

Effect of stress and interface kinetics on the growth of a cylinder of ternary alloy in contact with its melt

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ABSTRACT

The linear stability analysis of the growth of a cylinder made of a ternary alloy in contact with its melt has been investigated from a theoretical point of view, in presence of stress and interface kinetics. It is found that instability is facilitated as the number of diffusing species increases from two to three. The radii characterizing the different growth regimes of the cylinder and the fluctuation have been determined as a function of the diffusion, elastic and kinetics parameters of the problem. It has been established that unlike interface kinetics that penalizes the growth of the fluctuation, the stress favors its development. In particular, a regime where the growth of the fluctuation is faster than the cylinder one has been identified in the early step of the cylinder development, this regime resulting from a pure elasticity effect.

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1. Introduction

The morphological evolution of growing precipitates in contact with a melt or embedded in a solid matrix is a long-standing problem in materials science and metallurgy. Since the reference works of Mullins et al. dealing with the destabilization of a spherical particle growing from its melt [1] or the destabilization of a planar front during the solidification of a binary alloy [2], different effects have been considered for various geometries of particles. For example, the effects of stress due to the concentration dependence of the lattice parameter has been investigated in the linear regime of growth from its melt of a spherical particle of dilute binary alloy [3]. Likewise, when the particle is growing in a solid matrix, the effect of misfit strain due to the lattice mismatch between the particle and matrix phases has been analyzed. It has been established in both cases that stress enhances the development of surface fluctuation [4]. Still for spherical particles, the effects of far-field flux of temperature and interface kinetics have studied in the linear and non-linear regimes on the destabilization of the particle growing in an undercooled liquid. Critical conditions for the flux have been identified at which self-similar growth occurs [5,6]. For cylindrical solid, the linear stability analysis has been carried out and the critical radius beyond which the particle can undergo morphological changes has been determined [7]. The non-linear regime has been then discussed [8]. Considering linear and quadratic kinetic laws,

the interface kinetics has been found to perturb the development of fluctuation [9]. For core-shell heterostructured cylinders, the spheroidization under misfit stress has been also analyzed when surface, interface and volume diffusion processes are activated [10]. For multicomponent systems, a fully time-dependent analysis of the shape stability has been provided for a planar interface [11]. Later, taking into account the diffusive interaction between species, the dendritic growth of the multicomponent system has been studied [12], the temporal exponents for the average particle radius, the far-field supersaturations and the precipitate number density have been then calculated through asymptotic analysis for the coarsening process [13]. Recently, the linear stability of a planar front has been re-examined for a multicomponent alloy and the development of the fluctuation has been found to be facilitated as the number of diffusing species increases [14]. The case of rapid solidification has been then considered assuming that the segregation coefficients and liquidus slopes depend on the front speed [15]. It has been found that the oscillatory mode can disappear due to the addition of a single large-diffusivity element. The modification of the cellular and pulsatile instabilities due to weak boundary-layer flow has been finally investigated [16].

In this work, the effects of misfit stress and interface kinetics have been investigated on the development of fluctuations on the solid-liquid interface of a cylinder made of a ternary alloy growing by diffusion from its melt at constant temperature. While the interface kinetics is found to penalize the fluctuation development of the cylinder radius, it is demonstrated that the instability is enhanced for the ternary alloy (with two diffusing species)

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Nomenclature

Symbols & Definitions

R	cylinder radius
R_i	interface radius between both solid phases
ϵ_*	eigenstrain
C_L^i	concentration of the species $i = 1, 2$ in the liquid
C_S^i	concentration of the species $i = 1, 2$ in the solid
$C_L^{i,\infty}$	concentration of the species $i = 1, 2$ far from the interface in the liquid
$C_L^{i,s}$	concentration of the species $i = 1, 2$ at the interface in the liquid
D_{ij}	diffusion coefficients
t	time
∇	gradient operator
S_i	concentration parameter
ν_E	Euler constant
λ_i	diffusion parameter
R_{λ_i}	external radius in the liquid
m_i	liquidus slope of species $i = 1, 2$
α	interface kinetic coefficient
γ	surface energy
T_M	melting temperature
L	latent heat of the solvent per unit volume
$\Gamma = \gamma T_M / L$	solid-liquid interface tension

μ	shear modulus of the solid
ν	Poisson ratio of the solid
$\delta C_L^{i,\infty} = C_L^{i,\infty} - C_{L,0}^i$	concentration parameter
$\delta C_{SL}^i = C_S^{i,0} - C_{L,0}^i$	concentration parameter
$\delta C_\infty = m_1 \delta C_L^{1,\infty} + m_2 \delta C_L^{2,\infty}$	concentration parameter
Δ	concentration parameter
K_{el}	dimensionless stress parameter
R_*	nucleation radius
R_x	radius related to interface kinetics
e	fluctuation amplitude
τ	relative growth rate of the fluctuation with respect to the radius growth rate
R_G	critical radius for the cylinder growth satisfying $\dot{R} = 0$
R_c^{CP}	critical radius for the fluctuation growth satisfying $\dot{e} = 0$ for a stress-free cylinder $\epsilon_* = 0$, without interface kinetics effect $R_x \rightarrow 0$
R_C	critical radius for the fluctuation growth in the stress-free cylinder $\epsilon_* = 0$
R_r	relative growth radius satisfying $\tau = 1$ in the stress-free cylinder $\epsilon_* = 0$
R_c^\pm	critical radii for the fluctuation growth, with $R_c^+ > R_c^-$
R_r^\pm	relative growth radii, with $R_r^+ > R_r^-$

compared to a binary one. A new unstable regime due exclusively to elasticity has been also identified at the early beginning of the cylinder growth. The different radii beyond which the fluctuation grows and grows faster than the cylinder radius have been finally identified.

2. Modeling and discussion

An infinite-length cylinder of dilute ternary alloy is assumed to be in contact with its melt (see Fig. 1). Using polar coordinate system (r, θ) , an eigenstrain $\epsilon_{rr} = \epsilon_{\theta\theta} = \epsilon_*$ is considered in a region of radius R_i embedded in the cylinder of radius R , with $R_i < R$ and ϵ_* a constant related to the eigenstrain located in the inner solid phase. Among the different origins of this strain, one can cite the lattice or thermal coefficient mismatches between both solid regions. The concentrations of the two diffusing species 1 and 2 in the liquid phase are labeled C_L^1 and C_L^2 , respectively, the temperature being fixed. The cross term of the diffusion matrix are taken to be zero, i.e. $D_{12} = D_{21} = 0$, and the diffusion in the solid phase is not considered. The set of equations ruling the diffusion-controlled

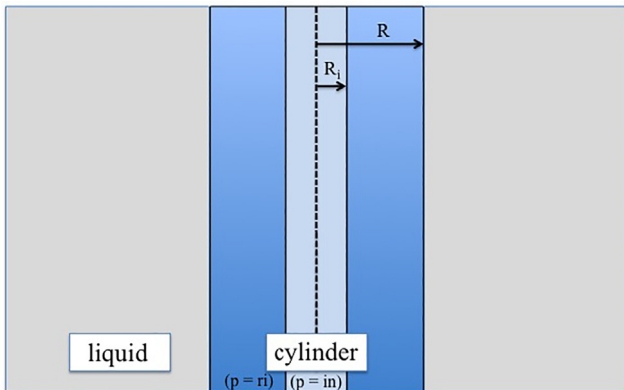


Fig. 1. A cylinder of ternary alloy is in contact with its melt. The external radius of the solid is labeled R and the interface radius between the inner region where the eigenstrain is located and the ring region is labeled R_i .

growth of the cylinder are first outlined. Following [7], the diffusion Eq. where no summation over repeated indices is implied:

$$\frac{\partial C_L^i}{\partial t} = D_{ii} \nabla^2 C_L^i, \tag{1}$$

supplemented with the boundary conditions:

$$C_L^i |_{r \rightarrow \infty} = C_L^{i,\infty}, \tag{2}$$

$$C_L^i |_{r=R} = C_L^{i,s}, \tag{3}$$

with t the time variable, ∇ the gradient operator, D_{ii} the diffusion coefficient of the species i , $C_L^{i,\infty}$ its concentration in the liquid far from the precipitate and $C_L^{i,s}$ and $C_S^{i,s}$ the corresponding concentration at the solid-liquid interface in the liquid and solid phase, respectively, can be simplified as follows. Introducing S_i , a quantity related to the concentration variations in the liquid for each diffusion species i as:

$$S_i = \frac{C_L^{i,\infty} - C_L^{i,s}}{C_S^{i,s} - C_L^{i,s}}, \tag{4}$$

Eq. (1) reduces to the Laplace Eq. in the hypothesis where $S_i \ll 1$:

$$\nabla^2 C_L^i = 0. \tag{5}$$

Introducing thus the radius R_{λ_i} defined as $R_{\lambda_i} = R / (\nu_E \lambda_i)$, with $\ln \nu_E^2 = 0.5772$ (Euler constant) and λ_i a parameter satisfying:

$$\lambda_i^2 \ln(\nu_E^2 \lambda_i^2) + S_i = 0, \tag{6}$$

the boundary conditions given by Eqs. (2) and (3) can be reformulated as:

$$C_L^i |_{r=R_{\lambda_i}} = C_L^{i,\infty}, \tag{7}$$

$$C_L^i |_{r=R} = C_L^{i,s}. \tag{8}$$

2.1. Radial growth

In the framework of the above hypothesis, the radial growth of the cylinder can be now investigated. In the polar coordinates

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