IOP Conf. Series: Materials Science and Engineering **338** (2018) 012052 doi:10.1088/1757-899X/338/1/012052

Continuum simulation of heat transfer and solidification behavior of AlSi10Mg in Direct Metal Laser Sintering Process

Akash Ojha, Mihir Samantaray, Dhirendra Nath Thatoi and Seshadev Sahoo*
Department of Mechanical Engineering, Institute of Technical Education and Research, Siksha 'O' Anusandhan, Bhubaneswar, OD, India-751030

Email: seshadevsahoo@soa.ac.in

Abstract: Direct Metal Laser Sintering (DMLS) process is a laser based additive manufacturing process, which built complex structures from powder materials. Using high intensity laser beam, the process melts and fuse the powder particles makes dense structures. In this process, the laser beam in terms of heat flux strikes the powder bed and instantaneously melts and joins the powder particles. The partial solidification and temperature distribution on the powder bed endows a high cooling rate and rapid solidification which affects the microstructure of the build part. During the interaction of the laser beam with the powder bed, multiple modes of heat transfer takes place in this process, that make the process very complex. In the present research, a comprehensive heat transfer and solidification model of AlSi10Mg in direct metal laser sintering process has been developed on ANSYS 17.1.0 platform. The model helps to understand the flow phenomena, temperature distribution and densification mechanism on the powder bed. The numerical model takes into account the flow, heat transfer and solidification phenomena. Simulations were carried out for sintering of AlSi10Mg powders in the powder bed having dimension 3 mm × 1 mm × 0.08 mm. The solidification phenomena are incorporated by using enthalpy-porosity approach. The simulation results give the fundamental understanding of the densification of powder particles in DMLS process.

1. Introduction

Aluminum alloys and composites have been extensively used in various sectors, such as automotive, aerospace and domestic industries due to the combination of excellent weldability, high heat conductivity, sufficient hardenability and good corrosion resistance [1]. Among diferent types of aluminum alloys and composites, some of them are complex structure which are difficult to manufacture using conventional casting processes. Furthermore, it produces the coarsened grain structure and large degrees of segregation due to the slow cooling rates during the conventional casting processes [2]. Therefore, novel processing methods are highly demanded to satisfy the need for obtaining complex components with fine and uniform microstructures. Among different types of rapid prototyping technology, Direct Metal Laser Sintering (DMLS) offers great advantages for the processing of metallic powders and composites. In DMLS process, the metallic powders interact with a high intensity laser energy, which helps to melt and solidify the powders in a laminated manner. In this rapid manufacturing process high rate of heating and cooling takes place, which directly affects the microstructure and mechanical properties of the built parts. The advantages of such layer-based manufacturing technology are high degree of freedom in design, minimal material wastage, potential elimination of tooling, light-weight design, elimination of production steps [3, 4]. This process is accompanied by fluid flow, heat transfer and solidification phenomena which makes it very complex. The schematic diagram of the direct metal laser sintering process is shown in Figure 1.

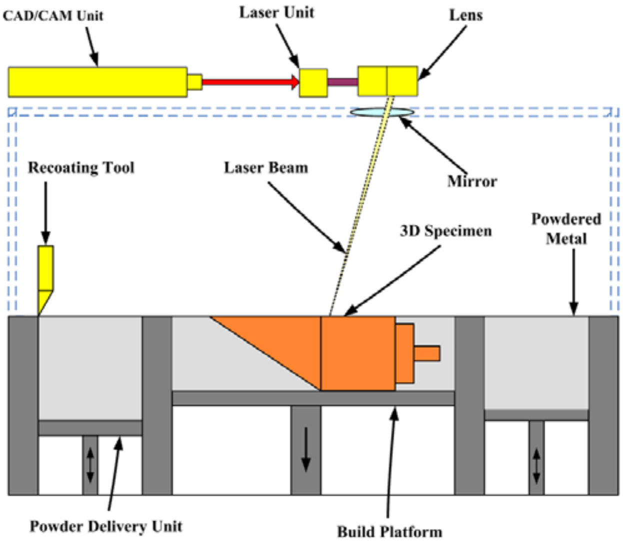

Figure 1: Schematic diagram of DMLS process

Over the past decades, several researchers tried to understand the fundamentals of sintering process during liquid phase sintering. A comprehensive thermal model of selective laser sintering has been developed by Zeng et al. [5]. The thermal behavior in the powder bed was investigated by Tang et al. [6] and studied the quality and dimensional accuracy of the solid structure based on processing condition. The authors considered the laser beam as a moving heat source. Dong et al. [7] proposed a transient three-dimensional finite element model to simulate the phase transformation of powders during the laser sintering process. In their model, they consider the thermal and sintering phenomena. Yuan et. al. [8] developed a numerical model for selective laser melting of Aluminum nano-composites using finite volume method. Also, they had investigated the molten pool behavior and temperature distribution with respect to process parameters. Xiao et al. [9] have examined a three-dimensional numerical model to understand the physical mechanism occurring in the laser sintering process. Sahoo et al. [10] have developed a thermal and microstructure model for Ti alloys in EBAM process by considering moving heat source. A thermal model was developed to predict the temperature distribution on a single powder layer, when laser beam irradiated with powder bed by Patil and Yadava [11]. They also studied the effect of laser spot size, hatching space and laser power on thermal behavior.

In DMLS process, rapid heating and cooling occurs due to short interaction of laser beam and powder particles. This leads to a large temperature gradient and thermal stress in the powder bed, which may cause defects in the final products. However, it is difficult to investigate the rapid melting and solidification phenomena experimentally during the sintering process. Therefore, it is important to explore numerical method to investigate fluid flow, the heat transfer and solidification behavior in DMLS process. In the present study, a mathematical model has developed for direct metal laser sintering of AlSi10Mg alloy by considering fluid flow, heat transfer, and solidification characteristics in the liquid pool.

2. Mathematical model

A mathematical model for sintering of AlSi10Mg alloy powder in direct metal laser sintering process is developed. For simplification of the model, the following assumptions are made:

(i) The powder bed is homogeneous and uniformly distributed;
(ii) Temperature dependent thermo-physical properties of the powders are considered;
(iii) Conduction, convection and radiation mode of heat transfer is considered;
(iv) A constant heat transfer coefficient is considered between powder bed and surrounding environment.

(v) Laser beam is taken as the input heat source which follows Gaussian heat source distribution

Considering the above mentioned physical assumption, governing equations for mass, momentum and energy are as follows:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho.\vec{V}) = M_s \tag{1}$$

Momentum equation:

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \vec{V}.\nabla\vec{V}\right) = \mu\nabla^2\vec{V} - \nabla p + M_s.\vec{V} + F \tag{2}$$

Energy equation:

$$\rho\left(\frac{\partial T}{\partial t} + \vec{V}.\nabla T\right) = \nabla.(\kappa\nabla\mathrm{T}) + S_H \tag{3}$$

where ρ, κ, μ, p represent density, thermal conductivity, dynamic viscosity and pressure, respectively. $\vec{V}$ is melt velocity, M_s is source term, and F refers to body force, S_H is the source term of the energy equation, which is defined as

$$S_H = -\rho\left(\frac{\partial \Delta H}{\partial t} + \nabla.(\vec{V}\Delta H)\right) \tag{4}$$

where ΔH , is the latent heat of phase change in the medium.

In the current model, the input laser heat source follows a Gaussian distribution [12]. So, the heat flux is defined as

$$q(r) = \frac{2AP}{\Pi r_0^2} e^{-2r^2/r_0^2} \tag{5}$$

where,
A = laser absorptance of the powder system;
P = Laser power;
r_o= radius of the laser beam;
r = radial distance between the laser beam and the center of the spot generated on the top surface of the powder bed.

Initial & Boundary Conditions
In this process, the laser beam interacts with the powder bed and the heat transfer takes place on the powder bed surface.
Initially, the powder bed layer is assumed to be at room temperature at t=0,

$$[T(x, y, z, t)]_{t=0} = T_0 \tag{6}$$

where, T_0 is the ambient temperture
Also, the input laser energy from the moving laser beam at initial stage is assumed to be zero.

The heat will transfer in convection and radiation mode on the upper surface of the powder bed and other sides of substrate and powder bed and in conduction mode within the powder bed. The boundary condition of heat transfer are as follows:

The net amount of heat transfer from each surface except the bottom surface is given by Equation (7);

$$-k\left(\frac{\partial T}{\partial z}\right) = \varepsilon\sigma(T^4 - T_0^4) + h(T - T_0) \tag{7}$$

where, k= thermal conductivity, ε= emissivity, σ= lattice-Boltzmann constant, T= powder bed temperature and T_0= ambient temperature

Assume that there is no heat loss on the bottom of substrate, so it meets the Equation (8)

$$\left[k\left(\frac{\partial T}{\partial Z}\right)\right]\ at(Z=0)=0 \tag{8}$$

Solution method

The numerical modelling of fluid flow, heat transfer and solidification are carried out by using ANSYS FLUENT 17.1.0 platform. With suitable boundary conditions, the mass, momentum and energy equations are discretized using control volume approach and then solved using Semi-Implicit Method for Pressure Linked Equation Consistent (SIMPLEC) algorithm. Characteristically, the time step is restricted to be no more than 10^{-5} s to satisfy the convergence criteria necessitated by the governing equations. The thermos-physical properties of AlSi10Mg and the processing parameters of DMLS process are given in Table 1 and Table 2.

Table-1: Thermo-physical properties of AlSi10Mg alloy [13]

Properties	Values
Thermal conductivity(k)	183 W/mK
Specific heat capacity (cp)	940J/kgK
Heat transfer coefficient (h)	80 W/m2K
Density (ρ)	2680 g/cc
Emissivity (ε)	0.36
Latent heat	5321018 J/kg
Solidus temperature	830 K
Liquidus temperature	869 K

Table-2: Process parameters of DMLS process

Parameters	Values
Laser Power	100 Watt
Scanning speed	2 m/s
Laser spot size	0.2 mm
Thickness of layer	0.08 mm
Laser absorptivity	0.95

3. Results and Discussion

A comprehensive numerical model for direct metal laser sintering of AlSi10Mg alloy is developed in the present investigation and the effect of laser power and scan speed on heat transfer and solidification behaviour are investigated. The model takes into account the coupled fluid flow, heat transfer and solidification phenomena in the powder bed. Simulations are carried out for sintering of AlSi10Mg in a powder bed having 3 mm × 1 mm × 0.8 mm. Figure 2 shows the computational domain used for simulation. The simulation results show the temperature distribution and melt pool characteristics on the powder bed.

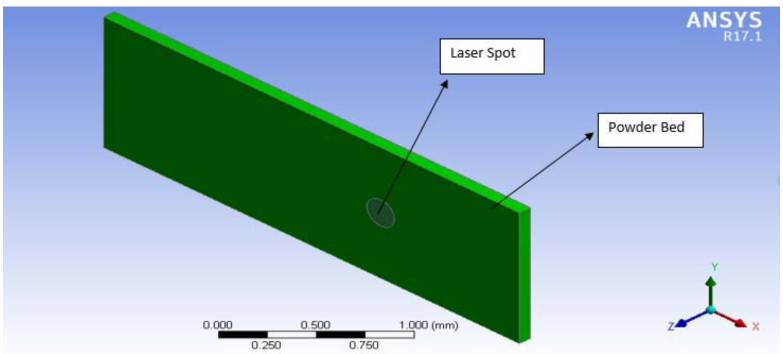

Figure 2: Computational domain used for simulation

Figure 3 shows the temperature distribution in the powder bed when the laser power is 100 Watt and the scan speed is 2 m/s. Color gradient represents the temperature distribution in the molten pool region. In the melt pool region, the solid-liquid region is differentiated by interface temperature i.e., 830 K. The temperature is higher in the melt pool region than in the other regions. The maximum temperature at the molten pool region which is around 906 K. From the temperature profile it clearly seen that, AlSi10Mg alloy is in liquid form below the laser spot.

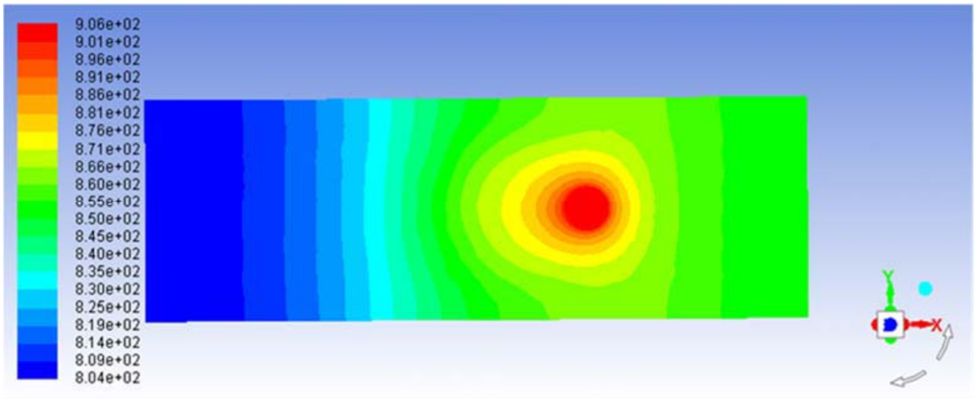

Figure 3: Temperature profile of AlSi10Mg powder bed in DMLS process

The velocity vector plot in the melt pool region of the powder bed is shown in Figure 4. The flow direction is indicated by the arrow head, and the color gradient represents the quantitative value of the velocity. It shows that the velocity of the liquid metal below the laser spot is approximately equal to the scan velocity. This is because due to no slip condition of the laser beam.

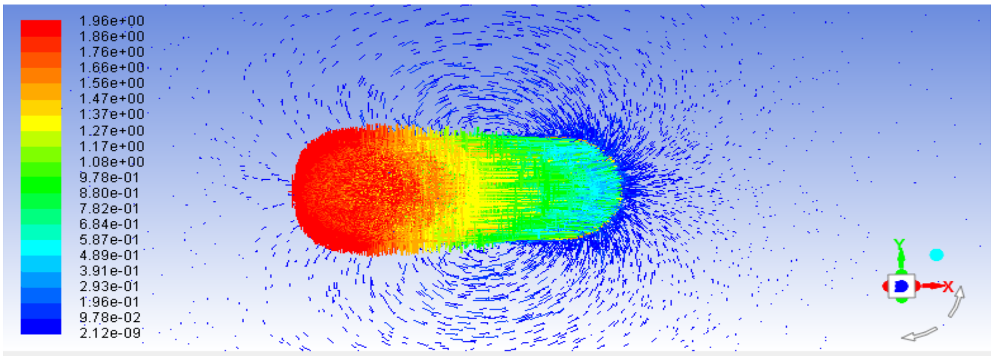

Figure 4: Velocity vector profile of AlSi10Mg powder bed in DMLS process

In this process, when the laser beam strikes at a particular location melting will occur and when the beam moves to the next location, solidification at the previous location takes place. Figure 5 represents the solidification profile of AlSi10Mg. It is represented by the variation of liquid fraction of AlSi10Mg, which varies from 0 to 1. From the solidification profile it is observed that, when the laser beam scans the powder bed, melting of the powder will occur due high rate of heat transfer. As the beam moves on the powder bed, the melting layer rapidly solidifies. So, the melting and solidification phenomena continues with the movement of laser beam.

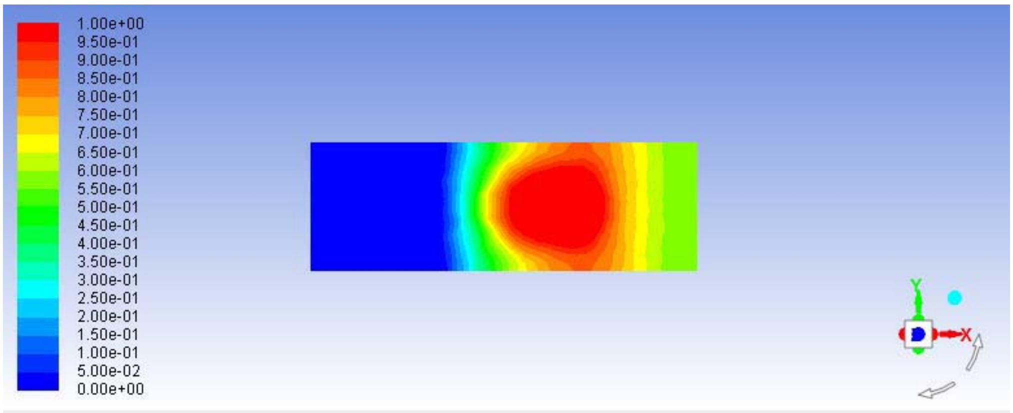

Figure 5: Solidification profile of AlSi10Mg powder bed in DMLS process

4. Conclusion

A three-dimensional numerical model was developed by using finite volume method (FVM) for DMLS process to investigate the temperature evolution, melt pool behavior and solidification phenomena. The simulation results provide a fundamental understanding of the heat transfer and solidification phenomena in this process. From the simulation results, it is quite evident that, the process parameters and material properties have a great influence on the quality and property of the sintered part.

Reference

[1] Olakanmi EO, Cochrane RF and Dalgarno KW. 2015, Progress *in Materials Science*. **74** 401.
[2] Nandy J, Sarangi H and Sahoo S. 2018, *Advances in Manufacturing*, DOI:10.1007/s40436-018-0213-1.
[3] Paul R and Anand S. 2012, *Journal of Manufacturing System*. **31** 429.
[4] Wong KV and Hernandez A. 2012, *ISRN Mechanical Engineering*, **2012** 1.
[5] Zeng K, Pal D and Stucker B. 2012, A review of thermal analysis methods in Laser Sintering and Selective Laser Melting. *23rd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference*, SFF 2012. 796.
[6] Tang Y, Loh HT, Wong YS, Fuh JYH, Lu L and Wang X. 2003, *Journal of Materials Processing Technology*. **140** 368.
[7] Dong L, Makradi A, Ahzi S and Remond Y. 2009, *Journal of Materials Processing Technology*. **209** 700.
[8] Yuan P and Gu D. 2015, *Journal of physics D: Applied Physics*. **48** 1.
[9] Xiao B and Zhang Y. 2009, *6th International Symposium on Multiphase Flow, Heat Mass Transfer and Energy Conversion*, Xi'an, China, Paper No. MN-18.
[10] Sahoo S and Chou K. 2016, *Additive Manufacturing*. **9** 14.
[11] Patil RB and Yadava V. 2007, *Int. J. Mach. Tools Manuf*. **47(7)** 1069.
[12] Roberts IA and Wang CJ. 2009, *International Journal of Machine Tools and Manufacture*. **49** 916.
[13] Nandy J, Sarangi H and Sahoo S. 2017, *IOP Conf. Series: Materials Science and Engineering*. **178** 1.