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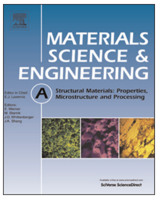

Influence of dendritic solute segregation on tensile properties of Al–4 mass% Cu alloy castings consisting of single columnar crystal

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ABSTRACT

Al–4 mass% Cu alloy ingots consisting of single columnar crystal were prepared and subjected to tensile testing. Tensile properties, such as the 0.2% offset proof stress, tensile strength and elongation, were obtained in directions parallel and perpendicular to the growth direction of the columnar crystal. The tensile properties in the growth direction of the as-cast specimen decreased with increasing primary arm spacing λ_p, but after solution heat treatment, they became independent of λ_p. On the other hand, tensile properties perpendicular to the growth direction decreased with increasing λ_p before and after heat treatment. From these results, it was concluded that the tensile properties in the growth direction were controlled by solute segregation, but those perpendicular to the growth direction were largely influenced by casting defects, such as cavities. The as-cast yield strength σ_y in the growth direction was analyzed based on a continuously distributed dislocation model considering solute distribution in the primary arm, and the relationship $\sigma_y = \sigma_{const} + kG^{1/8}\lambda_p^{-1/4}$ was obtained, where σ_{const} and k are constants, and G is the temperature gradient around the dendrite tip. The calculated yield strength was compared with the 0.2% offset proof stress $\sigma_{0.2}$ of the as-cast specimen. Also, the yield strength perpendicular to the growth direction was analyzed based on fracture mechanics, and the relationship $\sigma_y = K_y\,(\pi l_T/2)^{-1/2}$ was obtained, where K_y is the stress intensity factor at yielding, and l_T is the length of the cavity perpendicular to both the growth and the tensile directions and is related to λ_p. The calculated yield strength was compared with $\sigma_{0.2}$ of the as-cast and the heat treated specimens. The estimated value of K_y was comparable with the fracture toughness K_{IC} reported in previous work.

1. Introduction

Cast alloys have various grain structures, and considerable amount of second phases and casting defects, all of which have a significant effect on their mechanical properties. Considering complicated contributions of the cast structures on the mechanical properties, Yoon et al. [1] conducted a multivariable analysis and obtained the contribution ratio of cast structures on the tensile properties of cast alloys. However, the cast structures are related to each other, such that when the molten alloy is solidified with a lower cooling rate, both the grain size and the dendritic arm spacing become larger in the castings. On the one hand, it is well known that the yield strength of the wrought alloy has a linear relationship with the inverse square root of the grain size, which is referred to as the Hall–Petch relationship [2,3]. On the other hand, it is also known that the tensile properties of cast alloys are largely affected by the dendritic arm spacing rather than the grain size, and the relationship between the yield strength and the dendritic arm spacing is related to the Hall–Petch relationship [4–13]. Kumai et al. [4] explained that in the case of Al–Si alloy castings, the eutectic Si particles surrounding the dendritic arms act as a barrier against the movement of dislocations in the arm to establish the Hall–Petch relationship between the yield strength and the secondary arm spacing. However, for other alloys, such as Al–Cu and Zn–Al, which are not surrounded by second phases, it has not been verified why the Hall–Petch relationship holds true. Moreover, it has been reported that the tensile properties decrease linearly with the secondary arm spacing [14,15], that the tensile strength increases with the inverse of the secondary arm spacing or with the inverse power of the primary arm spacing [16,17], and that the tensile properties decrease with increasing secondary arm spacing but the Hall–Petch relationship does not hold true [18]. It has also been reported that there is no relationship between the tensile properties and the dendritic arm spacing [19]. Recently, Campbell [20] reported that the oxide layer called the bifilm largely affects mechanical properties of the cast alloys, and the Hall–Petch relationship does not hold true for the relationship between the tensile properties and the dendritic arm spacing. These results

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show that there are many issues to be solved concerning the relationship between the tensile properties and the cast structures.

Meanwhile, the relationship between the tensile properties and the cast structures is related to the grain structures in the cast alloy. In an alloy consisting of an equiaxed structure, the crystal grains show a random distribution so the tensile properties of the alloy are isotropic. When the alloy consists of a columnar structure, however, the crystal grains are arrayed in a particular orientation, and the tensile properties become anisotropic. In the previous work [21], tensile testing was carried out on Al–4 mass% Cu alloy ingots consisting of single columnar crystal. When the specimen was pulled in the growth direction of the columnar crystal, tensile properties decreased with increasing primary arm spacing, but after solution heat treatment, they took almost constant values. From these results, it was concluded that the tensile properties in the growth direction were controlled by dendritic solute segregation. On the other hand, when the specimen was pulled perpendicularly to the growth direction, the tensile properties decreased with increasing primary arm spacing before and after heat treatment. This result strongly suggested that the tensile properties perpendicular to the growth direction were largely affected by casting defects appearing along the dendritic cell boundaries. However, the previous work [21] did not include theoretical discussion on the relationship between the tensile properties and the primary arm spacing. Theoretical verification of the effects of the cast structures on the tensile properties of cast alloys consisting of single columnar crystal may also contribute to understanding the tensile properties of cast alloys consisting of equiaxed grains.

In the present work, previous results on the tensile properties of cast alloys consisting of single columnar crystal [21] are summarized, and then physical models are presented on the yield condition; the yield condition in the growth direction is discussed based on a continuously distributed dislocation model, and that perpendicular to the growth direction is discussed based on fracture mechanics, such that the cast alloy yields when a stable crack initiates at the cavity. Analytical results are compared with the experimental ones.

2. Experimental procedure and results

The experimental procedure and the results presented in the previous work are summarized in this section. Details are given in Ref. [21].

2.1. Experimental procedure

First, ingots consisting of columnar crystals were produced as follows. Molten Al–4 mass% Cu alloy was prepared using 99.99% pure aluminum and Al–50 mass% Cu alloy. After degassing with argon gas, molten alloy heated at 993 K was poured into a sand mold, which was preheated at 1073 K and set on a copper chill plate in the furnace. Upon completion of pouring, the furnace was switched off and the copper plate was cooled by water to directionally solidify the molten alloy. Ingots of 130 mm in width, 60 mm in depth and 240 mm in height were obtained. Then the longitudinal section of the ingot was polished and etched to confirm that columnar crystals grew to the top of the ingot. This ingot was labelled the 0th ingot. Then, as shown in Fig. 1, a block of 50 mm in width, 60 mm in depth and 130 mm in height was cut out from the 0th ingot so that the top surface of the block was parallel to the growth direction of the 0th ingot, and V-shape notches were introduced on the top of the block so that the upper part of the block would melt uniformly when the molten alloy was poured. This block, referred to as the 0th seed, was set in the sand mold in the furnace, and then the molten alloy was poured on the seed. Five minutes after pouring, the furnace was switched off and the copper plate was cooled by water for unidirectional solidification. The obtained ingot was the same size as the 0th ingot, and was referred to as the 1st ingot. This procedure was repeated to obtain the 4th ingot. A typical longitudinal section of the 4th ingot is shown in Fig. 2. Through observation of the longitudinal and cross sections, it was confirmed that the 4th ingot consisted of almost one columnar crystal.

At different positions of the 4th ingot, tensile specimens of 40 mm in gauge length and $10 \times 10\ \text{mm}^2$ in cross section were prepared parallel or perpendicular to the growth direction of the columnar crystal. Microstructures in the as-cast tensile specimens are shown in Fig. 3. The tensile direction of the specimen parallel to the growth direction (a) is parallel to the growth orientation

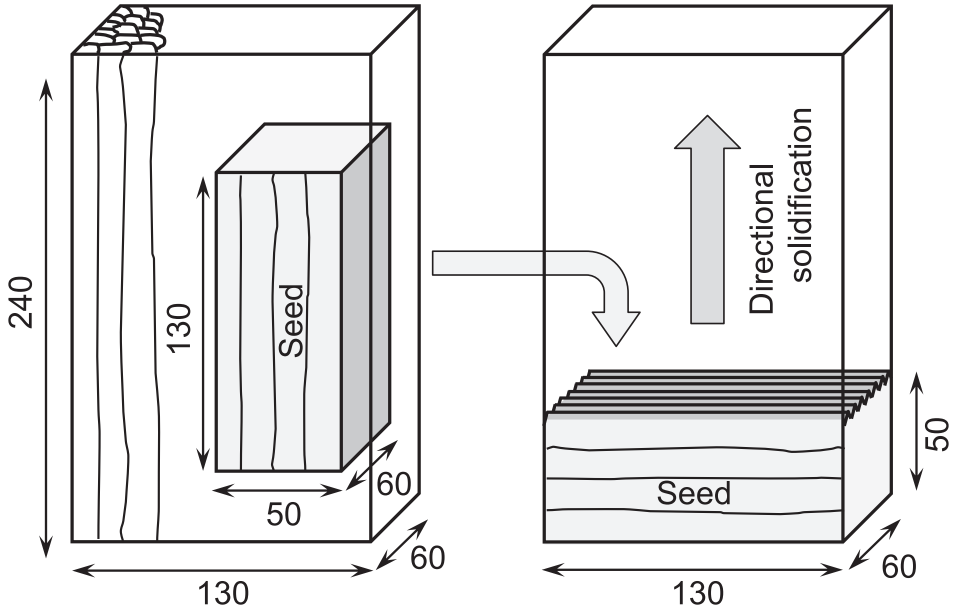

Fig. 1. Procedure for production of seed (a) and directional solidification from seed (b).