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GRAIN GROWTH MODELING FOR ADDITIVE MANUFACTURING OF NICKEL BASED SUPERALLOYS

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Abstract

In a laser based additive manufacturing process, the alloy powders undergo a rapid heating, melting, solidification and cooling process. The morphology and the scale of the solidification structure depend on the temperature gradient and the growth rate during the additive manufacturing process. A comprehensive three dimensional transient heat transfer and fluid flow model has been used to calculate the temperature distribution, thermal cycles and local solidification parameters during laser based additive manufacturing process for nickel based super alloys. The growth direction of columnar dendrites and the solidification texture are estimated based on the computed temperature field. The effects of the process parameters on the growth directions, morphologies and scale of the solidification structures are discussed.

Introduction

Additive manufacturing (AM) of alloys offers many advantages over the conventional techniques for producing 'near-net-shape' parts. AM allows layer-by-layer fabrication of parts with complex geometries that are used for applications in medical, aerospace, automotive and other industries [1-3]. Since texture affects mechanical and chemical properties of the fabricated components, its control is crucial for achieving desirable properties of AM parts. As the scanning strategy of the laser beam affects solidification pattern, components with same geometry can have different solidification texture [4-6]. Parimi et al. [4] reported an inclination of 50º - 60º of grain growth with scanning direction. However, for alternate hatching strategy, the grains of two successive layers are oriented almost perpendicular to each other. The solidification patterns depend on the local temperature field near the growth interface and the grain orientation of the substrate [7]. Liu et al. [9] have shown that columnar grains grow epitaxially on single crystal substrates and the solidification growth rates at solid-liquid interfaces is significantly affected by the AM process parameters.

Here we show that three-dimensional, transient heat transfer and fluid flow calculations can provide an understanding of grain growth in nickel based superalloys during AM process. Based on the calculated ratio of temperature gradient (G) to the growth rate (R), grain morphology is estimated. Growth of dendrites and its dependence on process conditions are discussed based on the computed temperature distribution.

Heat transfer and fluid flow model

The three-dimensional, transient, heat transfer and fluid flow model used here solves the equations of conservation of mass, energy and momentum. [1] These equations are available in standard text books [9] and published literature [7, 10] and are not repeated here. The model computes temperature and velocity fields at various locations from AM process variables, such as the laser power, power density distribution, scanning speed, chemical composition, particle size, feed rate and thermo-physical properties of the alloy powder. [1, 3] In laser assisted AM, a fraction of the laser beam energy is transferred from the laser beam to the alloy powders and substrate. The laser energy is considered in the energy conservation equation as a volumetric heat source, S_v as,

$$S_v = \frac{D\eta_a P}{\pi r^2 h_d} \exp\left[-D\left(\frac{x^2 + y^2}{r^2} \right) \right] \tag{1}$$

where *D*, η_a is, *P* are the power distribution factor, the laser absorption coefficient and the laser beam power, respectively. The symbol *r* refers to the radius of the laser beam, h_d is the thickness of the material layer being deposited on the substrate, *x* and *y* are the co-ordinates from the axis of the laser beam on the surface. [11-13]

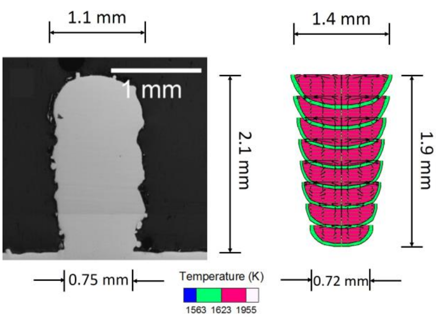

Figure 1. Comparison between the numerically calculated and the corresponding actual build shape [5].

The boundary conditions for the thermal analysis include heat exchange by convection and radiation with the surroundings. The boundary conditions for the velocities at the free surface are based on Marangoni convection. [1, 7, 10] The transient heat transfer and fluid flow calculations are performed for a solution domain representing the substrate, deposited layers, and the surrounding gas. The calculations are continued until the simulation of all the layers is completed and the specimen cools.

Figure 1 shows a comparison between the numerically calculated and the corresponding actual build shape [5]. A fair agreement between the calculated build shape and size, and the corresponding measured build profile in figure 1 indicates that the modeling results can be used to estimate the grain growth with confidence. Based on the computed temperature distribution, G/R ratios are calculated at various locations of solidification front. Figure 2a shows the G/R ratio for the laser based deposition [4, 6] of IN 718 on the solidification map [14]. It reveals that columnar dendrites or a mixture of columnar and equiaxed dendrites are observed depending on the solidification velocity and the temperature gradient. However, direction of the grain growth is along the maximum heat flow direction. For AM, maximum heat flow direction is perpendicular to the trailing edge of the molten pool towards the substrate [15]. Hence, columnar dendrites grow on the top of the substrate perpendicular to the trailing edge of the pool as shown in Figure 2 (b). Because of lower G/R ratio near the top surface of the molten pool, equiaxed grains can be observed as shown in Figure 2 (b).

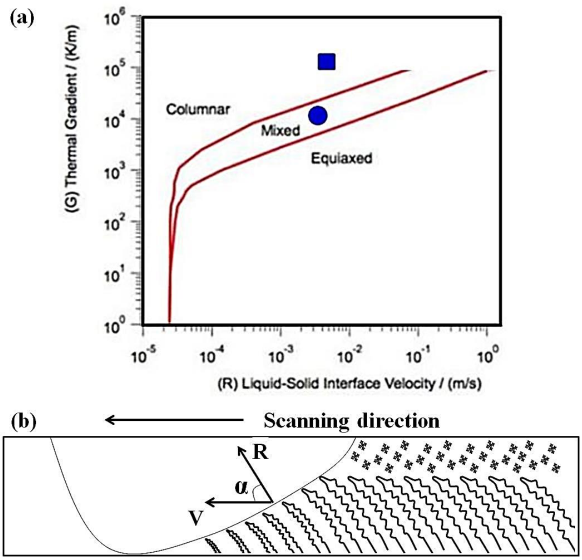

Figure 2. (a) Solidification map of IN718. The symbol square indicates columnar dendrite region, and circle indicates the columnar and equiaxed dendrite region. (b) Illustration for columnar and equiaxed dendrites in the longitudinal mid-section of a depositing layer

Figures 3 (a) and (b) show the simulated and experimentally observed columnar and equiaxed grains[4] in the longitudinal mid-section of the deposit. The solidification condition is in the mixed region in Figure 2(a) as indicated by the circle. For the first layer, columnar grains start to grow epitaxially from the substrate and their growth is blocked by the formation of equiaxed grains in the upper part of the layer. The columnar grains in the second layer also grow epitaxially from the equiaxed grains on the top of the first layer. Competitive growth of grains with different orientations occurs and those closely aligned with the maximum heat flow direction at the solid/liquid interface obtain preferential growth. However, equiaxed grains also form in the upper part of the second layer. Similar grain growth processes take place during the deposition of subsequent layers.

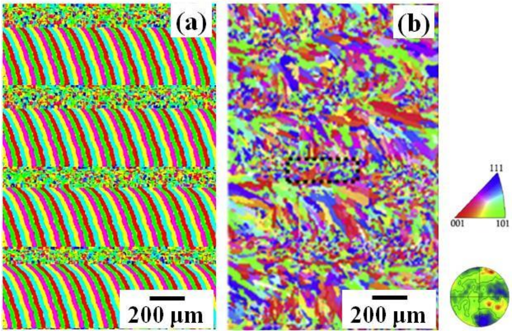

Figure 3. (a) Calculated grain orientations, (b) EBSD for unidirectional scanning of IN718 [4]

Figures 4 (a) and (b) show the simulated and experimentally observed columnar grains[6] in the longitudinal mid-section of the deposit. The solidification condition is in the columnar region in Figure 2(a) as indicated by the square. For the first layer, columnar grains start to grow epitaxially from the substrate and no equiaxed grains formed in the deposit. The columnar grains in the second layer then grow epitaxially from the columnar grains in the first layer. Similar grain growth processes take place during the deposition of the subsequent layers. Therefore, elongated columnar grains through several layers are generated by the continuous epitaxial growth.

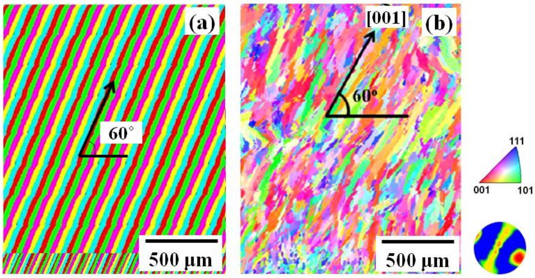

Figure 4. (a) Calculated grain orientations (b) EBSD for unidirectional scanning of IN718 [6]

Conclusions

The solidification textures of a nickel based alloy during AM could be estimated using heat transfer and liquid metal flow modeling. For laser assisted AM of IN718 by unidirectional scanning, the solidification texture can be a mixture of columnar and equiaxed grains with significantly amount of equiaxed grains in the upper part of the layers. However, the solidification texture can also consist of elongated columnar grains through several layers from continuous epitaxial growth depending on solidification rate and temperature gradient. The numerical modeling results help to understand the mechanism of formation of the solidification texture and provide a basis for customizing solidification textures during additive manufacturing of IN718.

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References

[1] V. Manvatkar, A. De, and T. DebRoy, "Heat transfer and material flow during laser assisted multi-layer additive manufacturing," *J. Appl. Phys.* 116 (2014), 1.
[2] V. Manvatkar, A. De, and T. DebRoy, "Spatial variation of melt pool geometry, peak temperature and solidification during laser assisted additive manufacturing process," *Mater. Sci. Tech. Ser.* 31 (2015), 924.
[3] T. Mukherjee et al., "Printability of alloys for additive manufacturing," *Sci. Rep.* 6 (2016), 19717.
[4] L.L. Parimi et al., "Microstructural and texture development in direct laser fabricated IN718," *Mater. Character.* 89 (2014), 102.
[5] G.P. Dinda, A.K. Dasgupta, and J. Mazumder, "Laser aided direct metal deposition of Inconel 625 superalloy: Microstructural evolution and thermal stability," *Mater. Sci. Eng. A*. 509 (2009), 98.
[6] G.P. Dinda, A.K. Dasgupta, and J. Mazumder, "Texture control during laser deposition of nickel-based superalloy," *Scripta Mater*. 67 (2012), 503.
[7] T. Debroy, and S.A. David, "Physical processes in fusion welding," *Rev. Mod. Phys*. 67 (1995), 85.
[8] Z. Liu, and H. Qi, "Effects of substrate crystallographic orientations on crystal growth and microstructure formation in laser powder deposition of nickel-based superalloy," *Acta Mater*. 87 (2015), 248.
[9] S.V. Patankar, *Numerical Heat Transfer and Fluid Flow* (New York, McGraw-Hill, 1982).
[10] S.A. David, and T. DebRoy, "Current issues and problems in welding science," *Science*. 257 (1992), 497-502.
[11] A. Frenk et al., "Analysis of the laser-cladding process for stellite on steel," *Metall. Mater. Trans. B*. 28 (3) (1997), 501-508.
[12] V. Neela, and A. De, "Three dimensional heat transfer analysis of LENS™ process using finite element method," *Int. J. Adv. Manuf. Technol*. 45 (9-10) (2009), 935-943.
[13] W.M. Steen, *Laser Material Processing*, 2nd ed. (New York, Springer-Verlag, 1998), 83.
[14] R.R. Dehoff et al., "Site specific control of crystallographic grain orientation through electron beam additive manufacturing," *Mater. Sci. Technol*. 31 (2015), 931-938.
[15] H.L. Wei, J. Mazumder, and T. DebRoy, "Evolution of solidification texture during additive manufacturing." Sci. Rep. 5 (2015), 16446.