Eutectic spacing and faults of directionally solidified Al–Al$_3$Ni eutectic

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Received 14 June 1999

Abstract

The Al–Al$_3$Ni eutectic was directionally solidified at a thermal gradient of 4.5 K/mm in a vacuum Bridgman-type furnace in order to study eutectic spacing selection criterion. The microstructure was examined in transverse and longitudinal sections and the interrod spacings were measured at different growth velocity. It has been shown that the interrod spacing is not unique and displays a limited range for rodlike Al–Al$_3$Ni eutectic alloy. The initial growth velocities are not responsible for the eutectic spacing range, while such faults as branching, ending and diameter change have a significant influence on the eutectic spacing adjustment. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Eutectic spacing; Faults; Al–Al$_3$Ni eutectic

1. Introduction

The development of controlled eutectic structures by the directional solidification technique is important from the technological viewpoint, since eutectic structures generally give rise to a fine periodic microstructure and thus exhibit improved mechanical properties. The mechanical properties of a given eutectic alloy largely depend upon the microstructure. Two important parameters of eutectic structure, which can be controlled experimentally, are the relative volume fractions of the two phases and the eutectic spacing. The volume factions are controlled to some extent by the composition of the alloy [1], whereas the eutectic spacing is controlled by the imposed growth rate. Thus, it is necessary to establish a proper relationship between the eutectic spacing and the controlling parameters and study the eutectic spacing selection criterion. The J–H model predicts a wide range of spacings for steady-state growth at a certain growth velocity [2]. However, the experimental studies show that only a limited narrow range of eutectic spacing is actually selected by the system at a given growth velocity [3–8]. Although many efforts have been made in the study of the spacing selection mechanism, the principle that controls the selection of spacing over this narrow band has not been established. Many investigations for eutectic spacing have been performed in the lamellar eutectics, whereas there is little concern for the relationship between the interrod spacing range and the controlling parameters in rod-like eutectic alloy. This paper aims to investigate the variation of the interrod spacing range with growth velocity and the influence of faults on the spacing in Al–Al$_3$Ni rod-like eutectic.

2. Experimental procedure

The samples were prepared from pure Al and Ni of 99.99% purity. Alloys of eutectic composition (5.95 wt% Ni) were obtained by melting these elements in a vacuum induction furnace in a MgO crucible. The samples were cast into rods of 8 mm diameter in graphite, and then machined to about 6.0 mm diameter. The directional solidification experiments were carried out in a vertical vacuum Bridgman-type resistance heated furnace with a vacuum of 1.0 Pa in order to prevent any oxidation, as described in Ref. [9]. The samples were contained in a graphite tube of 6.2 mm/9.0 mm (ID/OD) in the center of the furnace. The lower part of the tube was placed into a water chamber in order to ensure a well defined thermal gradient. The maximum temperature in the furnace was 800°C, and the thermal gradient at the solid/liquid interface was 4.5 K/mm. At the beginning of the experiments, the samples were heated to a pre-determined temperature. After a 100 min holding time to stabilize the thermal conditions, the samples were lowered and directionally solidified at a given pulling velocity. Then, the microstructure was examined on the transverse sections and longitudinal sections. The interrod spacings were measured by metallographic observation of
transverse sections of these samples taken from the region of steady-state growth. The spacing distributions were determined by individually measuring the distance of each nearest neighbor for individual rods. Approximately 300–500 measurements were made on each of the samples. The average spacings were the average value of measurements.

3. Experimental results and discussion

The directionally solidified Al–Al$_3$Ni eutectic is composed of the Al phase and Al$_3$Ni phase which is embedded in the Al matrix in rod-like form, as shown in Fig. 1. The regularity and shape of the Al$_3$Ni phase are variable with the solidification conditions. The morphology of the Al$_3$Ni phase transferred from lamellar-like to rod-like with the increase of the growth velocity. The spacing measurements indicated that the spacing in the Al–Al$_3$Ni system is not unique, but displays a limited range. The results of the inter-rod spacing measurements at different growth velocity are given in Fig. 2. The spacing ranges decrease and become narrow when the growth rates increase. The variation in the average eutectic spacing, maximum eutectic spacing and the minimum eutectic spacing with the growth rates for the Al–Al$_3$Ni system is shown in Fig. 3, which can also be written in the following form:

$$\lambda_{\text{Max}} = 101.1 \quad \lambda_{\text{Ave}} = 46.1 \quad \lambda_{\text{Min}} = 10.7 \quad (1)$$

In order to investigate the influence of the initial growth velocity on the inter-rod spacing distributions, initial growth

Fig. 1. The microstructure in the transverse sections of Al–Al$_3$Ni eutectic directionally solidified at different rates of: (a) 1.5 µm/s; (b) 2.8 µm/s; (c) 5.6 µm/s; and (d) 10 µm/s; at a thermal gradient of 4.5 K/mm.

Fig. 2. Effect of growth velocities on distributions of inter-rod spacing of Al–Al$_3$Ni eutectic at a thermal gradient of 4.5 K/mm.

Fig. 3. Variation in the maximum, average and minimum eutectic spacing with pulling velocities in the Al–Al$_3$Ni system at a thermal gradient of 4.5 K/mm.

Fig. 4. Effect of initial growth velocities on eutectic spacings distributions in Al–Al$_3$Ni eutectic at a thermal gradient of 4.5 K/mm (F1: $V_1 = 6.9$ µm/s to $V_2 = 4.2$ µm/s; F2: $V_1 = 0.0$ µm/s to $V_2 = 4.2$ µm/s; F3: $V_1 = 1.4$ µm/s to $V_2 = 4.2$ µm/s)
velocity change experiments were performed. Firstly, an Al–Al\textsubscript{3}Ni eutectic alloy was directionally solidified at 4.2 μm/s until a steady-state interface growth was achieved. The distribution of spacing was measured. Next, an experiment was carried out in which alloy was first directionally solidified at 1.4 μm/s to stabilize the growth state, and then the growth rate was increased to 4.2 μm/s, the stable eutectic spacing distribution curve for the region solidified at 4.2 μm/s was characterized. Finally, the alloy was first directionally solidified at 6.9 μm/s for sufficient time to establish the steady-state condition. Then the growth rate was decreased quickly to 4.2 μm/s and the solidification was continued until a steady-state growth was re-established. The spacing distribution curve was obtained from inter-rod spacing measurement in the region where the steady state was established at 4.2 μm/s velocity. These results of three runs are shown in Fig. 4. Note that the inter-rod spacing distribution curves in each of these three experimental runs were nearly identical to that for the slow velocity of 4.2 μm/s, which indicates that the different initial velocity is not responsible for the observed distribution of spacing.

During the period of directional solidification, the growth state of the eutectic changed when the growth velocity was changed from one certain value to another. This induced the microstructure and eutectic spacing to be adjusted to achieve another steady state through some mechanism. The microstructure was examined in a sample for which the growth rate was changed from 1.4 to 4.2 μm/s. The specimen, which was cut from the region where the spacing is adjusting, was ground, polished and etched with HF + H\textsubscript{2}O solution. It was found by the SEM observation that there are many such faults as branching, ending, diameter change and connecting of Al\textsubscript{3}Ni phase, as shown in Fig. 5a–c. SEM observations were also performed on the specimen in the stable growth state. Faults of the Al\textsubscript{3}Ni phase also exist in the stable solidified microstructure. The size distribution of Al\textsubscript{3}Ni phase in the transverse section under steady state at different growth velocity is shown in Fig. 6 and the branching of Al\textsubscript{3}Ni phase is shown in Fig. 5d. However, the number of the faults in steady-state growth is much smaller than that in the unstable growth states, which indicates that the formation of all kinds of faults in the directionally eutectic alloy is important for the eutectic spacing adjustment.

4. Conclusions

In summary, the inter-rod spacing is not a unique value but displays a limited range for the rod-like Al–Al\textsubscript{3}Ni eutectic alloy. The spacing range decreases with the increase of the growth velocity. The initial growth rate change experiments show that the different initial growth rates are not responsible for the eutectic spacing range, while such faults as branching, ending and diameter change have a significant influence on the eutectic spacing adjustment.

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