Distortion Analysis of SLM Product of SS316L using Inherent Strain Method

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Abstract. As one of additive manufacturing (AM) technologies, selective laser melting (SLM) which uses higher energy input enabling fully molten powder bed materials is nowadays increasingly applied to build full dense components without post processing. In the present work, specimens made of stainless steel powder SS 316L were to be processed using SLM Solutions 280 HL, characterized and compared to the simulation from Finite Element Analysis (FEA) Software. The powders have been melted to produce cantilever specimens with different build orientation by using fixed major process parameters such as laser power, hatching distance and layer thickness as well as scan speed. The experiment starts with the FEA simulation which focused on Inherent Strain Method (ISM) and followed by experimental process. While the distortion of the specimens after the process to be the main concern and to be discussed based on the build orientation of the specimens. The measurement distortion of the specimens was conducted by using KEYENCE 3D scanner. It is found out that the build orientation play a big role on distortion of the specimens made from SLM. Meanwhile, result of distortion from the experiment and FEA simulation are close to each other. It is expected that this basic FEA study will provide basic information and estimation towards the distortion and computational time by simulating product prior to commencement of real product manufacturing. Thus, by using ISM will reduce the computational time and reduce the waste material by simulating the process before the experiment have been held.

1. Introduction
Additive manufacturing (AM) is a processes that joint materials by adding layer-by-layer which follows the geometry from computer aided design (CAD) drawing in order to form final product. The process are varies which depends on the heat source such as electron beam, laser or arc and also how the material is deposited [1]. AM also allows production of complex parts directly from the design without using expensive tooling or forms such as punches, dies or casting molds thus it reduces the needs for many conventional processing steps. For these reasons, AM is now widely recognized as a new standard for the design and production of high performance components for aerospace, medical, energy and automotive applications. Aerospace examples include complex fuel injector nozzles that previously required assembly of multiples parts and lightweight engineered structures that result in significant cost savings [2]. In this paper, the distortion of the produced part from SLM has been investigated. SLM is a process uses a layer-wise building principle where the powder is deposited in a bed and molten locally
in a layer according to CAD drawing [3]. The material is locally and rapidly heated above its melting temperature and then allowed to solidify and cool in order to form a dense geometry [4]. This process involves large thermal gradients [5]. This complex thermal process can lead to large thermal strain and consequently large residual stress or distortion in the manufactured metal parts [6]. According to [7], AISI 316L and PH 17-4 stainless steels, Maraging steel Grade 300, Inconel 625 and 718, Al10SiMg, CoCr and Ti6Al4V alloys are among the most used and studied materials for SLM. In this study, commercial stainless steel 316L (SS 316L) powder have been used to produce parts from SLM process. According to [8], it is almost impossible to minimize the distortion of the final product from SLM without simulation tools. In order to predict the residual distortion and stress in the AM process, finite element method (FEM) have been used to model the AM process [6]. Based on the numerical approaches, finite element method (FEM) simulation can be implemented for optimization SLM parameters such as laser scanning strategies, build-up directions and design support structures [9]. In this paper, inherent strain method (ISM) have been proposed in order to investigate the distortion of the product which prior to SLM process. In ISM, only pure mechanical computation has been considered which the phase transformation and microstructure predictions have been neglected in order to gain solution speed [10].

The work presented in this paper is focused on the development and application of an alternative in order to predict SLM distortion based on ISM approach. In the simulation, ISM is a mechanical approach where no transient thermal analysis is involved. A commercial stainless steel 316L (SS 316L) powder have been fed into SLM Solutions 280 HL in order to produce cantilever specimen. SIMUFACT Additive has been chosen as FEM software for modelling the whole SLM process. It has been previously developed for calculating of welding distortion of large parts and it requires to adjust the volume of the shrinking elements and their initial temperature.

2. Simulation Procedure using Inherent Strain Method (ISM)

2.1. Theory of Inherent Strain Method (ISM)

In the micro-welding process, the material along the weld path will first be heated, melted, and then solidified in a short time span, which would result in large temperature gradient and complex deformation path. After welding is completed, the welded part cools to the ambient temperature. Figure 1 shows the basic deformation of nodes and element of the specimen during SLM process.

![Figure 1. Original definition of inherent strain for welding mechanics [9].](image)

By definition, the inherent strain in the element is defined as the residual strain in the stress-relieved state with reference to the under formed state in Figure 1 (a) before the welding take place:

\[ \varepsilon^* = \frac{(d\varepsilon^* - d\varepsilon_0)}{d\varepsilon_0} \] (1)

After the welding process, the metal part is cooled down to the ambient temperature and thermal strain in the part vanishes. Since the reference temperature employed here is always the ambient temperature of the entire system, thermal strain is not concerned and only mechanical strain is involved.
The first term on the left-hand side is the total mechanical strain \( \varepsilon \) after the welding is finished, while the second term on the right-hand side is the mechanical elastic strain \( \varepsilon_e \), which is directly proportional to the stress released. Practical application of the original inherent strain theory to welding problems makes a key assumption that the elastic strain insignificant compared to the plastic strain. Hence it can be assumed that all the elastic strains vanish and inherent strain \( \varepsilon^* \) becomes equal to the plastic strain \( \varepsilon_p \) generated from the welding process:

\[
\varepsilon^* = \varepsilon_p
\]  

(3)

2.2. **Inherent Strain Method (ISM) using pure mechanical simulation**

In simulation, the inherent strains are to be considered during building process by thermal strains, plastic strains and phase transformation. These strains can be calibrated from experiments by measuring the distortion of printed cantilever beam at certain cutting height and running simulations with the same parameters from the experimental in order to match printed cantilever as a reference. Some process parameters such as layer parameters and inherent strain estimation are to be counted, therefore, material properties which were taken at room temperature is pure mechanical computation. During simulation of mechanical calibration method, no temperature effects are shown or calculated. Unlike Detailed Transient Analysis (DTA) which considered the thermal effects such as in thermo-mechanical simulation which increasing the computational time and limited to small scale specimen. Inherent Shrinkage Method (ISM) takes the strains that are usually applied during cooling of molten metal down to room temperature. Since the inherent strains value are from thermal shrinkage which consist of compressive stress as mentioned from [11], the value with respect to x, y and z axis are to be negative.

The strain increment, \( \varepsilon \), in a thermo-mechanical equation consist of an elastic strain, \( \varepsilon^e \), plastic strain, \( \varepsilon^p \), thermal strain, \( \varepsilon^\text{thermal} \), and phase transformation, \( \varepsilon^\text{phase} \). Thus, total residual strain, \( \varepsilon_{tot} \), can be calculate by using Equation 1.

\[
\varepsilon_{tot} = \varepsilon^e + \varepsilon^p + \varepsilon^\text{thermal} + \varepsilon^\text{phase}
\]  

(4)

Unlike in mechanical simulation which during numerical calculation, thermal effects have been neglected. The value of inherent strain, \( \varepsilon^* \) is defined as the difference between the total residual strain and elastic strain as seen in Equation 2.

\[
\varepsilon^* = \varepsilon_{tot} - \varepsilon^e
\]  

(5)

By using Equation 5, the inherent strain can be used to calculate the residual stresses without the information of the thermal effect such as thermal strain and phase transformation. Where \([K]\) is the elastic stiffness matrix, \([u]\) is the nodal displacement vector, \(f^*\) is the nodal force vector induced by the inherent strains. When the displacement vector \([u]\) has been solved using Equation 3, the total strain, \(\varepsilon\), and consequently the residual stress, \(\sigma\), can be calculated.

\[
[K][u] = [f^*]
\]  

(6)

\[
f^* = \int [B] [D] [\varepsilon^*] \, dV
\]  

(7)

Where \([B]\) denotes the nodal deformation matrix and \([D]\) denotes the material elastic matrix. The inherent strain, shown in Figure 2, can be seen as the input for the FEM computation of the stresses and
can be determined in either of the two ways, through a thermal-elasto-plastic simulation or experimental measurements.

\[
\varepsilon = [B] [u] \quad (8)
\]

\[
\sigma = [D^e] ( [\varepsilon_{tot}] - [\varepsilon^*] ) \quad (9)
\]

**Figure 2.** Flow chart of FEM computation of stress with the inherent strain as input.

3. **Experimental Setup**

Cantilever shape and dog bone specimens were fabricated by SLM Solution 280 HL. Both specimens and the base plate were made from SS 316L. Dog bone specimens were manufactured in a SLM Solutions 280 HL machine meanwhile base plate has been fabricated by using Computer Numerical Control (CNC) milling machine in order to get specified dimension to fit into SLM 280 HL machine. Figure 3 shows the fabricated specimens by SLM process, consist of 8 dog bone samples with 2 different build direction: horizontal and vertical, followed by 3 cantilever specimens with three different build orientation: 0°, 45°, and 90°. All printed samples were fabricated by using process parameters showed in Table 1.

**Figure 3.** Fabricated specimens by using SLM
Table 1: SLM process parameters

| No. | Description               | Parameter   |
|-----|---------------------------|-------------|
| 1   | Laser power               | 275W        |
| 2   | Hatch distance            | 0.12mm      |
| 3   | Layer thickness           | 50µm        |
| 4   | Scan speed                | 700mm/s     |
| 5   | Scan strategy (Hatch style)| Bi-directional |
| 6   | Oxygen content            | < 0.1%      |

After manufacturing, cantilever specimens were partially cut 1mm from the baseplate by using water jet cutting machine and electrical discharge machine (EDM). The final vertical distortions (Z direction) of each samples were measured and the value of the distortion have been collected as $\Delta Z_{\text{max}}$.

Figure 5 shows the image of fabricated dog bone specimens. Both dog bone specimens have two different build direction which plays an important role which affected the final geometry of printed SLM sample. In this paper, sample with horizontal build orientation have been considered since the value of Z distortion can be clearly seen on a sample with horizontal build orientation. All fabricated specimens by using SLM process have been removed from the base plate by cutting the support structure using hand cutter tools. Figure 6 shows the image of the base plate after removing all the specimens.
4. Simulation Setup & Procedure
In this paper, FEM approach has been used in order to calculate the pure mechanical simulation. Purely mechanical analysis approach of Simufact Additive requires the input of inherent strain values prior to the simulation. These inherent strain values depend on material properties and process parameters. Figure 7 shows the information of basic inherent strain method (ISM). From Figure 7, thermal strains and phase transformation have been neglected thus it will reduce the computational time since in mechanical simulation, only value of inherent strain are needed in order to get the value of stress, strains, and distortion as the outputs.

All values for inherent strain can be obtained from the experimental work which cantilever specimens have been used for calibration method. Figure 8 shows the image of flow chart methodology for the whole process for ISM simulation and experimental.
4.1 Calibration Method

For this study, 3 cantilever beams with three different build direction (0°, 45°, 90°) have been printed in order to investigate the value of the distortion for each cantilever beam specimen, values of the distortion then to be used as $\Delta Z_{\text{max}}$. Reference height have been set as 9mm since the cutting height between the cantilever beam specimen to the base plate is 1mm. Figure 9 shows the result of the distortion of each specimens have been investigated by using KEYENCE 3D scanner and Table 2 is the value of $\Delta Z_{\text{max}}$. 

Figure 8. Inherent strain method (ISM) flow chart.
Figure 9. Result of distortion for each cantilever specimens with different build orientation: (a) 0°, (b) 45°, (c) 90°.

Table 2. Value of $\Delta Z_{\text{max}}$.

| Build Orientation (°) | 0     | 45    | 90    |
|-----------------------|-------|-------|-------|
| $\Delta Z_{\text{max}}$ (mm) | 1.594 | 1.445 | 1.766 |

Figure 10 shows the image of the printed cantilever inside the red circle indicator before the sample have been removed from the base plate. In the calibration method, the parameters used in the simulation are shown in Table 3. The cutting parameter have been set 1mm from the base plate which is similar to the experimental. Figure 14 shows the result of the calibration simulation and the value of new inherent strain which respect to each cantilever beam specimens are to be considered as $(\varepsilon_x, \varepsilon_y, \varepsilon_z)_{\text{new}}$. The value of new inherent strain then to be collected and the value have been used in the mechanical simulation in order to predict big scale part simulation.
Figure 10. Printed SS316L cantilever beams.

Table 3. Calibration method simulation parameters

| Parameter             | Value |
|-----------------------|-------|
| Layer thickness, mm   | 0.05  |
| Scan width, mm        | 10    |
| Beam width, mm        | 0.08  |
| Laser power, W        | 275   |
| Velocity, mm/s        | 700   |
| Efficiency, %         | 25    |
| Material              | SS 316L |

4.2 Mechanical Calibration Method

Cantilever specimens with three different build orientation have been simulate. In order to get the new value of inherent strain, apple to apple comparison between experimental and simulation have to be done such as position, material, and cutting height of the cantilever specimen. Figure 11 shows the simulated cantilever specimen and the base plate. In this study, material of SS316L have been assigned to the cantilever specimen and also the base plate. All the general properties, chemical composition, thermal properties and mechanical properties and flow curve of the material SS316L powder have been determined by Simufact Material 2019. All the information about SS316L powder have been used for SIMUFACT Additive to solve the numerical equation in finite element analysis.
4.3 Build Properties

In SIMUFACT Additive, build properties consist of two sections to be defined. Figure 12 shows the calibration parameters for the whole process such as measuring point coordinate and $\Delta Z_{\text{max}}$ for every cantilever specimens. Next, the build parameters such as machine parameters including beam width, velocity, power and efficiency and the material properties will be taken into account in order to estimate the inherent strain value which prior to the calibration process. Figure 13 shows the image of build parameters and the red rectangular shape shows the value of inherent strain after the machine process parameters and material properties have been calculated by the software. In this study, the type of inherent strain distribution has been defined as orthotropic distribution since the value of inherent strain which respect to $Z$-axis were to be counted.
4.4 Calibration result
In this section of calibration results, status of every current step are shown in graph $\Delta Z_{\text{max}}$ over the number of calibration steps. In this study, the overall step are set to 50 steps in order to complete the calibration process. From the graph $\Delta Z_{\text{max}}$ over the number of calibration steps illustrated in Figure 14, once the process parameters and material properties have been calibrated, SIMUFACT Additive have been able to estimate the value of new inherent strain by solving the Equation. 10.

$$S = \sum_{i=1}^{n} r_i^2$$  \hspace{1cm} (10)

Where $r_i$ is the difference between $z_{i,\text{sim}}$ and $z_{i,\text{exp}}$. $i$ is the number of running index, $n$ represents the number of sample points, $z_{i,\text{sim}}$ is the simulated distortion and $z_{i,\text{exp}}$ is the measured distortion from the experiments. In this research, the new value of inherent strain is $\varepsilon_{xx} = -0.0140362$, $\varepsilon_{yy} = -0.0139978$, and $\varepsilon_{zz} = -0.0455615$. Next, the new value of inherent strains will be used for mechanical simulation in order to simulate SLM product with same material which is SS316L. shows the image of printed cantilever specimens in SIMUFACT Additive after the samples have been cut 1mm from the base plate.
5. Result and discussion

Mechanical simulation in SIMUFACT Additive used macroscopic scale so called layer model. All SLM parts are extremely large compared to the actual size of every micro-weld and each weld seam. Thermal history and phase transformation are to be neglected in mechanical simulation in order to reduce the computational time. The value of inherent strains have been determined during mechanical calibration and the values of inherent strain then will be used as input for mechanical simulation. Noted that, the inherent strains from mechanical calibration can only be used on components with same material and built with the same parameters. Figure 16 shows the build parameters assigned in SIMUFACT Additive during mechanical simulation. In this study, two dog bone samples with different build orientation have been simulate in order to investigate the value of distortion. The value of new inherent strain, $\varepsilon_{xx} = -0.0140362$, $\varepsilon_{yy} = -0.0139978$, and $\varepsilon_{zz} = -0.0455615$ have been assigned in build parameters as input for SIMUFACT Additive to complete the mechanical simulation. The parameters used for both dog bone samples in this mechanical simulation are set similar with parameters from Table 1.

From the mechanical simulation of two specimens with different build orientation, Figure 17 shows that specimen with horizontal build orientation produce more value of distortion compared to sample with vertical build orientation. Moving heat source for horizontal build specimen have more time exposure compared to vertical build specimen during metal powder melted layer by layer during build up process. This is due to horizontal build specimen have bigger area of surface in the process chamber compared to vertical build specimen. Result from simulation made by SIMUFACT Additive shows that the
maximum value of distortion from the horizontal build specimen is 3.40mm meanwhile vertical build specimen have only 1.81mm. From the value of distortion from both simulated specimens, it is clearly shown that build orientation of the parts during manufacturing process will affect the final geometry of the SLM product. The value of new inherent strain from mechanical calibration simulation by SIMUFACT Additive can be used to other SLM parts with bigger and complex geometry. It is clearly shown that result of new value of inherent strain from calibration process can be used for mechanical simulation process since the simulation of both samples with two different build orientation was completed without any error.

![Figure 17. Dog bone specimens with two different build orientation.](image)

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