Numerical simulation of residual stress in laser based additive manufacturing process

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Abstract: Minimizing the residual stress build-up in metal-based additive manufacturing plays a pivotal role in selecting a particular material and technique for making an industrial part. In beam-based additive manufacturing, although a great deal of effort has been made to minimize the residual stresses, it is still elusive how to do so by simply optimizing the processing parameters, such as beam size, beam power, and scan speed. Amid different types of additive manufacturing processes, Direct Metal Laser Sintering (DMLS) process uses a high-power laser to melt and sinter layers of metal powder. The rapid solidification and heat transfer on powder bed endows a high cooling rate which leads to the build-up of residual stresses, that will affect the mechanical properties of the build parts. In the present work, the authors develop a numerical thermo-mechanical model for the measurement of residual stress in the AlSi10Mg build samples by using finite element method. Transient temperature distribution in the powder bed was assessed using the coupled thermal to structural model. Subsequently, the residual stresses were estimated with varying laser power. From the simulation result, it found that the melt pool dimensions increase with increasing the laser power and the magnitude of residual stresses in the built part increases.

1. Introduction

Direct metal laser sintering (DMLS) is a laser based additive manufacturing technology received much attention nowadays due to its ability to produce complex shapes directly from the powder materials by using computer aided design (CAD) data. It creates metallic build parts through the layer-by-layer addition of materials. The key benefits of this process are freedom of design of any shape, minimal of material wastage, elimination of production steps and less expense over conventional manufacturing processes [1-3]. In this process a high intensity laser beam interacts with the powder layer which creates melt pool on a layer of spread powder. The melt pool rapidly solidifies and then another layer of powders is spread on top of the solidified layer and the process continues to add a new layer successively to build the parts [4]. The powder layer in DMLS process undergoes rapid melting and solidification during sintering, so a large thermal gradient will develop in the part which leads to build up residual stresses. The resulting residual stress influences the material properties and the distortion of the final product such that its geometry deviates from the required build dimensions and degrades the mechanical strength of the build part. For these reasons, tremendous efforts have been placed to understand and control residual stress formation during additive manufacturing.

The physical process associated with direct metal laser sintering process includes heat transfer and sintering of powders. Recently, many investigations have been carried out to develop computer models for the laser sintering process. Labudovic et al. [5] developed a transient thermal model for direct laser metal powder deposition process by using ANSYS. The author investigates the

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temperature profiles, fusion zone dimension and residual stresses in the powder bed from the simulated model and found that, the residual stress increases as the number of layer increase. Temperature distribution and residual stresses during laser sintering of hot-work tool steel powders with respect to laser power and scanning rate were investigated by Ibraheem et al. [6] using finite element approach. Mercelis and Kruth [7] investigated theoretically and experimentally the residual stress in selective laser melting and selective laser sintering. From their investigation they found that, high value of stress exists in the built part which connected to the substrate and the parts that are removed from the base plate contain much lower stress levels. Also, they found that built part suffered deformation during removal from the substrate.

Thermal behavior of the molten pool during selective laser melting of TiC/AlSi10Mg nanocomposites was simulated by Yuan and Gu [8]. From their simulation results, they found that, the convective heat transfer and dimension of the molten pool was significantly affected by Marangoni convection. A Finite Element Method (FEM) calculation of single-scan electron beam melting of Ti6Al4V was carried out by Vastola et al. [9] to understand how residual stresses are related to the process parameters, including beam size, beam power, scan speed, and bed preheating temperature. They found that the powder bed preheating temperature have the largest quantitative impact on the residual stress. Zhao et al. [10] developed a finite element model for predicting the thermo-mechanical response of Ti-6Al-4V built part using a laser sintering system by using COMSOL platform. From the simulation results, the authors studied the behavior of the melt pool size, temperature history and change of the residual stresses on the powder bed with the change of laser power and scan speed. The result of the simulation provides a better understanding of the complex thermo-mechanical mechanisms of laser sintering additive manufacturing processes. In the present work, a thermo-mechanical model is developed for the investigation of residual stress in the AlSi10Mg build parts during direct metal laser sintering. The developed model was used to estimate the transient temperature dispersal in the powder bed. Subsequently, the residual stresses were investigated at different laser power.

2. Numerical Modelling

The numerical method used to investigate the residual stress in DMLS process is a coupled thermo-mechanical transient model. In this coupled model, thermal analysis is carried out first, and the results of thermal analysis are used as a thermal load input for the stress analysis. The governing equation for heat transfer analysis is

$$\rho C\frac{\partial T}{\partial t}=\frac{\partial T}{\partial x}\left(K\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)+Q \quad (1)$$

Where ρ is the material density (kg/m3);

C is the specific heat capacity (J/kg K);

T is the temperature;

t is the interaction time;

K is thermal conductivity (W/mK);

Q = (x, y, z, t) is the volumetric heat generation (W/m^3).

Heat transfer due to convection and radiation is calculated by Newton's law of cooling and Stefan-Boltzmann law which are given below

$$q=h(T-T_0) \quad (2)$$

$$q=\sigma\epsilon(T^4-{T_0}^4) \quad (3)$$

Where h is the convection heat transfer coefficient (W/m^2K), T_0 is the ambient temperature (300K), σ is the Stefan Boltzmann constant (5.670×10^{-8} W/m^2K^4) and ϵ is the emissivity.

In the present model, the incident laser energy is considered as a heat flux boundary condition for the heat transfer analysis, in which the moving laser power source considered as the Gaussian heat source model. Based on Gaussian heat source model, the input heat flux is calculated by using the correlation [11]

$$q=\frac{2AP}{\pi\omega^2}e^{\left(-\frac{2r^2}{\omega^2}\right)} \quad (4)$$

Where A is the laser absorptance of the powder system, P is the laser power, ω represents radius of the Gaussian laser beam, and r is the distance of a point on the surface of the powder bed measured from the laser beam center.

To calculate the distribution of stress, the elastic finite element analysis simulation is used. The governing equation for stress is

$$\mathrm{div}\sigma = 0 \tag{5}$$

Whereσ is the stress. As the problem is elasto-plastic and involves thermal strains. Thermal strain can be represented as

$$\varepsilon^{th} = \alpha_e \Delta T = \alpha_e (T - T_{ref}) \tag{6}$$

where, T_{ref} is the reference temperature.

So, effective stress can be written as

$$\sigma_{eff} = \sqrt{{\sigma_1}^2 + {\sigma_2}^2 + {\sigma_3}^2} + 2\upsilon(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3) \tag{7}$$

Where σ_1, σ_2 and σ_3 are the three principal stresses, υ= poission's ratio

Initially, the powder bed layer is assumed to be at room temperature i.e., T (x, y, z, t) = To (x, y, z) = 300 K, at t=0. Also, the input laser energy from the moving laser beam at initial stage is assumed to be zero. When the sintering process starts, the rate of absorption of laser energy by the powder material also increases. Thus, heat flux is generated, and heat transfer takes place due to the temperature difference. From each surface of the powder bed, heat loss takes place by convection and radiation mode. But the bottom of the surface is considered as adiabatic. There is no loss of heat from the bottom surface of the substrate.

3. Simulation Method

The governing equations for heat transfer and mechanical analysis were discretized and solved by finite element method using ANSYS 17.0. The dimension of the computational domain is 10×1.5×1 mm^3 for powder bed and for substrate is 12.5×3×2 mm^3. Figure 1 shows the schematic diagram of the process and Figure 1 shows the computational domain used for simulation. Tetrahedral mesh structure is obtained for powder bed with fine meshing and hexahedral mesh for steel substrate is obtained with medium mesh. The total number of elements and nodes for transient thermal modelling are 20535 and 47500, respectively. Similarly, for stress simulation medium mesh are applied to both powder bed and substrate and total number of elements and nodes are 3850 and 19219, respectively.

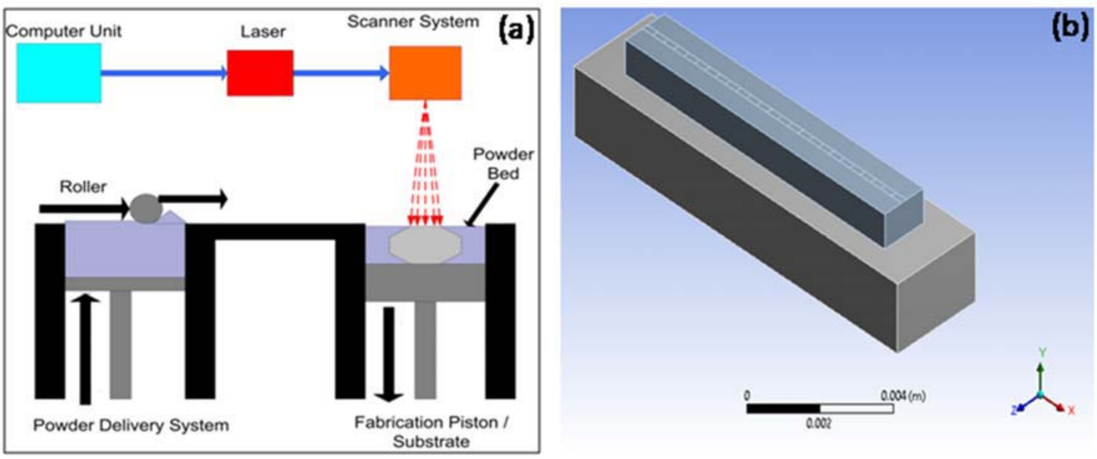

Figure 1. (a) Schematic diagram of the DMLS process (b) Computational domain used for simulation

The powder bed is considered as AlSi10Mg alloy and the substrate is made up of structural steel. The thermos-physical properties of AlSi10Mg and structural steel are given in Table 1 and Table 2.

Table 1. Thermo-physical properties of AiSi10Mg [12]

parameter	values
Laser absorptivity	0.9
Thermal conductivity (W/mK)	185
Density (Kg/m^3)	2650
Specific heat (J/Kg°C)	910
Young's modulus (MPa)	71000
Poisson's ratio	0.33

Table 2. Thermo-physical properties of structural steel [13]

Properties of steel	values
Thermal conductivity (W/mK)	60.5
Density (Kg/m^3)	7850
Specific heat (J/Kg°C)	434

4. Results and Discussions

In the present investigation, a transient thermos-mechanical model has developed based on finite element approach. The model used to investigate the residual stress on the built parts during direct metal laser sintering of AlSi10Mg alloy. The model considers conduction, convection and radiation mode of heat transfer in the powder bed as well as in the substrate. First thermal simulations are carried out and the results from the thermal simulation can be considered as the input for stress analysis. Simulations are carried out for sintering of AlSi10Mg powders in DMLS process by varying laser power from 70 watts to 100 watts, when the scan speed is kept constant i.e., 100 mm/s.

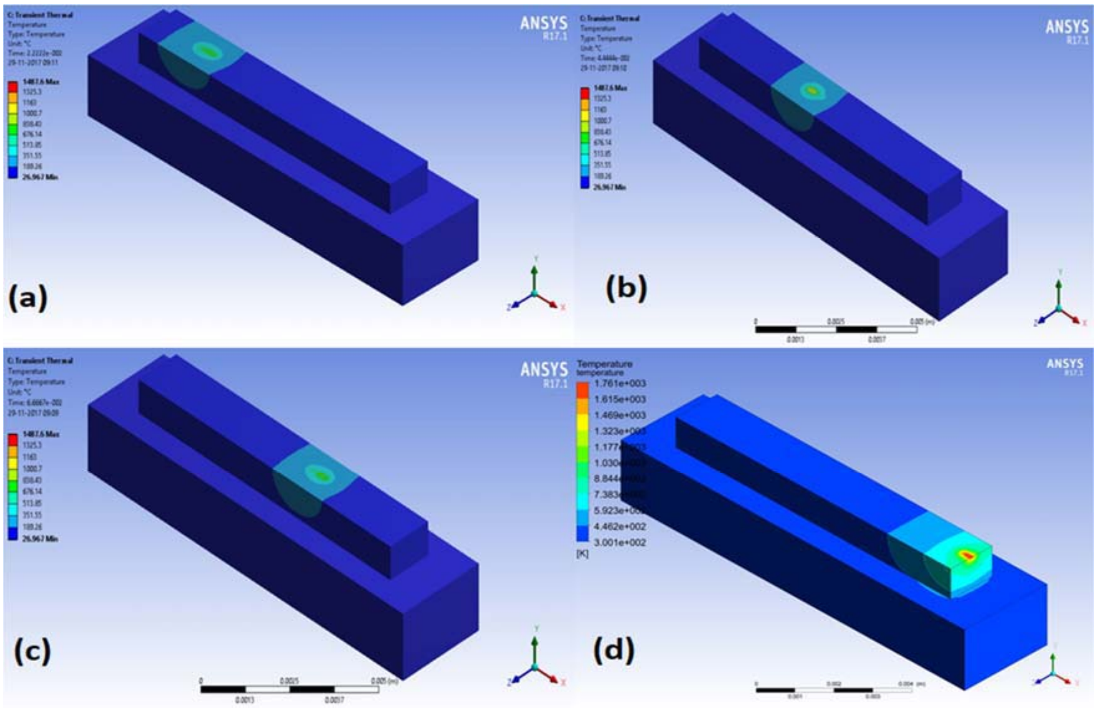

Figure 2. Thermal profile of AlSi10Mg built part at different time step (a) time=0.022 sec (b) time=0.044 sec (c) time=0.066 sec and (d) time=0.1 sec.

Figure 2 shows the thermal profile of AlSi10Mg built part at different time step, when the laser power is 100 watts and the scan speed is 100 mm/s. The temperature distribution in the powder bed is distinguished by color contour. In the thermal profile, the temperature contour of 830 K defines the solid-liquid interface. The temperature is higher than the melting temperature in the melt pool region than in the other regions. The melt pool dimensions are quite small and slightly larger than the laser spot size. As the DMLS process is a rapid manufacturing process, melting and solidification will occur within few seconds. So, the powders will melt and fuse rapidly, then cool down and reheat again when the laser beam passes on top of them again. Due to rapid heating and cooling, residual stresses are expected to develop in the fused part after it cools down to room temperature which is shown in Figure 3.

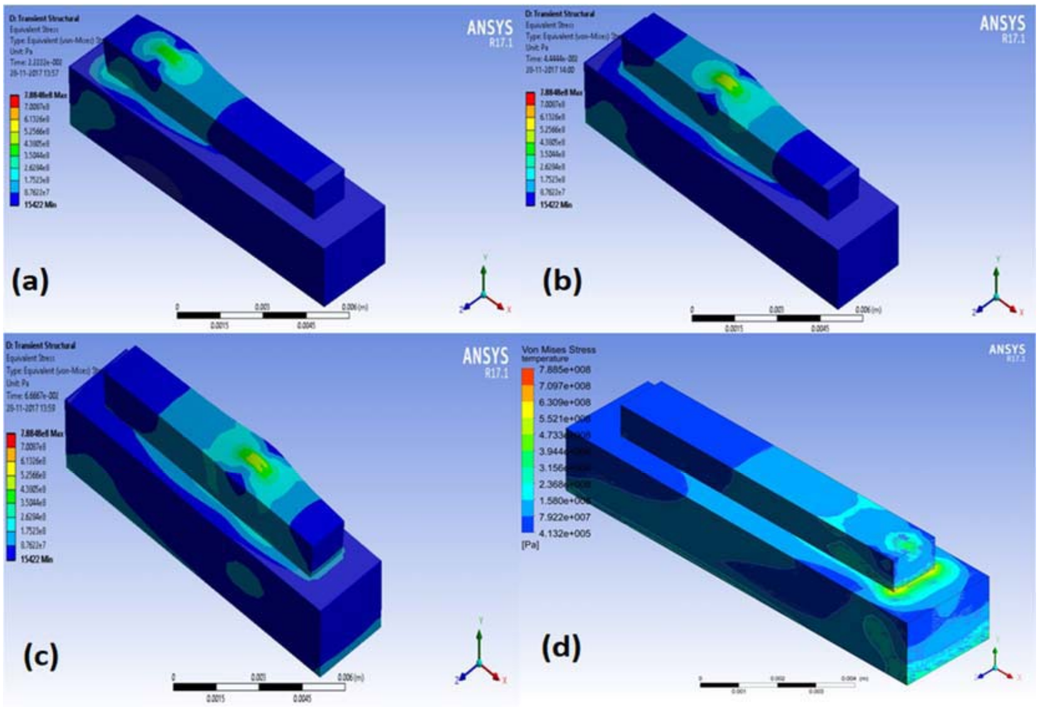

Figure 3. Residual stress profile at different time step (a) time = 0.022 sec (b) time = 0.044 sec(c) time = 0.066 sec and (d) time = 0.1 sec.

From the stress profile it is observed that, the magnitude of stress is maximum at the melt pool region. Also, there is some deformation occurs at the maximum stress region due to rapid cooling of built part. As the applied laser power increases the stress also increases. After 0.1sec it was observed that the stress at the start point of the powder layer is minimum and maximum stress only remains at the end position. It is because when the laser spot comes from 1st position to 2nd position, the temperature at the 2nd position is quiet high as compared to the 1st position so the 1st position has already solidified. This is because due to the temperature gradient from 2nd position the accumulated stress gets released from 1st position.

Figure 4 shows the graph between laser power and residual stress. It is observed that with increase in laser power, the magnitude of residual stress increases. As the laser power increases from 70 watts to 100 watts, the temperature in the molten pool increases. So, a large temperature gradient generates on the surface of the powder bed. Due to rapid melting and solidification, the amount of residual stress accumulation increases with increase in laser power.

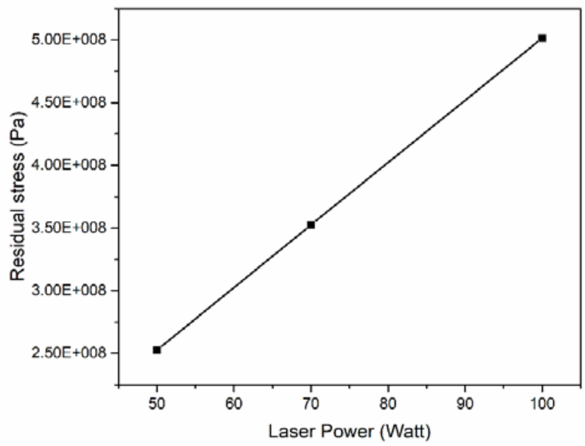

Figure 4. Residual stress vs. laser power

5. Conclusion

A finite element model is built for predicting the thermo-mechanical response of a AlSi10Mg alloy-built part manufactured with a direct metal laser sintering process. ANSYS 17.0 is used to model the coupled heat transfer and mechanical analysis. The thermal behavior, melt pool and residual stress are modelled using a 3-D thermo-mechanical analysis. From the simulation result, it is found that with increase in laser power the melt pool dimension increases. Also, the magnitude of residual stress in the built part increases significantly.

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