TEXTURE DEVELOPMENT DURING COLD ROLLING OF UNIDIRECTIONALLY SOLIDIFIED ALUMINUM

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ABSTRACT Texture development during cold rolling of unidirectionally solidified aluminum has been investigated. The starting materials had a {001}<100> cube texture and consisted of structures with grain boundaries parallel to the casting direction. They were cold rolled with two ways in which the rolling direction (RD) is parallel and perpendicular to the casting direction, i.e., the alignment of grain boundaries (GB). Because of the crystallographic symmetry of a cube texture, the starting samples before cold rolling have the identical initial texture. Therefore, the influence of aligned grain boundaries on the formation of rolling textures could be examined. In the case of RD//GB rolling, a {123}<634> orientation with some components is formed, being a main component of a pure metal type texture of rolled fcc metals and alloys. On the contrary, an initial cube orientation rotates around the transverse direction and a fiber texture with a main component of {012}<021> or {013}<031> orientation is formed in RD⊥GB rolling. The results obtained show that according to the alignment of grain boundaries on the basis of the rolling direction, cold rolling textures of the present material are quite different.

Keywords: *Unidirectionally solidified aluminum, Cube orientation, Cold rolling, Texture, Grain boundary*

1. INTRODUCTION

In the manufacture of aluminum thin sheets, several processes such as mechanical workings, homogenizing and hot rolling are usually required before the final cold rolling. If high quality thin-plate ingots are available, they can be directly cold rolled. Recently, a new continuous casting process using a heated mold has been developed [1]. This process makes it possible to produce thin-plate ingots, which are crack-free products with a smooth surface. Therefore, it can be expected that reducing the manufacturing processes and increasing the yield of products are achieved. However, since the ingots obtained by this process consist of a unidirectionally solidified structure, the cold rolled sheets have a pronounced anisotropy in mechanical property. Such an anisotropy is generally associated with crystallographic texture, so that from the practical point of view, it is necessary to know the texture development during rolling. There are a lot of studies on rolled single crystals and polycrystals, but much less is known about the rolling textures of unidirectionally solidified aluminum [2]. In the present study, unidirectionally solidified aluminum strips were cold rolled with two ways in which the rolling direction is parallel and perpendicular to the casting direction (i.e., aligned grain boundaries), and the textures after cold rolling were determined. In addition, texture formation has been discussed in conjunction with the

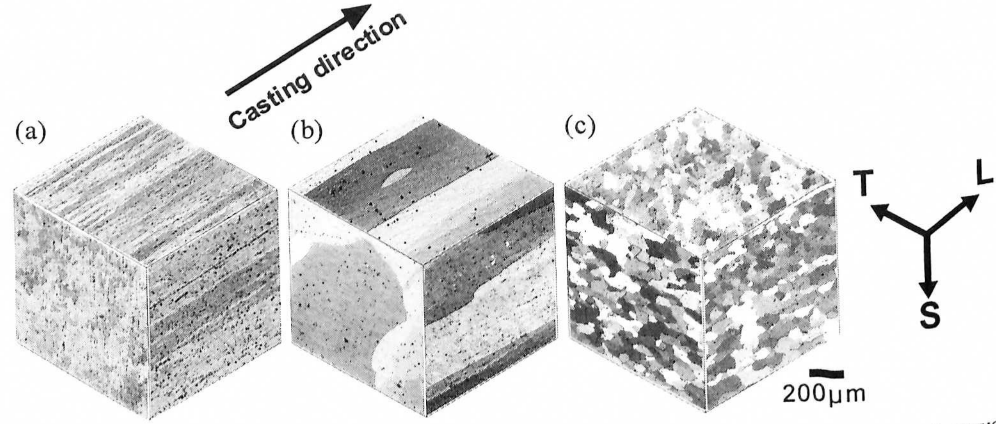


Fig.1 Optical micrographs showing grain structure of starting materials. T, L and S are transverse, longitudinal and short transverse directions, respectively. (a) Sample A, (b) sample B and (c) sample C.

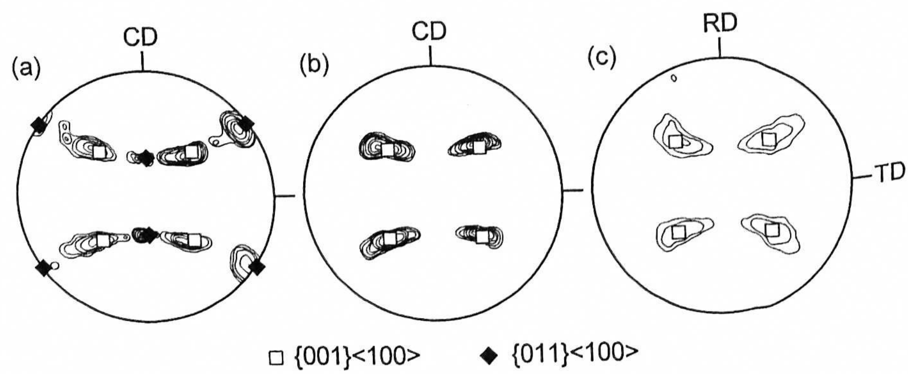


Fig.2 {111} pole figures of starting materials (CD: Casting direction).
(a) Sample A, (b) sample B and (c) sample C. (Levels: 2, 3, 5, 10, 15, 25, 35)

influence of grain boundaries on deformation.

2. EXPERIMENTAL

Materials used in this study were two kinds of unidirectionally solidified aluminum ingots with different chemical compositions (99.8 and 99.999mass%Al). For comparison, a commercial aluminum sheet (99.8%Al) was also employed. These materials shall be denoted as samples A, B and C, respectively. Both plate ingots (samples A and B) with a thickness of 3mm were produced by the continuous casting with an open type heated mold [1]. The sample C with the identical thickness was made by annealing of a cold rolled sheet. **Figure 1** shows grain structure of materials before cold rolling. As-cast materials (samples A and B) consist of a unidirectionally solidified structure with different grain sizes. The grain size of the sample B is larger than that of the sample A due to higher purity. The sample C is occupied with recrystallized equiaxial-grains. **Figure 2** shows {111} pole figures of the starting materials. All of them have a marked {001}<100> cube texture. Although the sample A has another component of a {011}<100> (Goss) orientation, the orientation density of {001}<100> is higher than that of {011}<100> (see **Fig.3**). From these materials, two plates of 50×40×3 mm^3 having different alignment of grain boundaries were cut out as shown in **Fig.4**, and then cold rolled up to 95% reduction in thickness

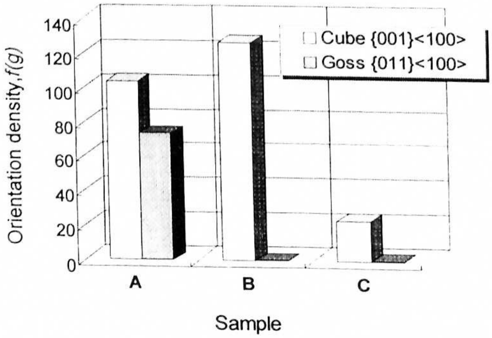


Fig.3 Orientation density of {001}<100> and {011}<100> in starting materials.

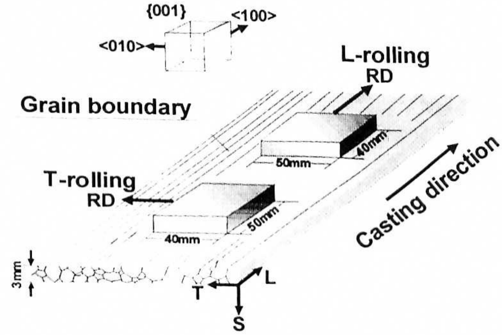


Fig.4 Sample preparation for cold rolling.

with two ways mentioned above, that is, (a) RD//GB and (b) RD⊥GB. For sample C, the rolling direction before annealing was conveniently used as a standard direction. They shall be called L-rolling (RD//GB) and T-rolling (RD⊥GB), respectively.

Textures in a central part concerning thickness of a sheet were measured by a conventional X-ray pole figure method. From the {111}, {100} and {110} complete pole figures, the orientation distribution function (ODF) with ghost correction was calculated using the iterative series-expansion method with positivity condition [3, 4].

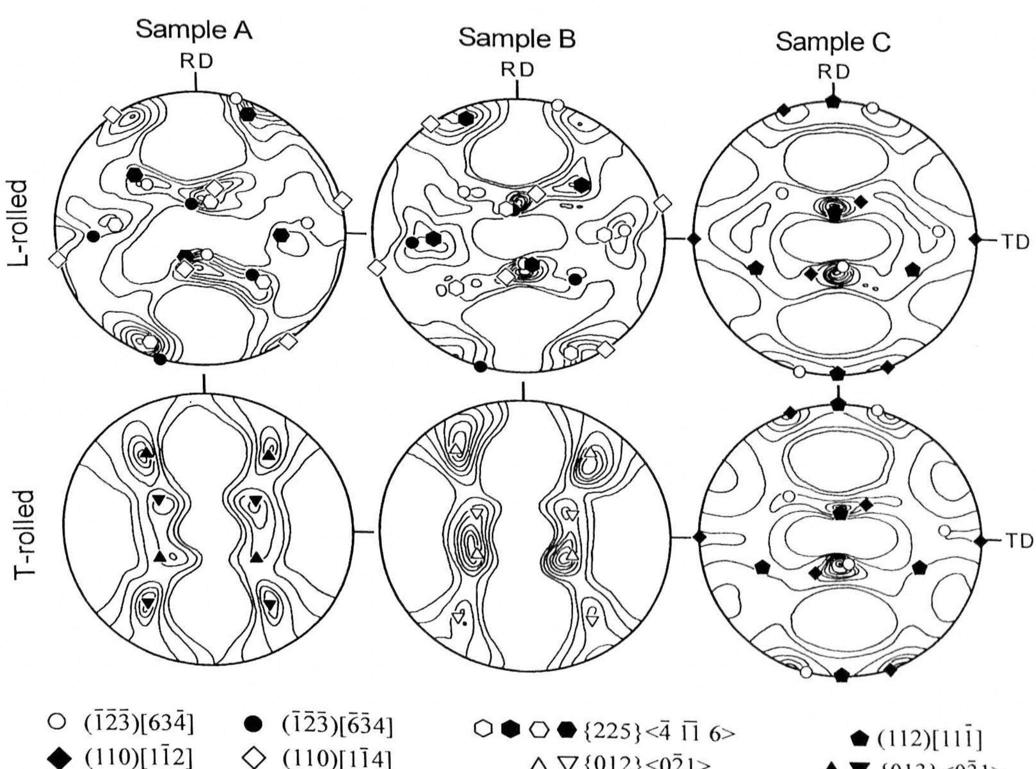
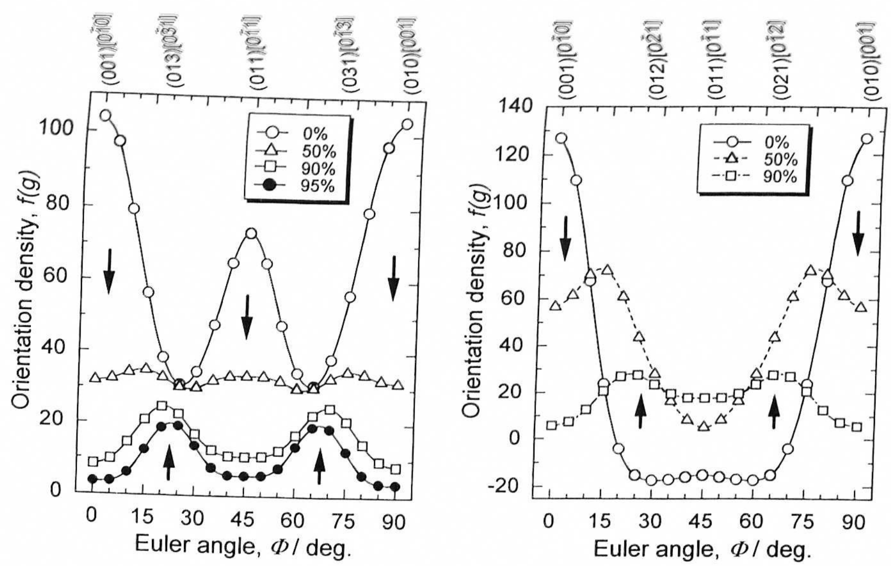


Fig.5 {111} pole figures after 90% cold rolling (Levels: 0.5, 1, 2, 3, 4, 5, 6, 8)

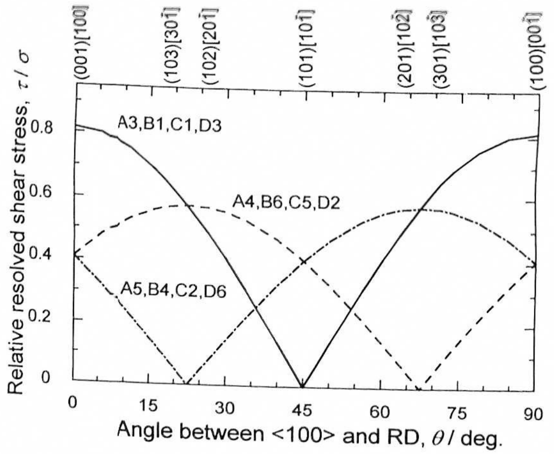


(a) (b)

Fig.6 Orientation density $f(g)$ along a line of φ_1=90° and φ_2=0° as a function of Φ for the ODFs of T-rolled samples. (a) Sample A and (b) sample B.

3. RESULTS and DISCUSSION

Figure 5 shows {111} pole figures after 90% cold rolling. L- and T-rolled samples before cold rolling have the identical texture, because of the crystallographic symmetry of a cube orientation. Sample C with an initial cube orientation and equiaxial-grained structure, shows a pure metal type rolling texture irrespective of the rolling direction. On the other hand, according to the alignment of grain boundaries on the basis of the rolling direction, cold rolling textures of unidirectionally solidified materials are quite different. Although there are differences in initial grain sizes and a secondary component of the starting textures between samples A and B (*see* Figs 1-3), no remarkable change in the final rolling textures is observed in both L-rolled and T-rolled samples. In the case of L-rolled samples, {123}<634>, {225}<4 11 6> and {011}<411> orientations are formed in samples A and B. In the pure metal type texture of rolled *fcc* metals and alloys, it is well known that the β-fiber develops at higher reductions of cold rolling. This fiber is represented by a continuous orientation tube that runs from {112}<111> (C), through {123}<634>, (S) to {011}<211> (Bs). The {123}<634> orientation is a main component of this β-fiber. The {225}<4 11 6> orientation is located in the neighborhood of the S position. By a 15° rotation around the sheet normal, the {011}<411> orientation is related to the Bs component. Only the C orientation is absent in the present rolling textures. Since observed components are mostly situated on the β-fiber, the deformation textures of L-rolled samples are fundamentally similar to those of equiaxial-grained polycrystal materials. On the contrary, the initial cube orientation rotates around [010] // TD and a fiber texture with a main component of a {012}<021> or a {013}<031> orientation is formed in the T-rolled samples. The texture development during T-rolling can be clearly shown in **Fig.6** by orientation density along a line of φ_1=90° and φ_2=0°. In the case of sample B, with increasing rolling reduction, the orientation density of the {012}<021> orientation becomes stronger while the initial cube orientation decreases. Also in the sample A, the



similar textural change occurs. Although a cube orientation is not altered by a 90° rotation around the sheet normal, the {011}<100> Goss orientation, which exists in only the sample A, is transformed into a {011}<110> orientation. The orientation density of starting {001}<100> and {011}<110> components decreases at 50% reduction. At 90% reduction, the {013}<031> orientation, which is close to {012}<021>, becomes to be a major component of the rolling texture. This orientation is still stable at 95% reduction.

Figure 7 shows variations of relative resolved shear stress of {111}<110> slip systems for observed orientations having a common [010] direction (i.e., TD). As shown in **Fig.8**, the symbols A-D and the numbers 1-6 represent {111} slip planes and <110> slip directions, respectively. If a stress system is assumed to operate in rolling in which σ is equal to the compressive stress parallel to the rolling plane normal and -σ is equal to the tensile stress parallel to the rolling direction [5], the resolved shear stress acting on the slip system is given by:

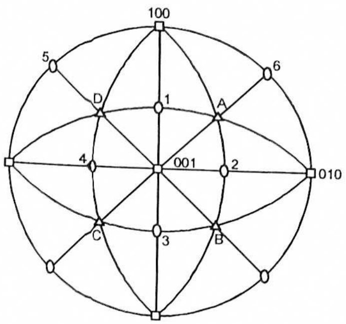


Fig.8 Standard (001) streographic projection. Slip planes, {111} (A-D). Slip direction, <110> (1-6).

$$\tau = \sigma(a_c b_c - a_t b_t) \qquad (1)$$

Here, a_c and b_c are the direction cosines of the normal direction with respect to a slip plane normal and a corresponding slip direction, and a_t and b_t are those of the rolling direction with respect the slip plane normal and slip direction. An exact cube orientation is stable for rolling deformation because the slip systems of A3, B1, C1 and D3 operate equally. However, if an orientation is shifted from an exact cube position, A3 and D3, or B1 and C1 operate preferentially so that (001)[100] rotates towards (102)[20$\bar{1}$]. By this crystal rotation around TD, the relative resolved shear stresses of A3, B1, C1 and D3 decrease and then those of eight slip systems (A3, B1, C1, D3, A4, B6, C5 and D2) are equal at the position between (103)[30$\bar{1}$] and (102)[20$\bar{1}$]. In fact, such orientations have been reported to be formed in a rolled aluminum single crystal with an initial orientation of {001}<100> [6]. Consequently, the deformation behavior during T-rolling is very single crystal-like in spite of the polycrystalline material. This suggests that the influence of grain boundaries on deformation is different with the alignment of them. To confirm the influence of grain boundaries on deformation, observations of slip lines on upper surfaces of sample A after 0.3% tensile deformation were carried out (**Fig.9**). As-cast samples were tensile deformed in the direction parallel and perpendicular to the grain boundaries, respectively. According to the alignment of grain boundaries based on the tensile direction (TD), the appearances of slip lines are different. Although slip lines of the TD⊥GB sample are linear, they are discontinuous in the vicinity of the grain boundary for the TD//GB sample. This indicates that grain boundaries

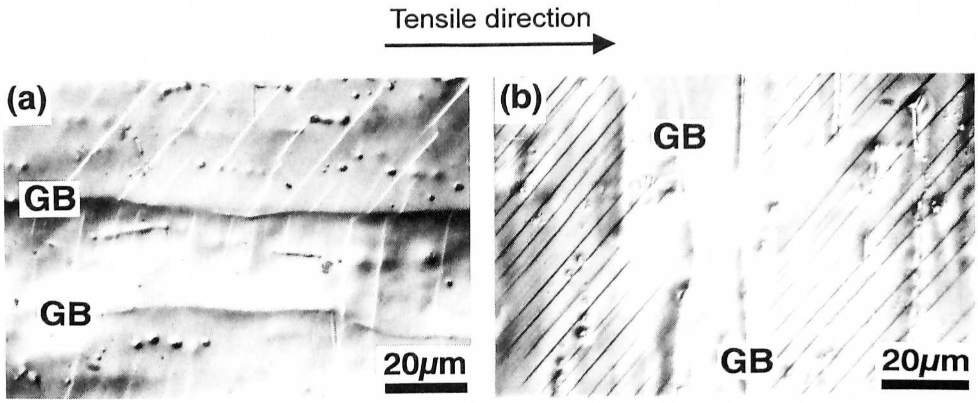


Fig.9 Optical micrographs after 0.3% tensile deformation of as-cast sample A, showing slip lines on upper surfaces. (a) TD//GB and (b) TD⊥GB (TD: tensile direction, GB: grain boundary).

parallel to the tensile direction influence deformation behavior strongly compared with those perpendicular to the tensile direction. Therefore, it can be thought that each grain of the T-rolled sample behaves as a single crystal, while grains in the L-rolled samples as well as those of polycrystalline materials are under constraint by grain boundaries. In summary, it is concluded that according to the alignment of grain boundaries, deformation behaviors during cold rolling of the present materials are single crystal-like and polycrystal-like, respectively.

4. CONCLUSIONS

Unidirectionally solidified aluminum with a {001}<100> cube orientation and an aligned boundary structure was cold rolled with two ways in which the rolling direction is parallel and perpendicular to the grain boundaries. Although the starting materials before cold rolling have the identical initial texture because of the crystallographic symmetry of a cube orientation, obtained cold rolling textures were quite different according to the alignment of grain boundaries (GB) on the basis of the rolling direction (RD). In the case of RD//GB, rolling textures are comparatively similar to those of polycrystalline materials, that is, a pure metal type rolling texture. On the contrary, a main component of the RD⊥GB sample is an orientation that is interpreted by a slip rotation during rolling of a cube oriented single crystal. The results obtained suggest that depending on the alignment of grain boundaries, deformation behaviors during cold rolling of the present material is polycrystal-like and single crystal-like, respectively.

Acknowledgements

The authors wish to express their appreciation to Osaka Fuji Co. and Showa Aluminum Co. for supplying materials. We also acknowledge Mr. H. Inoue provided useful discussions.

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