714	70.3836	70.3076
Width	11.9409	11.9122	11.9828
Height	8.9578	8.9387	8.8292
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	8.9481	8.9184	8.8567
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	10.5335
9	10.5631	10.6154	10.4518

c) Deviation

	0°	45°	90°
Length	-0.0723	0.0372	-0.0101
Width	0.0211	0	-0.004
Height	-0.0097	-0.0203	0.0275
1	1.5657	1.533	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	0.004
7	-0.0746	-0.0089	0.0075
8	1.5653	1.4603	1.6448
9	1.5933	1.651	1.619

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.
- 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 industry, other factors affecting product quality, as well as the different weightings of the additive manufacturing criteria, should be considered.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study 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.

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Figures

Figure 1

Mechanism of the selective laser melting process.

a) 3D model at the design stage

b) Printed part

Figure 2

The SLM printed part in comparison with the designed part.

Figure 3

Systematic procedure for calculating inherent strain.

Figure 4

Heat model absorbed by a part.

Figure 5

Goldak heat source in the finite element model of the AM process.

Figure 6

Method for calculating inherent strain of an entire part by consideration of the Heat Treatment Effect Zone (HTEZ).

Figure 7

Phase change diagram of SS 316L material and determining the length of HTEZ.

Figure 8

Calculating the heat treatment effect zone (HTEZ) surface.

Figure 9

Definition of TG in the thermal analysis model (adapted from [37]).

Figure 10

Temperature distribution.

T1 = 2160 K
T2 = 1800 K
T3 = 1173 K

1st HTEZ
TGx = 0.8333;
2nd HTEZ
TGx = 0.6517;

Figure 11

Calculation of TG in the ZX plane.

Figure 12

HTEZ surface in in the ZX plane.

Figure 13

HTEZ surface in the XY plane.

Figure 14

HTEZ surface in the ZY plane.

Figure 15

Model for carrying out the experiments on the SLM machine.

Figure 16

Experiments on the SLM machine.

Figure 17

Specimens printed by SLM.

Figure 18

Measurement positions on the cantilever beam.