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Onset of the initial instability during the solidification of welding pool of aluminum alloy under transient conditions

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ABSTRACT

Onset of initial morphological instability is predicted by using a new analytic model and quantitative phase field model during the solidification of the welding pool of Al–Cu alloy under transient conditions. In the linear growth stage of the welding pool, the dynamic evolution of the interface instability is analyzed, and the interface behaviors under infinitesimal fluctuations are also investigated. The results show that the mean wavelength at the crossover time evaluated from this analytic model is in good agreement with those obtained by the quantitative phase field simulations and the experiments. The linear growth stage takes up quite a long time of the whole solidification of welding pool and thus it should be primarily considered in investigating the transient growth of welding pool. This study establishes a valid numerical framework for studying the dendrite growth under transient solidification conditions and provides a new approach for studying the transient solidification of welding pool.

1. Introduction

As one of the most important synthesis techniques, welding has been applied broadly in many field of the manufacturing industry. Solidification behaviors and the resulting microstructure of the welded joint have significant impacts on its properties [1]. Prediction of the microstructure formation during the solidification of the welding pool can provide important and supporting informations for technology process optimization. However, the solidification of the welding pool is a fairly complex process and it is difficult to observe its highly dynamic evolution through the conventional experimental methods. Fortunately, the numerical simulation technology nowadays has provided an efficient way to predict the morphological changes during the solidification of the welding pool and investigations have got outstanding achievements. Nevertheless, they almost ignored or rarely concentrated on the initial instability during transient growth. In the studies of Yin [2], Zhan [3] and Ma et al. [4], the microstructures of molten pool were simulated by the cellular automaton (CA) methods and there is no actual interface morphology is considered for the initial solid seeds which are formed by the initial instability, but a relatively simple layer solid on the boundaries of the simulation domain. Using phase field (PF) methods, other studies [5,6] did have considered the linear growth stage of the planar interface, but the solidification of welding pool has been assumed to be under steady-state conditions throughout the entire welding process, which have many differences with the real conditions.

The resulting solidification microstructures of the dynamical instabilities of the solid–liquid interface are largely responsible for the mechanical properties of solid and in particular metallic alloys [7]. Since the initial instability of the advancing interface appears at the beginning of the solidification of the welding pool, prediction of detailed dynamics of such initial instability turns out to be great importance. The researches on the initial instability have been conducted for dozens of years. The dynamical theory of the solidification instability was first analyzed by Mullins and Sekerka (MS) in the limit of infinitesimal amplitude of interface deformation [8]. However, the mean spacing of the unstable interfaces predicted by MS does not correspond to that observed experimentally, indicating the limitations of the MS theory in predicting the interface behaviors [9,10]. Warren and Langer (WL) [11] later developed a generalization of the MS theory by incorporating the nonsteady-state dynamics, which has been proven to be a great success since the prediction of interface spacing made by this generalized theory in steady-state directional solidification shows good consistence with the experiments [10,12–15]. By using Fourier synthesis, Wang et al. [16] developed a simple model to describe the dynamic evolution process of interface morphology at the early instability stage. This model is further validated by the results obtained from the WL model, PF simulations and experiments. These investigations conducted previously were in the context of steady-state conditions, i.e. the interface is pulled by a

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constant thermal gradient and at constant pulling speed. Although steady-state directional solidifications is an important academic paradigm and extensive experimental and theoretical works during the past several decades have yielded deep insights into many field [17–24], steady-state solidification is just an ideal process obtained only by carrying out careful experiment in laboratory, rather than a realistic representation of the conditions prevalent during industrial productions. In particular welding process, solidification normally occurs under transient growth conditions, i.e. the thermal gradient and solidification speed are neither constant nor independent of each other [25]. However, simulation on the dendrite morphologies developed in welding pool under transient growth condition has been seldom reported, let alone the initial instability in the solidification. Once again, since the microstructure revolutions during actual transient growth conditions start with the initial instabilities of the planar interface, the initial growth stage should be deserved particular attention, especially during the transient solidification of welding pool. This paper presents a new analytic model based on the WL theory which is capable of predicting the onset of initial morphological instability in directional solidification of the weld pool under transient condition. Based on this model, the dynamic evolution of the initial interface instability in the linear growth stage of the solidification of welding pool is described. Quantitative PF simulations of this revolution and experiments are conducted to provide comparison which validation of the presented model.

2. Modeling and experiments

2.1. Theoretical modeling

The transient directional solidification process is assumed to be effectively two dimensional, and starts with a planar interface and moving in the z direction at a time-dependent pulling speed $V_p(t)$. The latent heat of fusion is assumed to be sufficiently small and the thermal conductivities of the liquid and solid sufficiently large and close to one another that the temperature throughout the system is determined by the applied time-dependent temperature gradient $G(t)$. A frozen temperature approximation is adopted for the directional solidification, and the temperature field is defined as $T=T_0+G(t)z$, where T_0 is the melting temperature of pure metal. The origin of the moving z axis is always at the position of liquidus and thus this choice of position for $z=0$ means that the entire solidification front is always in the region $z<0$.

The solute diffusion equation in the liquid phase is given by

$$D\nabla^2 c_0(z,t)+v_i\frac{\partial c_0(z,t)}{\partial z}=\frac{\partial c_0(z,t)}{\partial t} \tag{1}$$

where $c_0(z, t)$ is the time-dependent concentration field in front of the planar interface, v_i is the interface velocity. Here, the boundary conditions should be satisfied. Firstly, assuming local equilibrium at the liquid–solid interface, the concentration on the liquid side satisfied

$$c_0(z_0,t)=\frac{G(t)z_0}{m} \tag{2}$$

and then, the conservation of solute at the interface requires

$$D\frac{\partial c_0(z,t)}{\partial z}\Big|_{z=z_0}=v_i(t)(1-k)c_0(z_0,t) \tag{3}$$

where D is the diffusivity of impurities in the liquid, z_0 is the position of the interface, m and k are the slope of the liquidus and partition coefficient, respectively. The interface velocity $v_i(t)$ is defined as $v_i(t)=V_p(t)+\partial z_0(t)/\partial t$. The transient concentration profile can be approximated by a function of the form [11]

$$c_0(z,t)=c_\infty+[c_0(z_0,t)-c_\infty]\exp\left[\frac{-2(z-z_0)}{l}\right] \tag{4}$$

where c_∞ is the concentration in the far-away field, and l is a time-dependent parameter describing the thickness of solute boundary layer. Combine the concentration profile with boundary conditions, we can get

$$v_i(t)(1-k)c_0(z,t)=\frac{2D}{l}[c_0(z_0,t)-c_\infty] \tag{5}$$

Integration of the solute diffusion equation from z_0 to the field far ahead of the interface implies

$$v_i(t)[c_\infty-kc_0(z_0,t)]=\frac{\partial}{\partial t}\left\{\frac{l[c_0(z_0,t)-c_\infty]}{2}\right\} \tag{6}$$

Finally, equations can be derived as follows

$$\frac{\partial l}{\partial t}=\frac{4D[mc_\infty/G(t)-kz_0]}{l(1-k)z_0}-\frac{lG(t)}{G(t)z_0-mc_\infty}\frac{\partial z_0}{\partial t} \tag{7}$$

$$v_i(t)=V_p(t)+\frac{\partial z_0}{\partial t}=\frac{2D[z_0-mc_\infty/G(t)]}{l(1-k)z_0} \tag{8}$$

$$c_0(z_0,t)=\frac{2Dc_\infty}{2D-V_{tip}(t)(1-k)l} \tag{9}$$

To carry out a linear stability analysis, an infinitesimal sinusoidal modulation with spacing frequency ω is assumed for the interface and concentration field, and the time-dependent linear growth coefficient is given by

$$\sigma_\omega(t)=[dA_\omega(t)/dt]/A_\omega(t) \tag{10}$$

where $A_\omega(t)$ is the amplitude. There a reasonable assumption in this equation is the neglect of the effect of fluctuating force [10,16]. The linear morphological stability analysis of the advancing interface based on the time-dependent concentration profile and the position of the planar interface obtained above yield the time-dependent dispersion relation of the perturbation [11],

$$q_\omega\left\{1+\frac{2}{l}\left[z_0-\frac{mc_\infty}{G(t)}\right]+\frac{\gamma T_0\omega^2}{G(t)L}\right\}=\frac{1}{D}\frac{\partial z_0}{\partial t}+\frac{2}{l}\left[z_0-\frac{mc_\infty}{G(t)}\right]\times\left[\frac{V_{tip}(t)}{D}+\frac{\sigma_\omega(t)}{V_{tip}(t)}+\frac{1}{z_0}+\frac{\gamma T_0\omega^2}{G(t)L}\right] \tag{11}$$

where $q_\omega=v_i(t)/(2D)+\{\omega^2+[v_i(t)/(2D)]^2\}^{1/2}$, γ and L are interfacial free energy and latent heat, respectively. The formal solution of Eq. (6) is

$$A_\omega(t)=A_\omega(0)\exp\left[\int_{t_i}^{t}\sigma_\omega(t)\,dt\right] \tag{12}$$

where t_i is the critical moment when $\sigma_\omega(t)$ changes from negative to positive and $A_\omega(0)$ refers to the initial amplitude of infinitesimal fluctuations. The interface could be presented as Fourier series [16]

$$z_0(x,t)-z_i(t)=\sum A_\omega(t)\cos\,[\omega x+\phi_\omega(t)] \tag{13}$$

where $z_i(t)$ is the basic interface position. $\phi_\omega(t)$ is the phase which is a stochastic variable with a mean distribution within [0, 2π] when $t<t_i$, while equals to $\phi_\omega(t_{0-})$ when $t\geq t_i$. Finally, by using the Eqs. (12) and (13), the interface evolution can be predicted in linear growth regime under transient conditions. Itis worth pointing out that due to this temperature field assumption, a change in G leads to an immediate change in the interface temperature of the interface, and this problem is hardly to avoid. Fortunately, the numerical solution of this model could be obtained discretely, by using a small enough time step, that problem would be weakened.