Numerical methods for predictions of mechanical properties and microstructural changes in laser additive manufacturing

***†Z. Zhang[1,2], P. Ge[1], J.P. Liu[1], Z.J. Tan[1], and Z.Y. Wan[1]**

[1]Department of Engineering Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, China
[2] International Research Center for Computational Mechanics, Dalian University of Technology, China

*Presenting author: zhangz@dlut.edu.cn
†Corresponding author: zhangz@dlut.edu.cn

Abstract

Laser additive manufacturing (LAM) is an efficient method for fabrication layer by layer. There are many different types of laser additive manufacturing. Laser Engineered Net Shaping (LENS) and Direct Metal Deposition (DMD) are usually combined with other technologies such as metal cutting process, which can be further developed as hybrid laser additive manufacturing. Direct Metal Laser Sintering (DMLS), Selected Laser Sintering (SLS) and Selected Laser Melting (SLM) can be directly used for the final product. In comparison with traditional manufacturing technologies, the producing cost can be saved by 15-30% and the production cycle can be generally reduced by 45-70% in additive manufacturing.
The computational mechanics with combination of computational material science can provide an efficient tool for better understanding the mechanism of microstructural evolutions in additive manufacturing. Monte Carlo method [1], Cellular Automata method [2] and phase field method [3] can be used for the simulations of the grain growth in one or two phases of alloys. Johnson-Mehl-Avrami-Kolmogorov equation [4] can be used for the controlling of phase transformation of β-phase to α-phase in laser additive manufacturing of TC4 alloy. With the obtained microstructures from numerical models, the mechanical properties of the additive manufactured material can be evaluated [5].
To predict the microstructural evolutions in LAM, the temperature history should be accurately described. As shown in Fig.1, the heat source in LAM can be divided into two parts: the heat input from laser on bed or deposited layer and the heating of the particles inside of the laser beam. The heating on particles can be expressed by,

$$Q_p = \frac{Q_t}{\pi r_b^2} \cdot 2\pi r_p^2 \cdot n \tag{1}$$

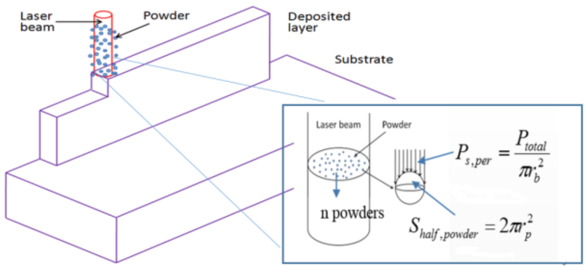

Figure 1. Heat source in LAM

The heating on the deposited layer can be written as double ellipsoid heat source,

$$q_{v1} = \frac{6\sqrt{3}Q_t f_f}{a_f bc\pi\sqrt{\pi}} \exp\left\{-3\left[\left(\frac{x+vt}{a_f^2}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2\right]\right\} \cdot \left(1 - 2\eta_s \cdot \frac{n \cdot 2r_p^2}{\left(a_f b + a_r b\right)}\right) \tag{2}$$

$$q_{v2} = \frac{6\sqrt{3}Q_t f_r}{a_r bc\pi\sqrt{\pi}} \exp\left\{-3\left[\left(\frac{x+vt}{a_r^2}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2\right]\right\}\cdot\left(1-2\eta_s\cdot\frac{n\cdot 2r_p^2}{\left(a_f b + a_r b\right)}\right) \tag{3}$$

where a_f, a_r, b, c are the axes in X, Y, and Z directions; f_f, f_r are the heat input coefficients on the two semi-ellipsoids.

By use of the proposed heat sources, the temperature history in LAM can be predicted, as shown in Fig.2. When the laser is moving to the next layer, part of the current layer can be re-melted. The re-heating and re-melting of layer can lead to new nucleation and coarsening for the formation of the β phase for TC4 alloy.

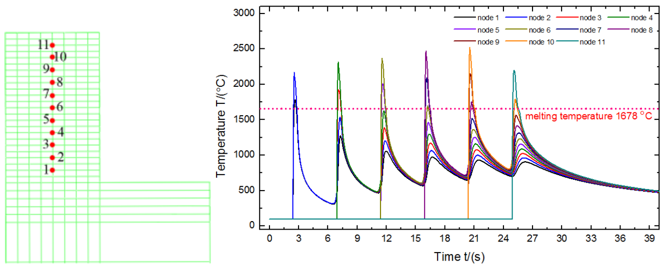

Figure 2. Temperature histories in LAM

The determination of the mechanical property of the LAMed TC4 alloy is strongly dependent on the volume fraction of the α and β phases [5],

$$\sigma_{\alpha+\beta} = f\sigma_\alpha + (1-f)\sigma_\beta \tag{4}$$

Different temperature cycles can lead to different microstructures in different layers, as shown in Fig.3.

Figure 3. Different microstructures in different layers

The flow stress in different temperatures can be predicted by Eq. 4 as well as a microstructure based finite element model, as shown in Fig.4. The flow stress can be decreased with the increase of temperatures, which can be fitted well with experimental observations for titanium alloys. By the obtained curves, the stress—strain curve can be easily obtained. Then, the predicted mechanical properties of TC4 can be used with combination of Crossland criterion for the further predictions of fatigue properties.

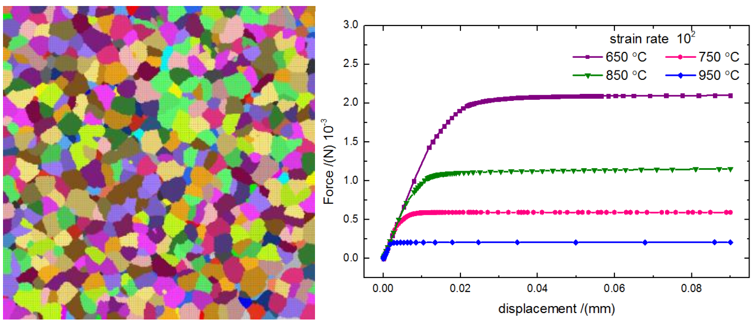

Figure 4. Mechanical response of microstructure based finite element model

Keywords: additive manufacturing, direct metal deposition, Monte Carlo method, fatigue

Acknowledgements: The authors would like to acknowledge the financial supports from the National Natural Science Foundation of China (Nos. 11572074 and 11172057).

References

[1] Zhang, Z., Wu, Q., Grujicic, M. and Wan, Z.Y (2016) Monte Carlo simulation of grain growth and welding zones in friction stir welding of AA6082-T6, *Journal of Materials Science* 51, 1882–1895.

[2] OuYang, D.L., Fu, M.W. and Su, S.Q (2014) Study on the dynamic recrystallization behavior of Ti-alloy Ti–10V–2Fe–3V in β processing via experiment and simulation, *Materials Science and Engineering A* 619, 26-34.

[3] Sahoo, S. and Chou, K. (2016) Phase-field simulation of microstructure evolution of Ti–6Al–4V in electron beam additive manufacturing process, *Additive Manufacturing* 9, 14-24.

[4] Lindgren, L.-E., Lundbäck, A., Fisk, M., Pederson, R. and Andersson, J. (2016) Simulation of additive manufacturing using coupled constitutive and microstructure models, *Additive Manufacturing* 12, 144-158.

[5] Zhang, X.P., Shivpuri, R and Srivastava, A.K. (2014) Role of phase transformation in chip segmentation during high speed machining of dual phase titanium alloys, *Journal of Materials Processing Technology* 214, 3048-3066.