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ScienceDirect
Acta Materialia 59 (2011) 3102–3115
Acta MATERIALIA
www.elsevier.com/locate/actamat

Dynamic effects in the lamellar–rod eutectic transition

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Received 17 October 2010; received in revised form 7 January 2011; accepted 26 January 2011

Abstract

Critical experiments in the Al–Cu system are carried out to establish the conditions for the stability of rod and lamellar eutectics. It is shown that the instability of a lamella initiates locally through the formation of a sinusoidal perturbation, and the fastest growing wavelength of perturbation, which corresponds to the rod spacing, is related to the local lamella spacing. The instabilities in adjacent lamellae are observed to be out of phase to give rise to a hexagonal arrangement of rods at the transition. The specific relationship found between the unstable lamella spacing and the resulting rod spacing at the transition is then taken into account to develop a general model of the rod–lamellar transition which also includes the relative undercooling and the presence of a spacing distribution. A microstructure map is presented which defines the regimes of rod, lamellar and mixed structures, which is shown to be in good agreement with the experimental results.

Keywords: Eutectic solidification; Interface dynamics; Aluminum alloys; Directional solidification; Lamellar–rod transition

1. Introduction

Eutectic microstructures represent generic two-phase microstructures that are of significant commercial importance. Two common forms of eutectics are lamellar and rod eutectics. The current model of the selection of either rod or lamellar eutectic in directional solidification is based on the competitive growth concept which compares the interface temperature of each morphology growing under steady-state conditions and assumes that the morphology with a higher interface temperature will be selected. The result predicts a sharp transition condition which depends on the volume fraction of the minor phase f_α and on the relative interface energy contributions for rod and lamellar eutectic [1–3]. This model assumes that rods and lamellar structures have unique spacing which corresponds to their respective minimum undercooling values. However, experimental studies show that the transition is diffuse, and both rod and lamellar eutectics have been observed to coexist over a finite composition range. Liu et al. [4] extended the basic competitive growth model to incorporate the stable range of spacing and predicted the presence of a rod–lamellar coexistence region over a range of compositions. These models, however, are based only on the relative interface temperatures, and the spacing is assumed to adjust rapidly to conform to the lower undercooling value. It is now well accepted that the morphological transitions should be based on the stability analysis, so that the fastest growing wavelength of perturbation on an unstable lamella will correspond to the resulting rod spacing. The conditions for the onset of instability on a lamella to form rods can be obtained through a detailed linear stability analysis or through critical experimental studies.

The aim of this paper is to present detailed experimental studies in the Al–Cu system to characterize both the steady-state eutectic morphologies and the dynamics of the transition between rod and lamellar eutectics which

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1359-6454/$36.00
doi:10.1016/j.actamat.2011.01.050

are based on morphological stability considerations. Two types of experiments are carried out over a range of composition and velocity in the hypoeutectic region of the phase diagram. In the first set of experiment the selection of microstructure under steady-state growth condition is determined to characterize the presence of lamellar, rod or mixed eutectic. These experiments are carried out in cylindrical capillary samples 0.8 mm in diameter, in which diffusive growth is present. In the second set of experiments, a variation in composition is established in the radial direction, and the effect of varying composition on the dynamics of the transition is characterized. The latter set of experiments is done in bulk samples 5.5 mm in diameter in which a radial composition variation is established due to the presence of convection. The variation in composition is measured experimentally, and the effect of composition or the volume fraction of the minor phase on eutectic morphologies and on the dynamics of instability is characterized. It is found that a given lamella becomes unstable with a wavelength that is related to the local lamellar spacing, and the fastest growing unstable wavelength is equal to 1.1547 times the lamellar spacing. Furthermore, the instabilities in adjacent lamellae are found to be out of phase, so that the resulting rods form a hexagonal array. The dynamic process of lamellar instability and the relationship between the local lamellar spacing and the resultant rod spacing is then incorporated into the lamellar–rod transition condition to characterize quantitatively the different regimes in which only lamellar, only rod and mixed rod/lamellar eutectics will be present. Based on the experimentally observed rod and lamellar spacing, a method is proposed to evaluate the relative contributions of the interface energy terms in the eutectic growth models. The results of this model are then compared with the experimental observations in the Al–Cu system.

2. Experimental procedure

Experiments are carried out in the Al–Cu system in which the eutectic composition is 33.2 wt.% Cu, and the eutectic consists of α-Al and a compound phase Al_2Cu, which is referred to as the θ phase. Hypoeutectic alloys of compositions ranging from 16.5 to 33.2 wt.% Cu are used in this study. Higher compositions in the hypereutectic region were also examined to observe the formation of α rods in the θ matrix.

For hypoeutectic alloys, the rejected solute is copper, which is heavier than Al, so that fluid motion is caused by the radial temperature gradient which gives rise to composition variation in the radial direction [5]. As demonstrated in several theoretical and experimental studies [5–9], the fluid flow effect in the present experimental system is found to become negligible in hypoeutectic Al–Cu alloys when a capillary sample $\leqslant$0.8 mm ID is used, so that the morphological evolution under diffusive growth conditions can be characterized as a function of composition and growth rate. Directional solidification experiments are thus carried out using two concentric tubes, as described earlier [6–9]. For this sample configuration, fluid flow effects can be reduced significantly to give diffusive growth in the inner capillary tube, 0.8 mm in diameter, whereas fluid flow effects are significant in the concentric region, which is referred to as the bulk region. The outer tube used in this study has a diameter of 5.5 mm, so that the concentric region is $\sim$2.1 mm wide radially, and a significant fluid flow is observed in this region which gives rise to a steady-state radial concentration profile, as demonstrated by Lee et al. [6], who characterized the effect of convection on eutectic growth. By examining the microstructural changes in the radial direction due to composition or volume fraction variation, the dynamics of rod–lamellar transition is established.

In hypereutectic alloys, the rejected solute, Al, is lighter, so that a strong double diffusive convection is present which can be approximated by the boundary layer model. In this case, the interface is planar at low growth rates, and the composition in the radial direction does not vary, but the composition of the bulk region increases with the increase in solid fraction so that no steady-state growth will be present. Thus, all quantitative studies were carried out in hypoeutectic and eutectic alloys only. Trivedi et al. [5] discussed in detail the difference in convection effects between a heavier and a lighter solute.

Solidification microstructures are investigated using optical metallography and scanning electron microscopy (SEM) techniques. Composition profiles in the solid in the radial direction are measured by electron probe microanalysis. Since the microstructure is composed of fine eutectic, composition measurements are averaged on a 100 μm line-scan (parallel to the quenched interface) with a beam size $\sim$2 μm in diameter. The standards of Al–4.0, 23.0 and 32.7 wt.% Cu are first determined by wet chemical analysis and then used to improve the accuracy of the composition measurements. Several composition measurements were carried out in each sample, and the experimental error for composition measurement was determined from a statistical test/retest method as ±0.2 wt.% Cu.

Microstructures are observed with a Zeiss microscope equipped with a high-resolution digital camera and with SEM. SEM images are more appropriate for spacing measurement and for calculations of the area fractions of rod and lamellar eutectic regions. The analysis of microstructures is conducted with ImagePro software, which has built-in functions of counting the number of relevant phases based on the contrast (different gray-scales of the two phases) to calculate the area, mass or geometrical center and the aspect ratio of the objects in the field of interest. In the region of rod/lamellar coexistence, there are some θ phases which assume neither rod nor perfect lamellar morphology. They are sometimes termed broken lamellar elliptical rods [10].