Preferred orientation formation in surface layer of aluminum sheet subjected to friction roll surface processing and temperature gradient annealing

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Abstract. Preferred orientation formation in surface layer of aluminum sheet subjected to friction roll surface processing (FRSP) and temperature gradient annealing has been investigated by SEM/EBSD analysis. FRSP imposed severe shear strain in the surface layer of the aluminum sheet, where the indentation was selected as 0.1mm and the feeding speed was set as 0.3mm/s. The annealing with steep temperature gradient in longitudinal direction was applied to the small specimen of 12mm long, 10mm wide and 1mm thick, which made microstructural evolution concentrated to the nearest layer to the surface. Shear strain more than 10 was imposed at a site of 14µm beneath the surface. The temperature gradient more than 20K/mm was attained even for aluminum which has high thermal conductivity. The {100} pole of ND/TD (FRSP plane/FRSP direction) FRSPed specimen showed very weak intensity of <001>//ND while the {111} pole implies <110>//TD. In contrast, the shear texture component {111}<110> mainly evolved in the specimen subjected to FRSP and the ordinary annealing. Evolution of the component {111}<110> after the temperature gradient annealing were compared with that after the ordinary annealing in consideration of stored strain energy in each crystallographic orientation.

1. Introduction
Severe plastic deformation (SPD) has attracted great interest owing to not only formation of extremely fine microstructure but also improvement of related properties. Numerous studies have been performed to produce ultrafine grains and make clear their formation mechanism in various SPD processes such as equal channel angular pressing (ECAP) [1], accumulative roll bonding (ARB) [2] and high pressure torsion (HPT) [3]. The crystallographic textures often appeared in the SPDed materials, because extremely large strain should be accompanied with necessary directional priority in slip deformation. The texture evolution during ECAP by only the two shear systems {111}<110> and {001}<110> (shear plane<shear direction>) in an Al-Zn-Mg-Cu alloy having a strong initial texture was reported [4]. To an aluminum single crystal ECAP was applied with consistence of theoretical shear plane and direction to crystal slip system [5], and moreover, a crystal plasticity finite element method model showed the textural change with the lattice rotation around the transverse axis of ECAP [6]. For ARB processed
aluminum the different local textures corresponding to the different microstructural regions were observed [7] and evolution of the textures with strong gradients was investigated in detail with experimental observations and numerical simulations [8]. However, attempts to the possibility of texture control by the SPD processes have been limited. On the other hand, it is well known that some of materials properties, such as corrosion, formability and wear, are strongly related to the surface microstructure and texture.

Friction roll surface processing (FRSP) has been attempted as another SPD process for the surface of the sheet materials in order to control microstructure and texture [9,10]. An attempt of FRSP to a commercial purity titanium sheet [9] revealed that a large plastic strain was imposed in the surface layer and caused grain refinement up to about 100nm. Characteristic shear textures were formed in the surface layer during FRSP and subsequent annealing, which was strongly related to the processing direction [9,10]. It should be noted that the shear texture formed in the FRSPed specimen remained preferential after annealing. Sakai et al. [11] already pointed out that the shear texture developed by the shear rolling had a broad one spreading around the typical shear components after annealing. It is, therefore, suggested that the shear texture formed by shear deformation tends to remain after annealing. Shear deformation and subsequent annealing could be a useful way for textural control.

As it is needless to say dependence of temperature on microstructural evolution, restoration process proceeds for the shorter time at the higher temperature [12]. The annealing with high temperature gradient can lead to a local preferred evolution of microstructure intendedly by using gradient stored strain in FRSPed specimen.

The purpose of the present study is to review texture evolutions in specimens subjected to FRSP subsequent annealing to commercial purity aluminum [13]. Further, textural evolution in the specimen subjected to FRSP and temperature gradient annealing is investigated in comparison with that in the specimen subjected to FRSP and the ordinary annealing.

2. Experimental Procedure

2.1. Material
Commercial purity aluminum sheet (1050) 1mm thick was received as a starting material. It was produced by a process of casting, hot rolling, cold rolling with a reduction of 90% and annealing at 623K for 3.6ks.

2.2. Friction roll surface processing (FRSP)
Rotational direction of roll, feeding direction of sample and FRSP direction are illustrated in Figure 1. A fixed roll with a dimension of $\phi 70 \times 5$mm, which was made of tool steel SK3, was rotated at 240 rpm. The indentation, defined as the depth at which the rotating roll was pressed down into the specimen, was

![Figure 1. Schematic illustration of Friction Roll Surface Processing (FRSP). Rotating roll is fed on ND plane in feeding direction, which is parallel to TD (the width direction of rolled sheet sample) in the present figure. This processing is called ND/TD FRSP.](image-url)
selected as 0.1mm. The feeding speed of specimen was set as 0.3 mm/s. FRSP was performed as described in our previous studies [9,10]: first, the interface where the roll and the specimen just touched was located, and this was regarded as the reference plane at which the indentation was zero. Then, the roll was placed to the given indentation without contacting the specimen. After rotating the roll, the specimen was moved forward until the entire surface was treated. This procedure resulted in making the working plane lower than the reference plane and led to a great amount of friction. The deformation mode in FRSP is similar to that in asymmetric rolling (ASR). Tangential speed of FRSP roll is faster than feeding speed on the surface layer of the material while a faster tangential speed of rolls in ASR is almost similar to a moving speed of surface material in ASR. After FRSP, the specimens were annealed at 573K, 623K or 673K for 3.6ks (1 h) in Ar gas and air cooled to study the texture evolution during annealing.

Here the plane and the direction of the specimen subjected to FRSP are expressed as plane/ direction sited before "FRSP", where the rolling, transverse and normal directions (RD, TD and ND, respectively) are used as the specimen axes. For example, ND/TD FRSP (See Figure 1) refers to the processing in which FRSP was performed on ND plane (the plane perpendicular to ND) of the specimen along the direction parallel to TD.

2.3. Microstructural analysis
Crystallographic textures of annealed specimens were evaluated using a scanning electron microscope/ electron back scatter diffraction pattern technique (SEM/EBSD; HITACHI S-3500H, TSL Orientation Image Microscopy system) after electropolishing. The electropolishing was carried out at 283K and 8V for 480s in a solution containing perchloric acid and ethanol with a ratio of 1/8. The scan areas were chosen on the cross sections of the specimen perpendicular to FRSP direction. Microstructure and texture evolution through the thickness of specimen was investigated from the processed surface to center of the specimen, the area was 400 µm×400 µm and the step size was 3µm. High magnification measurement was used with a smaller step size of 0.1 µm for the microstructure in the vicinity of the processed surface.

2.4. Temperature gradient annealing
The annealing with steep temperature gradient in longitudinal direction was applied to the small specimen of 12mm long, 10mm wide and 1.5mm thick as follows. Figure 2 illustrates the sectioned drawing of temperature gradient annealing instrument.
An infrared furnace was employed as heating device because of its high energy density. As the top face of the specimen was sited to the concentrated part of the infrared rays in the center of the furnace, the stainless specimen holder was specially designed to cool the bottom face by combined water cooling device with copper tube.

![Figure 2. Schematic illustration of apparatus for temperature gradient annealing.](image-url)
3. Experimental results and discussion

3.1. Texture of processed materials

Figure 3 shows the normalized pole figures of as-received, ND/TD FRSPed and subsequently annealed specimens measured by XRD. \{100\} and \{111\} pole figures of the as received specimen indicate typical cube texture (Figure 3(a)). As displayed in Figure 3(b), the \{100\} pole of ND/TD FRSPed specimen represents very weak intensity of <001>/ND while the \{111\} pole implies <110>/TD. Then, the main textural component is \{001\}<110> (\{FRSP plane\}<FRSP direction>). The central intensity of the \{111\} pole extended in RD likely means formation of the main component rotated about TD axis. After the annealing (Figure 3(c)), \{001\}<110> orientation is somewhat sharpened though the characteristically rotated spread of the main component remains after annealing.

These results probably show the texture formed mainly in the surface layer with thickness of 10µm order as they were obtained by X-ray diffraction with penetration depth ranging from 0.01 to 0.1mm. The texture after annealing is also mentioned below based on EBSD analysis on cross-section.

3.2. Microstructure after FRSP and temperature gradient annealing

Figure 4 shows inverse pole figure (IPF) and kernel average misorientation (KAM) maps of the sample subjected to RD/TD FRSP and temperature gradient annealing. The temperature gradient was kept almost as a mean value of 21.3K/mm during the annealing. The area from FRSP surface to 80µm depth is fine grained region without stored strain while the inner one to 150µm has high KAM more than 1.5 degrees and moreover, the deeper region seems as received grain structure. The fine grained region composed of ones of 4.6µm. Which is one third to the grain size of 13.9µm in the fine grained region of the ordinarily annealed sample.

The inner region with high KAM is found between the fine grained and the as-received ones. It is very characteristic manner, which is not observed in the ordinarily annealed sample. In addition, no coarse grained region was observed after the temperature gradient annealing. These facts suggest that restoration process takes place rapidly nearest the surface layer to compared with the deeper region. Such priority of the nearest surface layer in recovery and recrystallization probably leads to possibility of activation on nuclei related to the higher stored strain.
3.3. Texture after FRSP and temperature gradient annealing

Material deformation generated by FRSP is probably similar to that in asymmetric rolling (ASR). Preferred orientation components in asymmetric rolling were reported as H {001}<110>, E {111}<110> and F {111}<112> [14]. The texture after RD/TD FRSP and temperature gradient annealing (TGA) is summarized in Table 1. The 1050 aluminum used as a starting material had a considerably sharp Cube texture. The fraction of Cube within a tolerance of 15° decreased from 26.7% to 3.5% or 1.9% through FRSP and annealing. On the other hand, a shear texture component H changed from 3.6% to 4.8% or 2.9% according to the sort of annealing. The F orientation is defined as one of components with <111> parallel to RD for RD/TD FRSP. The orientation was found by 5.7% after the ordinary annealing and by 4.4% after TGA while it existed by only 0.4% before FRSP. It should be noted that E orientation evolved by three times from 3.3% to 10.3%, corresponding to higher strain near the surface.

Table 1. Fractions of textural components after RD/TD FRSP and two kinds of annealing (%)

| Texture component (FRSP plane/FRSP direction) | As received | Homogeneous Temperature at 623K | Temperature gradient at 623K |
|-----------------------------------------------|------------|--------------------------------|-------------------------------|
|                                               |            | Fine grains                     | Strain stored                 | As received grains |
| FRSP_{nd}/<001>                               | 44.2       | 15.9                           | 11.4                          | 12.3              | 35.8 |
| FRSP_{d}/<110>                                | 9.6        | 25.4                           | 28.2                          | 25.0              | 9.2  |
| FRSP_{nd}/<111>                               | 7.5        | 12.9                           | 20.4                          | 14.8              | 9.7  |
| Cube {001}<100>                               | 26.7       | 3.5                            | 1.9                           | 2.3               | 15.3 |
| H {001}<110>                                  | 3.6        | 4.8                            | 2.9                           | 2.9               | 2.2  |
| F {111}<112>                                  | 0.4        | 5.7                            | 4.4                           | 4.0               | 2.0  |
| E {111}<110>                                  | 3.3        | 3.5                            | 10.3                          | 6.4               | 3.6  |

3.4. Microstructure and preferred orientation in the surface layer after FRSP

It was found that FRSP/TGA enables the high fraction of E{111}<110> in fine grained and strain stored regions compared with other orientations. This is attributed to restoration process limited in highly stored strain region. E orientation recovers rapidly during annealing, and/or hardly store strain through FRSP. Then, E orientation grows preferentially by strain induced boundary migration. Figure 5 shows comparison between E orientation and the others in SEM/EBSD analyses for two fields of FRSPed sample without annealing. The KAM value of E orientation is lower than that of others. E orientation has higher IQ (image quality) and CI (confidence index) values than other orientations. The
IQ value was applied to analyze recrystallized volume fraction [15], while the stored strain energy was derived from the KAM value based on the relationship to dislocation density [16]. The facts on three values indicate that E orientation stores less strain than the other ones. It is, therefore, concluded that E orientation is not imposed strain during FRSP.

4. Summary
Preferred orientation formation in surface layer of aluminum sheet subjected to friction roll surface processing (FRSP) and temperature gradient annealing has been investigated by SEM/EBSD analysis beneath the surface. The temperature gradient 21.3K/mm was attained even for aluminum with high thermal conductivity. The shear texture component \{111\}<110> mainly evolved in the specimen subjected to FRSP and the ordinary annealing. More evolution of the component \{111\}<110> after the temperature gradient annealing were compared with that after the ordinary annealing in consideration of stored strain.

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Figure 5. Comparisons of E and other orientations in KAM, IQ and CI values for (a) field A and (b) field B of FRSPed sample.