Development of a predictive system for SLM product quality

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Abstract. Recently, layer by layer manufacturing or additive manufacturing (AM) has been used in many application fields. 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 in particular to industry have some barriers due to the quality of the manufactured parts which are affected by the high residual stresses and large deformation. SLM process is characterized by high heat source and fast solidification which lead to large thermal stress. The aim of this research is to develop a system for predicting the printed part quality during SLM process by simulation in consideration of the temperature distribution on the workpiece. For carrying out the system, model for predicting the temperature distribution was established. From this model, influences of process parameters to temperature distribution were analysed. The thermal model in consideration of relationship among printing parameters with temperature distribution is used for optimizing printing process parameters. Then, these results are used for calculating residual stress and predicting the workpiece deformation. The functionality of the proposed predictive system is proven through a case study on aluminium material manufactured on a MetalSys150 - SLM machine.

1. Introduction
Additive manufacturing (AM) technology has been applied widely for applications in different fields such as aerospace, automotive, biomedical, and energy industries. Selective laser melting (SLM) is a powder bed based AM process to manufacture metallic parts. SLM is the complex process of the interaction between a concentrated laser source and metallic powders. Figure 1 shows the mechanism of SLM process. In SLM, a very thin powder layer is distributed and selectively melted by a controlled laser. This procedure is repeated until a complete part is built [1,2]. The optical system with a set of optical mirrors enables the laser source to direct onto the powder bed surface. The optical system can contain additional elements that allow the melt pool shape and intensity to be monitored. The powder is deposited onto the build area by a deposition system such as scraper or roller system moving over the surface. Before each layer is scanned, this powder container is raised and powder is then pushed across the powder bed by the deposition system. Then, the build platform is lowered by one layer thickness, making the new powder layer on top. Lowering the base plate, depositing powder and scanning of the laser over the powder bed are the three steps that are repeated during the SLM process to produce a 3D part [2].
SLM has been applied widely for manufacturing the metallic parts. However, due to the rapid heating and cooling, several defects usually exist in a SLM part such as the high temperature gradient which generates high thermal stress and leads to part distortion and cracks [4-7]. The high viscosity and surface tension of the molten powder zone due to the balling effect may result in very poor surface finish. Also, un-melting powder and oxidized particle may also lead to porosity of the manufactured parts [8,9]. The quality of the final part is decided by powder properties, process parameters and SLM machine characteristics as shown in Fig.2 [2,10,11].

Figure 1. Mechanism of selective laser melting process.

Figure 2. Influence factors affecting the quality of printed part.
For getting the best quality of the printed part, influence factors must be considered such as material properties, machine specifications, printing conditions and process parameters. However, during SLM process, the localized compression and tension caused by the large thermal gradients and fast cooling will increase that lead to the significant residual stresses in SLM parts. Due to existing residual stresses, the localized deformation will result in a loss of part shape as well as other failure of the SLM part [1].

The paper presents a predictive system for analysing the temperature distribution and predicting the deformation of the printed part. These results are used for determining the optimal process parameters for SLM process and testing on the MetalSys150 - SLM machine.

2. Literature review
SLM process requires a high temperature for melting the metallic powders. Due to high temperature and fast cooling, residual stress will be generated in the printed part which leads to part distortion and negatively affect product performance. 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. On the other hand, to fix the part distortion of the printed part, the post processing must carried out that will increases the manufacturing cost [8,9]. 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. These methods can be classified into three groups. The first group is the simulation method [12]. The second group is the researches which focus on the experimental works [13]. The last group is the comparison of simulation and experimental results [7].

Simulation methods have been widely used to predict residual stress and part distortion of the SLM processes. However, this work depending on model size and computer performance takes many hours or many days to complete. It is only suitable for analysing the thermal-mechanical model to predict residual stress and distortion of printed part on a small domain [8]. With the real SLM part, it is difficult to predict part distortion due to requiring millions of micro-scale laser scans which will increases the computational ability of the computer hardware even using a very powerful work station [8, 9].

A multi scale approach is highly needed to achieve acceptable accuracy of part distortion and residual stress with low computational cost. 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 [9]. 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 [8].

In experimental works, an effort to better understand the factors influencing macro scale residual stresses, a destructive surface residual stress measurement technique coupling with a non destructive volumetric evaluation method were applied [1]. 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 [11].

3. Model of a predictive system
Figure 3 shows the necessity for developing a predictive system. The name card is designed in 3D model using CAD software. This data is transferred to the SLM machine for printing process. With the high temperature distribution and fast solidification during SLM process, residual stress is generated in the printed part which leads to the deformation of the part. The proposed system enables to predict the deformation of the printed part before printing. Currently, this information is used to re-design the CAD model. Then the final version of the CAD model is used for printing on the SLM machine to get the correct name card.
Figure 3. The necessity for developing a predict system.

For realizing the predictive system, the databases about temperature distribution, residual stress, and deformation from the experimental as well as simulation results must be built as shown in Fig.4. These databases are background for analysing the influence factors affecting to the quality of the SLM process. With results from comprising between the experiment and simulation, the system generates the optimal process parameters in consideration with the quality criteria for the printed part.

Figure 4. The derived important process parameters from analyzing 3D printing process.
3.1. Prediction of temperature distribution

Figure 5 shows the temperature gradient mechanism with deformation of the part in heating and cooling process. When laser source scans on the powder surface, energy is transferred from the top surface to subsurface through various physical changes such as heat transfer, radiation, convection, conduction, fluid flow within the molten pool, melting, evaporation, and chemical reactions. During SLM process, thermal expansion at layers of the printed part happens which lead to the part deformation.

Figure 5 describes the melt pool size in SLM process. A description of temperature values in the molten pool is thus provided by equation as follows, using geometrical features of the melt pool and the maximum temperature $T_{\text{max}}$ obtained by finite element simulations [14].

- for $y > 0$ (front semi-ellipse)
  $$T = T_m + \frac{1}{2}(T_{\text{max}} - T_m) \times \left(1 + \cos \left(\pi \left(\frac{x^2}{(e/2)^2} + \frac{y^2}{L_{\text{front}}^2} + \frac{z^2}{p^2}\right)\right)\right)$$  (1)

- for $y < 0$ (rear semi-ellipse)
  $$T = T_m + \frac{1}{2}(T_{\text{max}} - T_m) \times \left(1 + \cos \left(\pi \left(\frac{x^2}{(e/2)^2} + \frac{y^2}{L_{\text{rear}}^2} + \frac{z^2}{p^2}\right)\right)\right)$$  (2)

With $L_{\text{front}}$ : front part of the melt-pool length; $L_{\text{rear}}$ : rear part of the melt-pool length; $e$ : melt-pool width; $p$ : melt-pool depth; $T_{\text{max}}$ : maximum temperature (K); $T_m$ : melting temperature (K); and $p$ : melt-pool depth (μm).

Figure 6 shows the temperature distribution results using COMSOL tool for aluminium alloy - A390 alloy of composition Al–17% Si–4.5% Cu–0.5% Mg.
3.2. Prediction of residual stress and deformation

Strain with temperature change is calculated as follows [2]:

\[
\begin{bmatrix}
\epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\
\epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\
\epsilon_{31} & \epsilon_{32} & \epsilon_{33}
\end{bmatrix} = \begin{bmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{bmatrix} \cdot \Delta T
\]

(3)

With \([\epsilon_{ij}]\): strain tensor; \([\alpha_{ij}]\): coefficients of thermal expansion; \(\Delta T\): temperature difference. Formula for calculating the residual stress in consideration of temperature change is as follows:

\[
\sigma(T) = E(T) \cdot \alpha(T) \cdot [T_m - T]
\]

(4)

With \(E\) is stiffness of material; \(T\) is the temperature of pre-heating.

Figure 7. Screenshot of the system for simulating SLM process.
The interface of the predictive system is shown in Fig. 7. The 3D-CAD model is inputted in STL file format. The screenshot of the predictive system with three modules is shown in Fig. 8. Material information and SLM process parameter are inputted from module #1. Module #2 enables to determine the temperature distribution during SLM process. Then, the temperature information is used for analyzing residual stress and predicting deformation of the part as shown in module #3.

4. Experimental results

Experiment results were carried out with aluminum powder material having average particle size of approximately 45μm. SLM machine (MetalSys150, Winforsys co.,Ltd) with the YLR-200-AC-Y11, IPG Ytterbium Fiber Laser, 200W maximum output, air cooled, was used to print as shown in Fig. 9. The MetalSys150 machine had a meander scanning strategy that begins in the left to right of the part compared with scraper movement and builds vertically towards the back.

The SLM process for printing a part with aluminum powder is shown in Fig. 10 in which each single laser line is perpendicular to scraper movement direction and parallel for generally. Scanning strategy of layer n is same n-1 and n+1 one. Argon gas was filled into the chamber in order to keep oxygen degree remained at below 0.5 percent. Chamber temperature was at 280°C. The sets of cube specimens with diameter of 10mm produced on stainless steel substrate's surface directly without support trees. For printing part, the spot size of laser beam was 70μm, the layer thickness of 20μm, laser power with 180W, hatch distance having range from 0.035 to 0.09mm and velocities of laser having range from 1000mm/s to 6000mm/s. Parameters were in the range of parameters recommended by manufacturer. This work aims to depict part qualification using a observing the flaking phenomenon and counting the number of remain layer.

**Figure 8.** Modules of the predictive system.
5. Conclusions
This research focuses on the quality of the printed part by SLM in consideration of optimal printing process parameters with temperature distribution. SLM process is characterized by high heat source and fast solidification which lead to large thermal stress. The aim of this research is to develop a system for predicting the printed part quality during SLM process by simulation and carrying the experimental works in consideration of the temperature distribution.

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