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Influence of the Feathery Crystal on the Tensile Behavior of Commercial Pure Aluminum

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The structure and tensile behavior of an abnormal feathery crystal on the AA1N30 commercial pure Al slab cast by semi-continuous direct-chill process was investigated. The result shows that the lamellar feathery crystal has a {111} twin plane and an either <112> or <110> twin axis. Tensile deformation behavior of feathery crystal was strongly dependent on the tensile axis of specimens being parallel or vertical to the twin axis. This kind of anisotropic tensile behavior can be explained based on the difference of the Schmid factor, which was calculated on the relationship of tensile axis and grain orientation.

1. INTRODUCTION

During semi-continuous Direct-Chill (DC) casting, an extraordinary microstructure of feathery crystal, which is distinctly different in morphology from the normal equiaxial grain, can frequently be found in Al alloys.(1-3) The typical feathery crystal features an elongated lamellar structure.(4-6) Each lamella consists of two crystals in twin orientation, with a twin boundary (111) located along the symmetric plane of the lamella. This structure is highly undesirable to Al sheets because it will produce a quite unattractive streak defect on the Al surface after anodizing.(1-3) The appearance of feathery crystal is usually promoted by high casting temperature, fast casting speed, and rapid secondary cooling rate, i.e. raised temperature gradient.(4) To overcome this problem, the modification of the casting parameters and the addition of grain refiners can both be used for a foundry, although the latter is easier and simpler.(3) However, most studies on the feathery crystal have focused on its growth mechanism. The tensile behavior related to such an abnormal crystal has not been examined in detail. Based on the above, a commercial pure Al alloy (AA 1N30), which is susceptible to the feathery crystal, was preferentially used in this investigation. The crystallographic orientation, structural characteristic, and boundary character of the feathery crystal were analyzed first. A special attention was then paid to their influence on the tensile behavior of the Al slab. The differences of the tensile strength and total elongation are also discussed.

2. EXPERIMENTAL METHOD

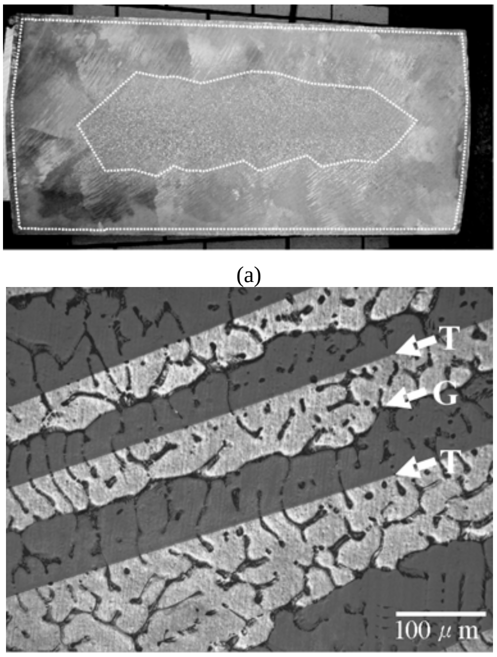
The material used in the present study was a commercial DC-cast AA 1N30 sheet ingot. The chemical composition of the material is given in Table 1. Samples for microstructural observation were taken from the steady state area, nearly 200 mm from the bottom of slab. Slices were sectioned 10 mm in thickness normal to the casting direction, and prepared for subsequent investigation of the macrostructure and microstructure. The slices were etched in a solution consisting of 45% HCl, 15% HNO_3, 15% HF, and 25% distilled water for 20 minutes at ambient temperature to reveal the abnormal feathery crystal structure. The morphologies of those structures were then examined by polarization optical microscope (POM). The crystallographic orientation and boundary character of the feathery crystal were characterized by the use of electron backscattering diffraction (EBSD) and transmission electron microscopy (TEM). Both detailed specimen preparations have been described elsewhere.(7) The tensile specimens were machined from the feathery crystal structure of the Al slab with the tensile axis parallel to the long axis (twin axis), with the tensile axis vertical to the long axis, and by random selection without any specific orientation. Tensile tests were conducted on a MTS testing machine with a constant cross speed of 5 mm/min.

Table 1 Chemical composition of AA 1N30, wt%

Element	Si	Fe	Cu	Mn	Mg	Ti	Al
Wt %	0.07	0.5	0.002	0.003	0.003	0.025	Bal.

3. RESULTS AND DISCUSSIONS

The cross section of an Al slab with an abnormal structure after etching treatment is present in fig. 1a. It shows that a lamellar structure consists of elongated grains, whose grain size varies from micrometers to several millimeters along the long axis direction. Another typical feature of feathery crystal is a twin boundary as shown in fig. 1b. According to the literatures(8-9), the material with a twin structure usually exhibits an anisotropic mechanical property that depends upon the orientation between the loading axis and the twin axis. This implies that the mechanical properties of Al slabs with the feathery crystal might differ from the normal Al slabs (equiaxial grain structure).

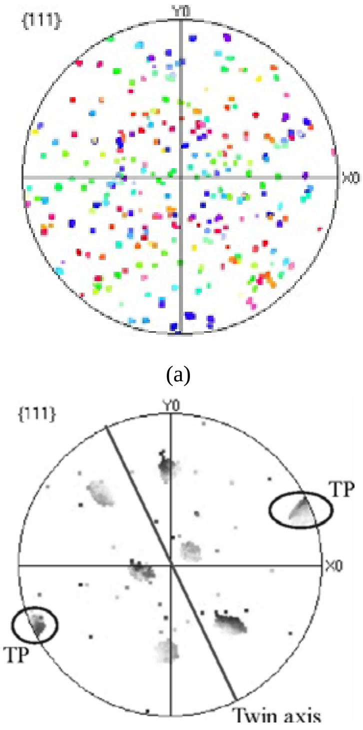


(a)

(b)

Fig. 1. (a) The cross section of an Al slab shows a typical feathery crystal structure, which is outlined by the dashed-lines. (b) Optical micrograph of the feathery crystal structure, where the T is the twin boundary and the G is the general grain boundary.

The local crystallographic orientation of a normal Al slab was examined by EBSD technique. The distribution of orientations of the measuring points was expressed in a {111} pole figure (fig. 2a), which clearly indicates a random distribution. In comparison, an Al slab with a feathery crystal exhibits a strongly twinned nature with mirror symmetry as shown in fig. 2b. The direction of the twin axis was determined to be [110] through the standard pole figures of texture. Therefore, the {111} twin plane was obtained from the pole of the stereographic projection normal to the direction of the twin axis.

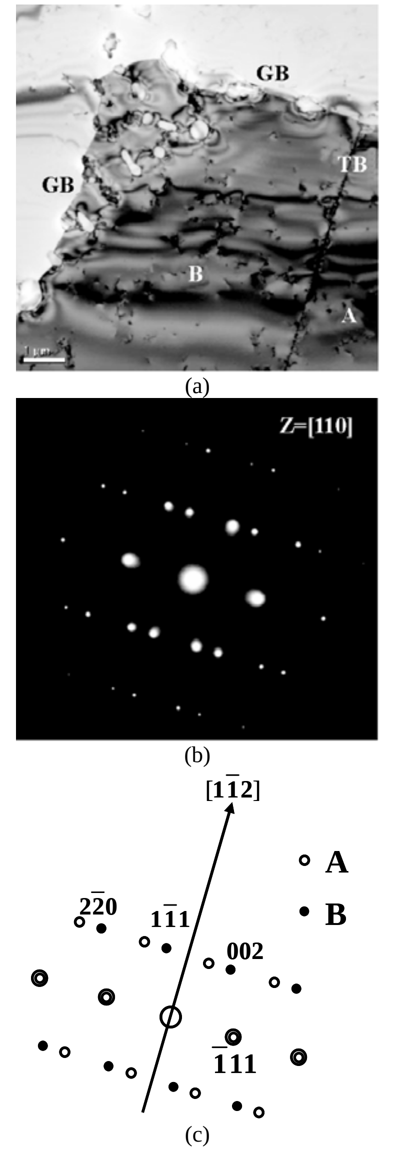


(a)

(b)

Fig. 2. The {111} pole figure of (a) the normal Al slab with a random distribution; and (b) the feathery crystal showing a preferred orientation with mirror symmetry (indicated by the red-line), where the TP is the twin plane.

A typical microstructure of feathery crystal produced via DC-casting is given in fig. 3a, which shows a lamellar structure consisting of a twin boundary and a general grain boundary. Principally, a straight line without any precipitate observed in TEM bright field (BF) image was the twin boundary, while a curved line with many precipitates was the general boundary. The nature of the twin boundary was characterized via selected area diffraction pattern (SADP) of fig. 3b, whose schematic illustration with corresponding indices is also given in fig. 3c. The zone axis of SADP was identified to be nearly [110], and then the $[1\bar{1}2]$ direction of the twin boundary (twin axis) was also determined. Summarizing the results of EBSD and TEM, it can be concluded that the feathery crystal has two possible twin axes, <110> or <112>, which are the same as that in the literatures.(4-6) Hence, the crystallographic orientation of the feathery crystal of the POM image can be easily defined according to the above results (fig. 4). It illustrates that the direction parallel to the twin boundary might be either <110> or <112>, while the direction normal to it is the <111> twin plane.



(a)

(b)

(c)

Fig. 3. Typical microstructure of the feathery crystal: (a) TEM bright field image, where the TB is the twin boundary and the GB is the general boundary; (b) the SADP of (a); and (c) corresponding schematic illustration of the SADP.

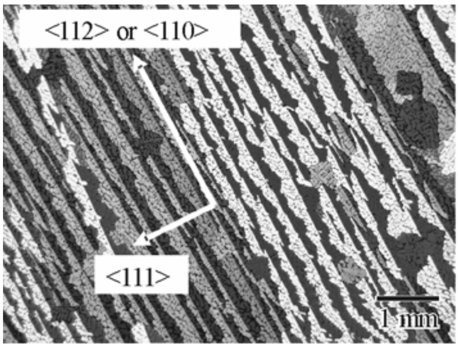


Fig. 4. Optical micrograph of the feathery crystal structure showing the direction vertical to the twin axis is (111) twin plane. The direction parallel to the twin axis is either <112> or <110>.

The stress-strain curves obtained by tensile tests are shown in fig. 5. The feathery crystal (F) exhibits a continuous strain-hardening behavior identical with the normal Al slab (N) with an equiaxial grain structure. However, the strength and the total elongation of feathery crystal were quite different from those of normal Al slab. These results of tensile properties are summarized in Table 2, in which the data of duplicate specimens with a good reproducibility are presented for each condition. For the feathery crystal specimen, both the yield stress (YS) and the ultimate tensile stress (UTS) of the random selection without any specific orientation (Fr) were higher than those of the N, while the total elongation was only half of the latter. Comparing the specimens of N, Fp (the tensile axis parallel to the twin axis), and Fv (the tensile axis vertical to the twin axis), the strength of the Fv was higher than all the other specimens, while the total elongation of the Fv was only 50% of the N and the Fp. As a consequence, the tensile behavior of the feathery crystal exhibits a strong dependence upon the angle of the tensile axis with respect to the twin axis.

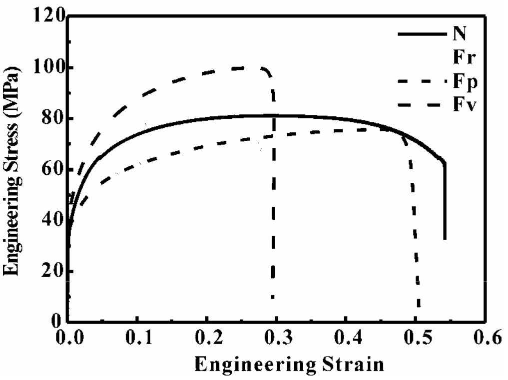


Fig. 5. Typical stress-strain curves of specimens with different loading angles obtained at ambient temperature, where N denotes the normal equiaxed grain structure, Fp the tensile axis parallel to the twin axis, Fv the tensile axis vertical to the twin axis, and Fr the random selection without any specific orientation.

Table 2 Summary of the tensile properties obtained at ambient temperature

Specimen	Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)
N	37 (±1)	81(±1)	54(±1)
Fr	43(±2)	83(±1)	32(±4)
Fp	39(±1)	76(±1)	46(±4)
Fv	50(±2)	102(±2)	26(±4)

The discrepancies of the tensile strength might be explained through a calculation of the Schmid factor. The assumption is that the feathery crystal was composed of the twin boundary entirely, and excluded the general grain boundary from the materials. According to the microstructure observations, the geometrical relationship between the tensile axis and the crystallographic orientation of the feathery crystal could be easily defined. For specimen Fv, the tensile axis was vertical to the twin axis, i.e. the load axis was the normal direction of the twin plane. Therefore, it can be concluded that the tensile axis was almost parallel to the <111> direction. On the other hand, the condition of the specimen Fp was much complicated because the tensile axis was parallel to the twin axis. As the aforementioned, there are two possible directions of the twin axes, <112>, and <110>, thus, the tensile axis of the Fp must be parallel to one of them. For specimen Fv, with a tensile direction $[\bar{1}11]$, there are six sets equivalent slip systems, $(\bar{1}1\bar{1})[011]$, $(\bar{1}1\bar{1})[\bar{1}01]$, $(111)[\bar{1}10]$, $(111)[\bar{1}01]$, $(\bar{1}\bar{1}1)[\bar{1}10]$, and $(\bar{1}\bar{1}1)[011]$, that can operate during tensile deformation. The Schmid factor for Fv was estimated to be 0.272. For specimen Fp (tensile direction was $[1\bar{1}2]$), only two sets equivalent slip systems, $(111)[0\bar{1}1]$, and $(\bar{1}\bar{1}1)[101]$, can be activated. But for another loading direction [110] for specimen Fp, there were four sets equivalent slip systems, $(111)[01\bar{1}]$, $(111)[10\bar{1}]$, $(11\bar{1})[10\bar{1}]$, and $(11\bar{1})[011]$, that can be activated. The Schmid factor of Fp for both directions was calculated to be 0.408. From the theory of critical resolved shear stress (CRSS) (10), the lower the Schmid factor is, the higher the loading stress is. As a result, the tensile strength of the specimen Fv was the highest of all.

The obvious difference in tensile ductility for the feathery crystal samples Fv and Fp might be attributed to the grain boundary character. As shown in the figure 3a, most hard-brittle second phases were preferred to precipitate on the general grain boundary results in an incoherent and weaker boundary structure. On the other hand, the twin boundary is regarded as a kind of special boundary with a coherent and stronger structure.(11) In addition, almost no second phase was found on it. Hence, the occurrence of fracture for a feathery crystal material would propagate along the weaker general grain boundary, particularly as the principal stress was perpendicular to such boundary. Consequently, the total elongation for specimen Fv was lower than that for specimen Fp.

4. CONCLUSIONS

(1) Through analyses of microstructure and grain orientation, the twin plane and its axis of the feathery crystal have been ascertained to be {111} and either <112> or <110> twin axis, respectively, in this study.

(2) Tensile deformation behavior of the feathery crystal was dependent on the tensile axis of the specimens being parallel or vertical to the twin axis. The strength and elongation of the parallel are 1.4 and 0.5 times those of the vertical, respectively.

(3) The anisotropy of the above tensile behavior can be explained based on the Schmid factor, which is lower when the tensile axis is vertical to the twin axis than when the tensile axis is parallel to the twin axis.

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