Numerical investigation and an effective predicting system on the Selective Laser Melting (SLM) process with Ti6Al4V alloy

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Abstract. Selective laser melting (SLM) is a powder bed based modern additive manufacturing process which is widely used to make full-density complex parts in a layer upon layer fashion. However, the high temperature in heating and fast cooling during SLM process result in the large tensile residual stress which affects to the quality of the SLM printed part such as part distortion and cracks. This study proposes to develop a system for predicting the quality of the printed part from the manufacturing planning to remove the failures before carrying out the real printing process. For developing such system, a three-dimensional (3D) finite element model with moving volumetric heat source has performed to predict the surface temperature distribution and the molten pool size of Ti6Al4V. From this model, interrelationship between process parameters and temperature distribution has derived out. Based on that, the deformation has predicted through calculating residual stress along with the result of temperature distribution to minimise or eliminate deformation and residual stresses and strains.

1. Introduction
3D printing known as additive manufacturing (AM) or layer by layer manufacturing enables to manufacture products from plastic to metal. 3D printing has been applied for applications in different fields such as aerospace, automotive, biomedical, and energy industries. This technology plays an important role in Industry 4.0 as the major technology that enables the financial reality of the industrial Internet of Things across many industrial applications [1]. Currently for fabricating metallic parts, there are many different AM processes using different combinations of stock material form, material delivery, and heat source are used. Selective laser melting (SLM) is the most attractive method for building layer by layer from metallic powders. However, applications of AM in general and SLM to industry have some barriers due to the quality of the manufactured parts which are affected by the high residual stresses and large deformation [2]. The poor quality of the SLM printed parts in comparison with the traditional manufacturing prevents the applications of this technology to industry. The aim of this research is to develop a system for predicting the printed part quality during SLM process to remove the failures before carrying out the real printing process. For accurately predicting quality before manufacturing, consolidation mechanisms used in laser and powder bed based layered manufacturing such as SLM must be analysed. Without understanding the consolidation mechanisms in each case, it will be difficult to develop a predictive system.
2. Literature review

In SLM process, high temperature is required for melting of metallic powders. Due to high temperature and fast cooling, residual stress will be generated in the printed part. The large residual stress results in the part distortion which is negative effect to the product performance [3]. Part distortion caused by the tensile residual stress not only reduces the part geometrical accuracy but also affects the functional performance of the printed parts [4]. On the other hand, to fix the part distortion of the printed part, the post processing must be carried which increases the manufacturing cost [5]. So, the temperature distribution and residual stress fields during the SLM process must be analysed to keep the quality of the printed parts. In the literature, many researchers have proposed methods for predicting the temperature distribution and residual stress during SLM process.

Li et al. proposed to divide a SLM process for a practical part into three scales such as micro scale, meso scale and macro scale [3]. With this approach, the temperature history and residual stress fields during the SLM process were predicted. Thermal information has been transferred through micro scale laser scanning, meso scale layer hatching, and macro scale part build-up [5].

The experimental works also focused on, Dunbar et al. [6] carried out the research work with both simulation and experiments. In which, the Inconel 718 powder material was used for printing part on the EOSINT M280 machine. Project Pan software was used for analysing the deformation. The dimension of the printed part was measured by using the coordinate measuring machine. The difference on the deformation of the printed part and predicted deformation is 12%.

For better understanding of the factors influencing the quality of the printed parts, the destructive surface residual stress measurement technique coupling with a non-destructive volumetric evaluation method was applied [2]. The applications of optical and scanning electron microscopy have been proposed. Residual stresses are measured qualitatively using a novel deflection method and quantitatively using X-ray diffraction [7]. However, the experimental works cause high cost, as well as cannot avoid failure during printing process.

This paper presents a predictive system which enables to drive out the temperature distribution, residual stress and strain in SLM process to remove the failure before carrying real printing process. A predictive system has developed with integrated modules such as temperature distribution, residual stress, deformation, and optimal printing process parameters. For carrying out this system, Comsol Multiphysics is used for solving the mathematical models of the heat transfer, residual stress and deformation. Then, the simulation results are used for developing the database of the system. The predictive system enables fast response to user about the quality of the printed part before carrying out the real printing process with the machine.

3. Systematic procedure

In powder bed based additive manufacturing processes selective laser melting (SLM) process requires

![Figure 1. Selective laser melting mechanism (adapted from [8]).](image-url)
high temperature for melting the metallic powders. Figure 1 shows the temperature gradient mechanism with deformation of the part in heating and cooling process. When laser source scans the powder surface, energy is transferred from the top layer to under layers through various physical changes such as heat transfer, radiation, convection, conduction, fluid flow within the molten pool, melting, evaporation, and chemical reactions [8].

Figure 1. Shows the temperature gradient mechanism with deformation of the part in heating and cooling process.

During SLM process, thermal expansion at layers of the printed part happens which lead to the part deformation. Systematic procedure for calculating stress and strain of the SLM printed part is shown in figure 2.

According to this procedure, for determining the part distortion due to high tensile residual stress and strain in the SLM printed part, the first step is the calculating temperature distribution generated during laser irradiating which must be determined.

Figure 2. Systematic procedure for calculating stress and strain.

Figure 3. Geometry and mesh modelling for simulation.
Afterwards, the residual stress and strain due to the thermal behaviour and deformation relating to the temperature distribution are achieved. The following sections present the temperature distribution, also the residual stress and deformation due to the thermal behaviour during the SLM process. Figure 3 shows the geometry and mesh modelling for simulating temperature distribution, residual stress and strain whose dimension is 1.0 mm (width) × 3 mm (length) × 0.2 mm (thickness).

4. Finite element modeling

To simulate the SLM process, the three-dimensional (3D) FE model is created using the software COMSOL Multiphysics. Firstly, a non-linear transient thermal analysis is conducted to acquire the temperature distribution generated during laser irradiating. Afterwards, a stress and a strain analysis are developed with an automatic change element type from thermal to structural, and the temperatures obtained from the previous transient thermal analysis are applied to the structural analysis model as a thermal load. The parameters used in the finite element analysis are summarised in table 1.

4.1. Thermal analysis

Figure 4 shows the heat transfer mechanism in SLM process. The governing equation for heat transfer in this SLM process is given as follows [9,10]:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mu \nabla T = \nabla (k \nabla T) + Q
\]

(1)

in which \( T \) is temperature; \( \rho, C_p, k \) are density, thermal capacity, and thermal conductivity factor, respectively. \( Q \) is the absorbed heat and \( \mu \) is the laser velocity.

Proper boundary conditions must be set to obtain the more accurate simulation results. The heat loss due to convection and radiation is considered and can be expressed as the equations 2 and 3, respectively [9].

\[
q_{\text{conv}} = h_c (T - T_{\infty})
\]

(2)

\[
q_{\text{rad}} = \varepsilon \sigma (T^4 - T_{\infty}^4)
\]

(3)

where \( T_{\infty} \) is the ambient temperature (K), \( h_c \) is the convective heat transfer coefficient (W/m².K), \( \varepsilon \) is the surface emissivity, \( \sigma \) is the Stefan-Boltzmann constant. Temperature dependent thermal properties (\( \rho, C_p, k \)) of Ti6Al4V alloy are listed in table 2. In addition to the thermal properties, mechanical and physical properties of Ti6Al4V alloy were also considered (table 3). In this work, the spatial distribution of the heat input is calculated using double ellipsoid model offered by Goldak et al. [11]. Nowadays the double ellipsoid heat source model is one of the most widely employed in the simulations of the laser-based manufacturing due to its relative simplicity and accessibility [12]. This model considers a
combined heat source composed of two ellipsoidal sources (figure 5). For a point \((x, y, z)\) inside the front semi-ellipsoid, the heat flux is defined as [11]

\[
Q(x, y, z, t) = \frac{6\sqrt{3}f_f P}{a_f b c \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_f^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right), \quad z \geq 0.
\]  

(4)

For a point \((x, y, z)\) inside the rear semi-ellipsoid, the heat flux is defined as [11]

\[
Q(x, y, z, t) = \frac{6\sqrt{3}f_r P}{a_r b c \pi \sqrt{\pi}} \exp\left(-\frac{3x^2}{a_r^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right), \quad z < 0.
\]  

(5)

Here, the heat flux \(Q(x, y, z, t)\) in this formulation is divided into two parts, \(x, y,\) and \(z\) are the local coordinates of a point with respect to the moving heat source, \(a_f, a_r, b\) and \(c\) are the set of lengths defining the front and rear semi-ellipsoids, respectively, \(P\) is the power of the laser beam. The parameter \(f_f\) is the correspondent front heat fraction and the rear part is represented by \(f_r\) both 0.6 and 1.4 respectively [11].

![Figure 5. Double ellipsoid heat source model (heat source moving through X-axis) [11].](image)

Table 1. Parameters for simulation of temperature distribution of Ti6Al4V.

| Name | Description | Value |
|------|-------------|-------|
| \(x_0\) | Path center X-Coordinate (mm) | 0 |
| \(y_0\) | Path center Y-Coordinate (mm) | 0 |
| \(P\) | Total laser power (W) | 150,120 |
| \(u\) | Laser velocity (mm/s) | 1000 |
| \(a_f\) | Length of \(x\)-semi axis in the front part of ellipsoid (µm) | 130 |
| \(a_r\) | Length of \(x\)-semi axis in the rear part of ellipsoid (µm) | 260 |
| \(b\) | Length of \(y\)-semi axis of ellipsoid (µm) | 130 |
| \(c\) | Length of \(z\)-semi axis of ellipsoid (µm) | 80 |
| \(\varepsilon\) | Emissivity | 0.35 [8] |
| \(\sigma\) | Stefan–Boltzmann constant (W/ (mm².K)) | 5.67x10^{-8} [8] |
| \(T_a\) | Ambient temperature (K) | 293 [8] |
Table 2. Temperature dependent thermal properties of Ti6Al4V [8].

| Temperature (°C) | Density (kg/m³) | Specific Heat (J/kg-K) | Thermal conductivity (W/m-K) |
|------------------|-----------------|------------------------|----------------------------|
| 25               | 4420            | 546                    | 7                          |
| 100              | 4406            | 562                    | 7.45                       |
| 300              | 4381            | 584                    | 8.75                       |
| 900              | 4294            | 734                    | 20.2                       |
| 1100             | 4267            | 660                    | 21                         |
| 1500             | 4205            | 732                    | 25.8                       |
| 1600             | 4198            | 750                    | 27                         |
| 1700             | 3886            | 831                    | 83.5                       |
| 1800             | 3818            | 831                    | 83.5                       |

4.2. The fundamentals of thermal stress analysis
The temperatures from the thermal analysis become the loads for the structural analysis. The same finite element mesh has used in the thermal analysis is employed in the thermal stress analysis and the boundary conditions. The relationship between the stress and the strain is defined as [13]:

\[
\{\sigma\} = [D]\{\varepsilon\}
\]  

(6)

where \{\sigma\} is the stress vector; \([D]\) is the elasticity matrix; \{\varepsilon\} is the elastic strain vector and for the ideal elastic-plastic body,

\[
\{\varepsilon\} = \{\varepsilon_e\} - \{\varepsilon_p\} - \{\varepsilon_t\}
\]  

(7)

Where \{\varepsilon\}, \{\varepsilon_p\} and \{\varepsilon_t\} are the total strain vector, the plastic strain vector, and the thermal strain vector, respectively.

Eq. (6) can also be written as:

\[
\{\varepsilon\} = [D^{-1}][\sigma] + \{\varepsilon_p\} + \{\varepsilon_t\}
\]  

(8)

since the material is assumed to be isotropic, the above stress-strain equation can be expressed in Cartesian coordinates as [13]:

\[
\varepsilon_x = \frac{1}{E}[\sigma_x - \mu(\sigma_y + \sigma_z)] + \varepsilon_x^p + \varepsilon_t
\]

\[
\varepsilon_y = \frac{1}{E}[\sigma_y - \mu(\sigma_x + \sigma_z)] + \varepsilon_y^p + \varepsilon_t
\]

\[
\varepsilon_z = \frac{1}{E}[\sigma_z - \mu(\sigma_x + \sigma_y)] + \varepsilon_z^p + \varepsilon_t
\]

\[
\gamma_{xy} = \frac{\tau_{xy}}{2G}, \gamma_{yz} = \frac{\tau_{yz}}{2G}, \gamma_{zx} = \frac{\tau_{zx}}{2G}
\]  

(9)

where E, G, \mu are the elastic modulus, shear modulus and Poisson's ratio, respectively. A typical calculation method of thermal strain from Eq. (9) is [13]

\[
\varepsilon_t = \alpha_e \Delta T = \alpha_e (T - T_o)
\]  

(10)

where \alpha_e is the coefficient of thermal expansion; \(T\) is the temperature at time \(t\), and \(T_o\) the reference temperature at \(t = 0\).
When the stress exceeds yield limit of the material, plastic deformation will occur. According to Prandtl-Reuss equations in plasticity theory, the plastic strain increment is proportional to the instant deviator stress and shear stress as follows [13]:

\[
\frac{d\varepsilon_p^x}{\sigma_x} = \frac{d\varepsilon_p^y}{\sigma_y} = \frac{d\varepsilon_p^z}{\sigma_z} = \frac{d\gamma_{xy}}{\tau_{xy}} = \frac{d\gamma_{yz}}{\tau_{yz}} = \frac{d\gamma_{zx}}{\tau_{zx}} = d\lambda
\]

\[\sigma_x' = \sigma_x - \sigma_m,\]
\[\sigma_y' = \sigma_y - \sigma_m,\]
\[\sigma_z' = \sigma_z - \sigma_m\]  \hspace{1cm} (11)

Where \(\sigma_x', \sigma_y', \sigma_z'\) are the deviator stresses of \(x, y\) and \(z\) directions in Cartesian coordinates, respectively; \(d\lambda\) is the instant positive constant of proportionality; \(\sigma_m\) is the mean value of stress and is defined as [13]:

\[\sigma_m = \frac{\sigma_x + \sigma_y + \sigma_z}{3}\]  \hspace{1cm} (12)

Then Eq. (10) may be substituted by,

\[\varepsilon_x = \frac{1}{E} \left[ \sigma_x - \mu(\sigma_y + \sigma_z) \right] + \int \sigma_x' d\lambda + \alpha_x \Delta T\]
\[\varepsilon_y = \frac{1}{E} \left[ \sigma_y - \mu(\sigma_x + \sigma_z) \right] + \int \sigma_y' d\lambda + \alpha_y \Delta T\]
\[\varepsilon_z = \frac{1}{E} \left[ \sigma_z - \mu(\sigma_x + \sigma_y) \right] + \int \sigma_z' d\lambda + \alpha_z \Delta T\]  \hspace{1cm} (13)

\[\gamma_{xy} = \frac{\tau_{xy}}{2G} + \int \gamma_{xy}' d\lambda, \quad \gamma_{yz} = \frac{\tau_{yz}}{2G} + \int \gamma_{yz}' d\lambda, \quad \gamma_{zx} = \frac{\tau_{zx}}{2G} + \int \gamma_{zx}' d\lambda,\]

In the structural analysis, there will be a residual deformation after cooling when the yield point is met. Both the elastic and the plastic deformations affect the deformation zone. The COMSOL Multiphysics analyses the deformation of the material after cooling according to the elastic-plastic strain state. Temperature dependent mechanical and physical properties are required for the stress analysis as listed in table 3.

**Table 3.** Temperature dependent thermal properties of Ti6Al4V [13].

| Temperature (°C) | Thermal expansion, \(\alpha_e\) \((1^\circ\text{C}^{-1} \times 10^{-6})\) | Elastic modulus, \(E\) (GPa) | Poisson’s ratio, \(\mu\) | Yield strength, \(\sigma_y\) (GPa) | Shear modulus, \(\tau\) (MPa) |
|-----------------|-------------------------------------------------|-----------------------------|--------------------------|-----------------------------------|-----------------------------|
| 25              | 2.9                                             | 114.7                       | 0.32                     | 11.47                             | 887                         |
| 200             | 3.4                                             | 105.3                       | 0.33                     | 10.53                             | 847                         |
| 500             | 4.4                                             | 89                          | 0.34                     | 8.9                               | 778                         |
| 800             | 5.7                                             | 75                          | 0.35                     | 7.5                               | 334                         |
| 995             | 6.9                                             | 72.3                        | 0.38                     | 72.3                              | 38                          |
| 1200            | 7.65                                            | 64.6                        | 0.39                     | 64.6                              | 27                          |
| 1400            | 7.9                                             | 56.8                        | 0.40                     | 56.8                              | 17                          |
| 1650            | 8.6                                             | 45.4                        | 0.41                     | 45.4                              | 3.8                         |
| 1900            | 9                                               | 0                           | 0.5                      | 0                                 | 0.38                        |
5. Results and discussion

5.1 Temperature distribution

In the SLM process, temperature distributions in the powder bed and the solidified layers change rapidly with time and space. In order to validate the modelling and numerical methods presented in this work, the simulation results are compared with the experimental work. Fischer et al. [14] scanned the pure titanium powder layer with a continuous laser beam and observed the peak skin temperature in the sintering process by a Raytheon infra-red camera. The process parameters of the experiment are laser power 3W and laser scan speed 1 mm/s. Figure 6(a) shows the temperature contour captured by the camera in this experiment, from which can be seen that the high temperature range is between 2500 K and 3000K. By using the same process parameters as the experiment, the calculated peak surface temperature after 0.75s is obtained and shown in Figure 6(b), which is like the published experimental result, and the maximum temperature is 2642K.

![Figure 6. Comparison of (a) maximum true temperature of molten pool (b) calculated surface temperature contours by simulation.](image)

For analysing the temperature distribution during SLM process for Ti6Al4V, formulas from 1 to 5 as well as the Ti6Al4V properties were used as the input information to the CAE analysis software and the input parameters for simulation of temperature distribution has listed of table 1.

![Figure 7. Temperature distribution at 0.0028s (a) laser power 120 W (b) laser power 150W.](image)
Figure 7 shows the temperature distribution at printing time 0.0028s (a) laser power 120W and scanning speed 1000 mm/s (b) laser power 150W and scanning speed 1000 mm/s. It has shown that maximal temperature increased from 2518 to 2980 K for laser power 120W and 150W.

5.2 Molten pool dimension
Figures 8 to 11 describes the procedure of molten pool calculation and predicted molten pool results for laser power 120W and scanning speed 1000 mm/s. The length of the molten pool is parallel to the scanning direction, whilst the width is perpendicular to the laser moving track. The depth of the molten pool is measured the layer thickness direction. With the melting temperature 1948 K, the length, width and depth of the molten pool obtained from finite element model are 275 μm, 94 μm and 37 μm, respectively. Figures 12 shows the predicted molten pool length, width and depth for laser power 150W and scanning speed 1000 mm/s are 401 μm, 118 μm and 55 μm, respectively.

![Temperature distribution and predicted molten pool size.](image)

**Figure 8.** Temperature distribution and predicted molten pool size.

![Temperature distribution curve when printing single track in X direction.](image)

**Figure 9.** Temperature distribution curve when printing single track in X direction.

![Temperature distribution curve when printing single track in Y direction.](image)

**Figure 10.** Temperature distribution curve when printing single track in Y direction.

![Temperature distribution curve when printing single track in Z direction.](image)

**Figure 11.** Temperature distribution curve when printing single track in Z direction.
5.3 Residual stress and deformation
For analysing the stress and strain during SLM process for Ti6Al4V, formulas from 5 to 12 as well as the Ti6Al4V properties were used as the input information to the CAE analysis software and the results in stress and displacement of the SLM are shown in figures 13 to 16. Figures 13 and 14 illustrates the results of von-mises stress in the SLM part with one track at same scanning speed 1000mm/s which are 1242.54 MPa for laser power 120W and 1538.95 MPa for laser power 120W at time 0.0028s.

Figures 15 and 16 illustrates the results of displacement of the SLM part in Z direction at same scanning speed 1000mm/s which are 0.01746 mm for laser power 120W and 0.02183 mm for laser power 150W at time 0.0028s.
5.4 Development of a Predictive system

To have the fast prediction and validation of temperature distribution, residual stress and deformation of the SLM printed part, a predictive system is developed. Java and Eclipse platform were used for programming four modules of the system including interface, thermal analysis, residual stress and deformation modules. Material properties such as elastic modulus, Poisson’s ratio, tensile strength, yield strength, melting point, coefficient of thermal expansion, and thermal conductivity are inputted and stored in material database. Printing process parameters including laser power, laser spot diameter, scan speed, scan spacing, and layer thickness are inputted and stored in process database.

Figure 17. Functional modules of the predictive system.

Figure 17 shows the functional modules of the predictive system. For developing these modules, the mathematical models for describing the temperature distribution, residual stress and strain as well as the results driving out from the commercial CAE tools as COMSOL were used. Figure 18 describes the screenshot of the predictive system with STL model as input model for simulation and prediction.
6. Conclusions
Selective laser melting is one of the 3D printing methods that uses widely for applications. However, to apply to the industrial practice the quality of the SLM printed parts is barrier. Currently, researches on experimental works enable to analyse the core factors affecting to the printed part’s quality. This research proposes to develop a predictive system which enables fast prediction and validation the temperature distribution, stress and strain. The melt pool information of single-track deposits could be an aid to select a process window determining an optimum set of process parameters. Then to drive out the appropriate process parameters enables to remove the fails before carrying out the real SLM process on the machine. This is the first step of our research in the project “Development of ICT based software platform and service technologies for medical 3D printing applications”. According to this result, experimental researches on effect of temperature distribution to residual stress and deformation with Ti6Al4V metal powder are the next steps of our research.

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