A Numerical Study on the Melt Track in Selective Laser Melting Using Aluminium Alloy 6061

Sing, S. L.; Loh, Loong Ee; Chua, Chee Kai; Liu, Zhong Hong; Zhang, Dan Qing; Mapar, Mahta

2014

Loh, L. E., Chua, C. K., Liu, Z. H., Zhang, D. Q., Sing, S. L., & Mapar, M. (2014). A Numerical Study on the Melt Track in Selective Laser Melting Using Aluminium Alloy 6061. Proceedings of the 1st International Conference on Progress in Additive Manufacturing (Pro-AM 2014), 97-102.

<https://hdl.handle.net/10356/84202>

https://doi.org/10.3850/978-981-09-0446-3_028

© 2014 by Research Publishing Services.

Downloaded on 26 Apr 2023 09:14:56 SGT

A NUMERICAL STUDY ON THE MELT TRACK IN SELECTIVE LASER MELTING USING ALUMINIUM ALLOY 6061

LOH L.E.

*School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50
Nanyang Ave
Singapore, 639798, Singapore*

CHUA C.K., LIU Z.H., ZHANG D.Q., SING S.L., MAPAR M.

*NTU Additive Manufacturing Centre, School of Mechanical and Aerospace Engineering, HW1-01-
05, 2A Nanyang Link
Singapore, 637372, Singapore*

ABSTRACT: Selective laser melting (SLM) is a type of additive manufacturing (AM), rapid prototyping or 3D printing method that is capable of building complex metallic structures. In this paper, the relationships of process parameters such as laser power and scan speed with the melt penetration, melt width, mass of material melted and evaporated are established based on a validated FE model on SLM that considers powder-to-solid transition, volume shrinkage and evaporation.

INTRODUCTION

Selective laser melting (SLM) is a type of powder-based additive manufacturing (AM), rapid prototyping or 3D printing process capable of building complex shapes where the desired object is fabricated layer by layer using a laser beam (Gu and Zhang, 2013). The powder under the laser beam will be completely melted and fuses with the previous layer. The object is first designed on a CAD-CAM software before being sliced into layers according to the user's pre-defined layer thickness and stored in the stl file format. This stl file will then be input into the SLM computer where the laser beam will scan each layer's cross-section accordingly. After a cross-section has been scanned, the building platform will move a layer thickness down before the recoater lays another layer of powder above the previously scanned layer. This process is repeated until the entire object is completely fabricated (Chua et al., 2010; Kruth et al., 2004; Santos et al., 2006). Currently, the optimum process parameter is identified by measuring the corresponding part density fabricated via Archimedes principle (Abe et al., 2003; Liu et al., 2011; Vandenbroucke and Kruth, 2007). Numerous work has been done to predict the change in material temperature during the fabrication process using the finite element method (FEM) (Contuzzi et al., 2011; Papadakis et al., 2013; Zhang et al., 2010). Element birth and death was used by to record the temperature history experienced by the layers (Roberts et al., 2009). Thermophysical properties of the material are reported to be important in predicting the temperature changes in laser-assisted manufacturing (Childs et al., 2005; Dai and Shaw, 2004; Yin et al., 2012). Temperature and stress distribution experienced during the laser fabrication process have also been predicted (Matsumoto et al., 2002; Mercelis and Kruth, 2006; Zaeh and Branner, 2010). Little is known as to the actual mass of powder melted and evaporated with the change in process parameter. An optimum set of process parameters identified by its high density fabricated may have undergone excessive material evaporation. To reduce material wastage, the energy density used to fabricate in SLM should not be excessive. As such, a validated numerical model will be used to predict the change in mass of

material melted and evaporated with the change in process parameters using a representative material aluminium alloy 6061.

SIMULATION AND EXPERIMENT

The detailed description of the validated numerical model can be found in the work of (Loh et al., 2014a), in which powder-to-solid transition, volume shrinkage and material evaporation are considered. The volume shrinkage is implemented through material removal. Experiments were carried out on a customized machine, SLM® 250^{HL} by SLM Solutions GmbH. Single scan lines at different process parameters as shown in Table 1 were scanned with and without aluminium alloy 6061 powder of an average size of 45 μm . Two scan lines of the same process parameters were scanned on each baseplate. The experiment was repeated thrice on three different baseplates. Each baseplate was wirecut at two different positions. Hence, for each process parameters, 12 readings (2x3x2) were taken and averaged.

Table 1 Process parameters selected for single line scans in this study

Parameters Labelling	Laser Power, P_L [W]	Scan speed, v [mms ⁻¹]
HH	350 (High)	1140 (High)
LL	150 (Low)	500 (Low)
LH	150 (Low)	1140 (High)

The cross section of the scan lines were measured according to its melt penetration (D), melt width (W) as shown in Figure 1. The samples were polished according to the standard polishing procedures and etched with Flick's reagent for 10 seconds (Loh et al., 2014b). Measurements and images were taken with the light optical microscope.

Figure 1 Typical melt penetration and melt width measured in experiment

RESULTS AND DISCUSSION

The mean, maximum and minimum values of the experimental melt penetrations and melt widths with and without powder for all the cases are as tabulated in Table 2 and Table 3. Fluctuations can be observed from the experimental results for both melt penetrations and melt widths. This is due to the inherent power fluctuation during the scanning process. Moreover, as the surface roughness

of the ground base-plate is of relative magnitude as the melt penetration itself, this contributes to the large fluctuation. A typical image on how the melt penetration and melt width are measured in the simulation is shown in Figure 2 and a similar measurement method as experimental is adopted.

Figure 2 Typical melt penetration and melt width measured in simulation with powder

Figure 3 A close up view of the material density at the laser beam front (a) without powder and (b) with powder (Loh et al., 2014a)

A close up view for both with and without powder cases are as shown in Figure 3 where evaporation and melting has occurred under the laser beam. Furthermore, Figure 3(b) shows that the powder turns into bulk solid as it cools after melting. The density of the material removed and evaporated (bright) is set to that of aluminium gas and remains as gas even as it cools.

Table 2 Averaged melt penetration without and with powder under different process parameters, experimentally measured and simulated

Cases	D^n [μm]		D^p [μm]	
	Experimental (mean, max, min)	Simulated	Experimental (mean, max, min)	Simulated
HH	57.9, 93.0, 36.4	61.5	55.0, 74.1, 37.7	42.3
LL	25.2, 35.7, 16.7	35.8	26.9, 33.9, 22.8	23.0
LH	19.6, 24.6, 15.8	23.9	18.9, 22.8, 13.6	18.2

Note: D^n and D^p denote melt penetration without and with powder respectively

Table 3 Averaged melt width without and with powder under different process parameters, experimentally measured and simulated

Cases	W^n [μm]		W^p [μm]	
	Experimental (mean, max, min)	Simulated	Experimental (mean, max, min)	Simulated
HH	129.9, 162, 97.2	120.0	164.0, 193.4, 140.0	138.6
LL	81.6, 98.8, 64.0	84.2	112.9, 126.1, 103.0	104.0
LH	75.1, 85.2, 64.0	87.8	78.9, 105.2, 60.5	87.8

Note: W^n and W^p denote melt width without and with powder respectively

By comparing the results shown in Table 2 and Table 3, for both with and without powder cases, penetration and width both increase with increased laser power and decreased scan speed. This is because the heat flow per unit area increases with increased laser power and decreases with increased scan speed. By comparing D^n and D^p , it is observable that both values have little difference. Such a phenomenon is quite contrary to experience as some of the energy of the laser beam is spent on melting the powder, therefore, D^p should be significantly smaller than D^n . One possible explanation is that the powder layer has a higher absorptivity than the bulk, therefore more energy of the laser is absorbed. Besides, volume shrinkage of the powder during melting also facilitates heat transfer and thus, penetration.

Under HH (350W-1140mm/s) and LL (150W-500mm/s) cases, W^n is significantly smaller than W^p due to two factors. Firstly, the absorptivity of the powder layer is higher than the bulk material thus, more energy is being absorbed by the powder to melt the bulk. Secondly, the powder layer is less dense than the bulk, causing it to be heated more rapidly and consequently, producing a high temperature gradient. Such a high temperature gradient will enhance heat conduction in all directions and therefore, the width of the molten powder area increases. The molten powder settles on top of the bulk beneath and due to the high temperature gradient, heat is transferred through conduction at the contact surface, increasing the melt width of the bulk. In the case of LH (150W-1140mm/s), W^n is only slightly smaller than W^p due to the small energy deposition with low power and high speed. As such, the factors mentioned above are attenuated and W^n and W^p are close.

Table 4 Simulated total mass of material melted and solidified, mass of gas evaporated and mass of powder melted and solidified under different process parameters with and without powder

Cases	$m_{\text{liq, tot}}^n$ [μg]	m_{gas}^n [μg]	$m_{\text{liq, tot}}^p$ [μg]	$m_{\text{liq, p}}^p$ [μg]	m_{gas}^p [μg]	$m_{\text{liq, p}}^p / m_{\text{gas}}^p$	Performance ratio
HH	10.80	5.22	14.30	5.29	6.41	0.83	177.8
LL	5.62	2.01	15.20	10.20	3.75	2.72	133.3
LH	2.89	1.67	8.20	6.22	2.51	2.48	454.2

Note: $m_{\text{liq, tot}}^n$ is the total mass of material melted and solidified, m_{gas}^n is the mass of gas evaporated while $m_{\text{liq, p}}^p$ is the mass of powder melted and solidified.

Table 4 shows the mass of material melted and then solidified, and mass of material vaporised under different process parameter with and without powder. It can be observed that $m_{\text{liq, tot}}^p$ under a layer of powder is higher than $m_{\text{liq, tot}}^n$ without powder. This is due to the higher powder layer absorptivity. More heat is absorbed by the powder to melt the material. This also applies to the mass of gas, where it is higher when with powder than without powder. Both $m_{\text{liq, tot}}^n$ and $m_{\text{liq, tot}}^p$ are observed to increase with increased laser power and decreased scan speed as the amount of energy deposited increases. As such, more heat is available to melt the material under the laser beam. Considering the mass of molten powder solidified and vaporized, it is observed that LL (150W-500mm/s) and LH (150W-1140mm/s) have close liquid-gas ratios of the powder layer, $m_{\text{liq, p}}^p / m_{\text{gas}}^p$ (2.48 and 2.72), while the ratio in HH (350W-1140mm/s) is 0.83. In the SLM process, it is more desirable to have molten powder solidified than vaporized, i.e. a higher liquid-gas ratio of the powder layer. These numerical results suggest that the high power will reduce the ratio while the scan speed has relatively small influence on it. Comparing LL (150W-500mm/s) and LH (150W-1140mm/s) cases, it is observed that at a lower scan speed, more powder is melted and vaporized than at a higher speed. If we consider the ratio between scan speed and mass of gas vaporized, we see that LH (150W-1140mm/s) can achieve a much higher performance ratio (454) than LL (133). As for $m_{\text{liq, tot}}^p$, a large amount of heat is used to melt the underlying base-plate in LL than LH, causing unnecessary power wastage.

CONCLUSION

The melt penetration and melt width was found to increase with increased laser power and reduced scan speed. The melt penetrations were of little difference with and without powder due to volume shrink and differences in bulk and powder absorptivities. However the melt widths were larger with powder due to the large absorptivity in the powder layer. Also, the low density of the powder layer caused a high thermal gradient that encouraged heat conduction. The total mass of molten and vaporized material was larger with powder than without powder. For the powder cases, it was found that high power leads to low liquid-gas ratio of the powder layer, while scan speed had little influence on the ratio. High scan speed had less vaporization of the molten powder and less melting of the base-plate than at a low scan speed. However, at a low scan speed, a higher mass of molten powder was achieved.

ACKNOWLEDGMENTS

The authors would like to thank Dr Song Jie on his advice in FE modelling, Associate Professor Ng Yin Kwee, Eddie for his software support and Mr Teo Hai Beng of CAE Laboratory for his technical assistance.

REFERENCES

- Abe, F., Santos, E.C., Kitamura, Y., Osakada, K. and Shiomi, M., 2003. Influence of forming conditions on the titanium model in rapid prototyping with the selective laser melting process. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 217, 119-126.
- Childs, T., Hauser, C. and Badrossamay, M., 2005. Selective laser sintering (melting) of stainless and tool steel powders: experiments and modelling. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 219, 339-357.
- Chua, C.K., Leong, K.F. and Lim, C.S., 2010. *Rapid prototyping: principles and applications*, World Scientific.
- Contuzzi, N., Campanelli, S. and Ludovico, A., 2011. 3D FINITE ELEMENT ANALYSIS IN THE SELECTIVE LASER MELTING PROCESS. *International Journal of Simulation Modelling (IJSIMM)*. 10.
- Dai, K. and Shaw, L., 2004. Thermal and mechanical finite element modeling of laser forming from metal and ceramic powders. *Acta Materialia*. 52, 69-80.
- Gu, D. and Zhang, G., 2013. Selective laser melting of novel nanocomposites parts with enhanced tribological performance: Nanocrystalline TiC/Ti nanocomposites parts were built via SLM technology and the densification, microstructures, microhardness and tribological Performance were investigated. *Virtual and Physical Prototyping*. 8, 11-18.
- Kruth, J.-P., Froyen, L., Van Vaerenbergh, J., Mercelis, P., Rombouts, M. and Lauwers, B., 2004. Selective laser melting of iron-based powder. *Journal of Materials Processing Technology*. 149, 616-622.
- Liu, Z., Chua, C., Leong, K., Kempen, K., Thijs, L., Yasa, E., Van-Humbeeck, J. and Kruth, J., 2011. A preliminary investigation on selective laser melting of M2 high speed steel, *Innovative Developments in Virtual and Physical Prototyping: Proceedings of the 5th International Conference on Advanced Research in Virtual and Rapid Prototyping*, Leiria, Portugal, 28 September-1 October, 2011. CRC Press, pp. 339.
- Loh, L.E., Chua, C.K., Yeong, W.Y., Mapar, M., Sing, S.L., Liu, Z.H. and Zhang, D.Q., 2014a. Numerical investigation and an effective modelling on the Selective Laser Melting process with aluminium alloy 6061. *Journal of Materials Processing Technology*. Submitted.
- Loh, L.E., Liu, Z.H., Zhang, D.Q., Mapar, M., Sing, S.L., Chua, C.K. and Yeong, W.Y., 2014b. Selective Laser Melting of aluminium alloy using a uniform beam profile. *Virtual and Physical Prototyping*. 9, 11-16.
- Matsumoto, M., Shiomi, M., Osakada, K. and Abe, F., 2002. Finite element analysis of single layer forming on metallic powder bed in rapid prototyping by selective laser processing. *International Journal of Machine Tools and Manufacture*. 42, 61-67.
- Mercelis, P. and Kruth, J.-P., 2006. Residual stresses in selective laser sintering and selective laser melting. *Rapid Prototyping Journal*. 12, 254-265.
- Papadakis, L., Loizou, A., Risse, J., Bremen, S. and Schrage, J., 2013. A computational reduction model for appraising structural effects in selective laser melting manufacturing. *Virtual and Physical Prototyping*. 1-9.
- Roberts, I., Wang, C., Esterlein, R., Stanford, M. and Mynors, D., 2009. A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing. *International Journal of Machine Tools and Manufacture*. 49, 916-923.
- Santos, E.C., Shiomi, M., Osakada, K. and Laoui, T., 2006. Rapid manufacturing of metal components by laser forming. *International Journal of Machine Tools and Manufacture*. 46, 1459-1468.
- Vandenbroucke, B. and Kruth, J.-P., 2007. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. *Rapid Prototyping Journal*. 13, 196-203.
- Yin, J., Zhu, H., Ke, L., Lei, W., Dai, C. and Zuo, D., 2012. Simulation of temperature distribution in single metallic powder layer for laser micro-sintering. *Computational Materials Science*. 53, 333-339.
- Zaeh, M.F. and Branner, G., 2010. Investigations on residual stresses and deformations in selective laser melting. *Production Engineering*. 4, 35-45.
- Zhang, D., Cai, Q., Liu, J., Zhang, L. and Li, R., 2010. Select laser melting of W-Ni-Fe powders: simulation and experimental study. *The International Journal of Advanced Manufacturing Technology*. 51, 649-658.