Simulation of Microstructure Phase-Field during Wire Arc Additive Manufacturing of Aluminum Alloys

Fuchen Wang[1], Weipeng Chen[1], Hua Hou[1,3], Yuhong Zhao[1,2,4*]
1. School of Materials Science and Engineering, Collaborative Innovation Center of Ministry of Education and Shanxi Province for High-performance Al/Mg Alloy Materials, North University of China, Taiyuan030051, China
2. Beijing Advanced Innovation Center for Materials Genome Engineering, University of Science and Technology Beijing, Beijing100083, China
3. School of Materials Science and Engineering, Taiyuan University of Science and Technology, Taiyuan030024, China
4. Institute of Materials Intelligent Technology, Liaoning Academy of Materials, Shenyang110004, China
*Corresponding address: e-mail: zhaoyuhong@nuc.edu.cn

Abstract: Wire Arc additive manufacturing (WAAM) technology has attracted wide attention due to its advantages of high deposition rate, low cost, stable product performance and high material utilization. However, the complex thermal history under rapid solidification limits the study of the solidification structure under rapid solidification. In this work, we studied the dendritic growth and solute segregation behavior at different scanning speeds in the WAAM process based on finite element and phase field methods. It is found that the dendrite growth under rapid solidification is strongly dependent on the temperature gradient. With the increase of temperature gradient, the dendrite growth rate is accelerated, and the solute segregation is more serious.

Keywords: WAAM;rapid solidification; dendrite growth; solute segregation

1 Introduction

At present, the integrated molding of complex parts is the trend in the manufacturing industry. Because the traditional manufacturing methods (machining, forging, powder metallurgy, etc.) can't realize the increasingly complex industrial needs. Therefore, Additive Manufacturing (AM) technology has gradually received widespread attention. The complexity of process parameters and the sensitivity of microstructures to processing conditions in WAAM make it difficult to accurately grasp the evolution of microstructures under rapid solidification. However, investigating the evolution of solidified tissues under rapid solidification in additive manufacturing by experimental methods is bound to incur a lot of unnecessary consumption. Based on the finite element, phase field method framework, Keller et al. [1] investigated the microstructure evolution during laser powder bed melting of nickel-based high-temperature alloys and verified the reliability of the simulation results using experiments. However, in the current phase field simulations, researchers tend to ignore the non-equilibrium-dominated solidification effects under rapid solidification. This can lead to biased predictions of the microstructure. In this work, investigates the influence of non-equilibrium effects on the microstructure evolution under rapid solidification. The microstructure evolution at different scanning speeds was investigated. The results show that with the increase ofscanning speed, the temperature gradient during solidification decreases, the growth rate of dendrites decreases, and the solute segregation is weakened. The results provide a general strategy for optimizing the WAAM processing.

2 Experimental procedure

In this work, a 3D finite element model was used to calculate the temperature gradient at different scanning speeds during the WAAM process.
In this work, the governing equation for the phase-field simulation is given by the following equation [2, 3]:

$$\tau a_s^2(\vec{n})\frac{\partial \phi}{\partial t}=\vec{\nabla}\cdot\left[a_s(\vec{n})^2\vec{\nabla}\phi\right]+\sum_{m=x,y}\partial_m\left(|\vec{\nabla}\phi|^2 a_s(\vec{n})\frac{\partial a(\vec{n})}{\partial(\partial_m\phi)}\right)+$$

$$\phi-\phi^3-\lambda(1-\phi^2)^2\left(U+\frac{\left(z-\int_0^t V_p(t')dt'\right)}{l_T}\right)$$

$$\left(\frac{1+k-(1-k)\phi}{2}\right)\frac{\partial U}{\partial t}=\vec{\nabla}\cdot\left(D_l q(\phi)\vec{\nabla}U-\vec{j}_{at}\right)+[1+(1-k)U]\frac{1}{2}\frac{\partial \phi}{\partial t}$$

where $a_s(\vec{n})$ is the interface energy anisotropy,$\theta$is the angle between theinterface normal and the coordinate axis， α_0 isthe angle of misorientation of the crystal to the coordinate axis,ε_4 is the strength of the surface tension anisotropy,λ is the coupling constant.V_p is the solidification speed,l_T is the thermal length,m is theliquidus slope,c_l^0 is the concentration of the liquidphase when the temperature is T_0,k is the non-equilibrium partition coefficient, $k=(k_e+V_p/V_D)/(1+V_p/V_D)$, k_e is theequilibrium partition coefficient, V_D is the solute diffusion velocity. D_l is the liquid diffusion coefficient ， $\vec{j}_{at}=-a(\phi)[1+(1-k)U](\partial\phi/\partial t)\left(\vec{\nabla}\phi/\left|\vec{\nabla}\phi\right|\right)$ is the antitrapping current, $a(\phi)=c_1\left(1-[c_2/ln(1+\varepsilon)](1-\phi^2)\right)$ ， $c_1=1/2\sqrt{2}$, $c_2=[1/4(1-k_e)](V_S/V_D)ln(k_e+1/2k_e)$, $V_S=D_l/d_0$ ， d_0 is the capillary length, $q(\phi)=[1-\phi+k_e(D_s/D_l)(1+\phi)]/[1+k_e-(1-k_e)\phi]$ is theinterpolation function, D_s is the solid diffusion coefficient.

3 Results and discussion

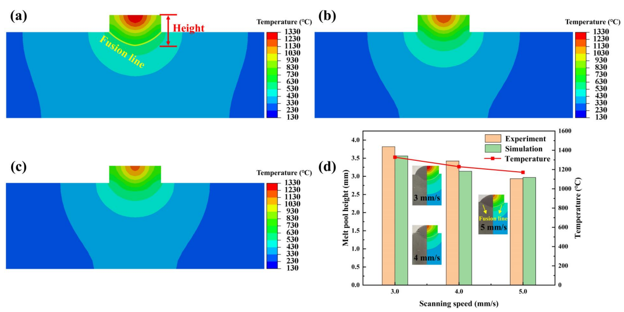

Figure 1 Finite element temperature distribution at different scanning speeds: (a) 3 mm/s; (b) 4 mm/s; (c) 5 mm/s.

Figure 1 shows the finite element analysis results at different scanning speeds. The maximum temperatures in the melt pool at different scanning speeds are 1,330 °C, 1,230 °C, and 1,171 °C, respectively. This is mainly because the effective heat input decreases with the increase of scanning speed. Figure 1(d) shows the variation of the height of the melt pool. The height and maximum temperature of the melt pool are inversely proportional to the scanning speed. Meanwhile, we compared the molten pool morphology of the WAAM experimental results and the finite element simulation results at different scanning speeds, as shown in Figure 1(d). It can be observed that with the increase of scanning speed, the errors between the melt pool depths obtained from the experiments and those from the finite element simulation are 0.257 mm, 0.283 mm, and 0.033 mm, respectively. The melt pool morphology obtained by finite element simulation is in good agreement with the experimental results.

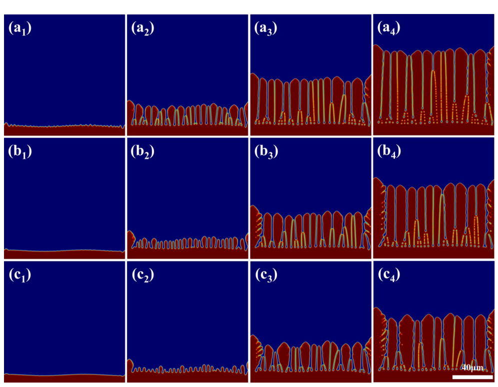

Figure 2 Dendritic morphology at different scanning speeds: (a_1) -(a_4) 3 mm/s; (b_1) -(b_4) 4 mm/s; (c_1) -(c_4) 5 mm/s

As shown in Figures 2(a_1) -(c_1), a lower scanning speed causes the solid-liquid interface to destabilize earlier. This is because the scanning speed has a significant effect on the temperature gradient during solidification in the WAAM process. As the scanning speed increases, the temperature gradient during dendrite growth decreases and the driving force for dendrite growth decreases, so it can be observed that the dendrite growth rate decreases as the scanning speed increases. As shown in Figures 2(a_2) -(c_2), the solid-liquid interface is destabilized, and the planar interface generates dendrites and penetrates deep into the liquid phase. Due to the negative temperature gradient at the solid-liquid interface front, the growth of dendrites is promoted. Therefore, at the junction of the WAAM substrate and the deposited layer, the dendrites first grow in the form of columnar dendrites during solidification. Since there is a preferential orientation in the process of dendrite growth, the growth tendency of dendrites parallel to the direction of heat flow is more intense. Therefore, the phenomenon of competing growth of dendrites occurs in the early stage of solidification, as shown in Figures 2(a_3)-(c_3).

4 Conclusions

(1)As the scanning speed increases the heat input to the WAAM process decreases and the temperature gradient during solidification decreases.

(2)As the temperature boost decreases the driving force for dendrite growth during solidification decreases and the dendrite growth rate decreases. Solute segregation is reduced.

5 Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos.52074246, 52275390, 52205429, 52201146), the National Defense Basic Scientific ResearchProgram of China (JCKY2020408B002, WDZC2022-12), the Key Research and DevelopmentProgram of Shanxi Province (202102050201011, 202202050201014).

References

[1] Keller T, Lindwall G, Ghosh S, et al. Application of finite element, phase-field, and CALPHAD-based methods to additive manufacturing of Ni-based superalloys. Acta Materialia, 2017, 139: 244-253.

[2] Echebarria B, Folch R, Karma A, Plapp M. Quantitative phase-field model of alloysolidification. Physical Review E, 2004, 70(6 Pt 1):061604.

[3] Kavousi S, Asle Zaeem M. Quantitative phase-field modeling of solute trapping in rapidsolidification. Acta Materialia, 2021, 205:116562.