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To cite this article: Y. Takayama et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 375 012017

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# Preferred orientation formation in Al-3mass% Mg subjected to shear deformation and subsequent annealing

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Abstract. Shear deformation is imposed on materials by several advanced techniques for microstructural and textural control. Shear texture evolved during deformation tends to remain after subsequent annealing. Preferred orientation formation with shear deformation and annealing in Al-3mass%Mg alloy rolled sheet has been investigated by SEM/EBSD technique. S-shaped specimen was prepared from the alloy sheet to impose shear strain in compression. The central objective part of the S-shaped specimen was sheared with rotation about the normal axis so as to develop preferred orientations of {111} parallel to the original shear plane and <110> parallel to the original shear direction before deformation. In-situ EBSD analysis revealed that the preferred orientations formed by shear deformation remain and evolve as recrystallization texture during subsequent annealing. The evolution of the shear recrystallization texture depended obviously upon sample direction parallel to shear direction.

#### 1. Introduction

Severe plastic deformation (SPD) has attracted great interests owing to both formation of extremely fine microstructure and improvement of related properties. Numerous studies have been performed to produce the 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]. 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 angle[6]. These imply correspondence of microscopic shear system with macroscopic shear deformation.

Sakai et  $al_{[7]}$  pointed out that the shear texture developed by the shear rolling had a broad one spreading around the typical shear components after annealing. Shi et al. [8, 9] reported that the shear texture formed in the commercial purity titanium sheet subjected to a friction roll surface processing (FRSP), which was proposed as a SPD process for the surface of the sheet materials in order to control microstructure and texture, remained preferential after annealing.

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In the present study, preferred orientation formation with shear deformation and annealing in Al-3mass%Mg alloy rolled sheet has been investigated by SEM/EBSD technique.

# 2. Experimental procedure

Al-3mass%Mg alloy was prepared as a 90% rolled sheet of 1mm thick. Chemical composition of the alloy is listed in Table 1. S-shaped specimen as shown in Fig. 1 was cut from the sheet with its longitudinal direction parallel to rolling or transverse direction (RD or TD) for the compressive shear test. A central neck part was sheared by compressing the specimen in vertical or longitudinal direction during the test after annealing at 653K for 3.6ks in Ar and scanning electron microscope/ back scatter diffraction (SEM/EBSD) analysis. Shear strain was calculated from change in relative positions of Vickers hardness indents, which had been sited on the neck part as 750µm square lattice of four fiducial markers before the test.

Table 1 Chemical composition of Al-3mass%Mg alloy used (mass%).

Si	Fe	Cu	Mn	Mg	$\mathbf{Cr}$	Zn	Ti	Al
0.0104	0.0057	0.0028	0.0043	2.9312	0.0004	0.0021	0.0005	Bal



Fig. 1 S-shaped specimen.

Fig. 2 Objective squares before and after shear deformation (in TD-compressive shear test). Grain orientation was analyzed on shear plane and direction for the measured data rotated by each angle about ND axis.

To examine changes in microstructure and texture the S-shaped specimen was annealed for 2.7ks and in-situ analyzed by SEM/EBSD repeatedly during step heating controlled with heater temperature.

### 3. Experimental results and discussion

#### 3.1. Macroscopic change in the central part of the S-shaped specimen

The objective square in the central part of the S-shaped specimen (which was composed of the four fiducial markers with an interval of 750 $\mu$ m) deformed into the parallelogram with rotation about normal direction (ND) axis as illustrated in Fig. 2 (TD compressive shear). In the figure, TD and RD were rotated by 7.20° and 32.88° in counter clock-wise to original directions, respectively. Because shear deformation takes place by conjugate shear stresses along TD and RD in the square of the figure, change in grain orientation with shear deformation should be analyzed for the measured data reversely rotated by each angle about ND axis as TD or RD corresponds to the original one. The former is called as *TD shear analysis* here while the latter is called as *RD shear analysis*.

## 3.2. Change in microstructure through TD-compressive shear and step heating

3.2.1. TD-compressive shear test. Figure 3 displays the inverse pole figure (IPF) maps before and after TD-compressive shear test with a shear strain  $\gamma$ =0.47, which was calculated from change in relative positions of the indent markers. The grain orientation in TD is expressed as color. Grain size before the test was measured as 63.2µm by the planimetric method [10]. The map after the deformation (Fig. 3(b))



Fig. 3 IPF maps representing microstructures (a) before and (b) after TD-compressive shear deformation. Yellow parallelogram refers to the square region before the deformation. White square indicates objective area for the in-situ SEM/EBSD analysis during step heating.

reveals local grain rotation as change in color and stored shear strain in grain interior as gradation. Larger strain appears as unanalysed points in the figure.

*3.2.2. In-situ analysis during heating.* Figure 4 shows IPF and kernel average misorientation (KAM) maps in restoration process during step heating in the square region of Fig. 3(b). It is known that intragranular misorientation or KAM increases with increment of imposed strain at ambient temperature and decreases with decrement of dislocation density in recrystallization process [11]. Recrystallized grains with low KAM or strain relief appear at 559K and cover larger area gradually to 607K. Mean KAM lowered from 1.95 degrees at 543 to 0.83 degrees at 607K for the whole area.

Preferred orientation evolution was investigated from the EBSD data, which was rotated by -7.2° or -32.88° about ND axis to return TD or RD to the original direction as shown in Fig. 2. Changes in fractions of <111> $\perp$  TD<sub>0</sub> (TD<sub>0</sub>: original TD before deformation) and <110>//TD<sub>0</sub> are displayed in Figs. 5(a) and 5(b). The fractions were calculated for the whole analyzed area before step heating and for the recrystallized area (KAM<1°) during step heating. As shown in the figure, the shear textures <111> $\perp$  TD<sub>0</sub> and <110>//TD<sub>0</sub>, which mean that slip plane and direction are consistent with shear plane and direction, respectively, evolved considerably to fractions of 19.3% and 23.0% after shear deformation in the specimen subjected to TD-compressive shear test. The fractions of the shear textures include more fractions of components close to ideal orientations compared with the shear deformation textures. Moreover, the fraction of <110>//TD<sub>0</sub>, amounts to three forth of the whole recrystallization area at 607K. These results support the fact that shear deformation texture remains preferential after annealing.

On the other hand, Figs. 5(c) and 5(d) show changes in fractions of  $<111>\perp RD_0$  (RD<sub>0</sub>: original RD before deformation) and  $<110>//RD_0$  in the same way. The shear textures  $<111>\perp RD_0$  and  $<110>//RD_0$ , also evolve by shear deformation and subsequent step heating. However, their fractions are obviously smaller than those of  $<111>\perp TD_0$  and  $<110>//TD_0$ . In particular, the fractions of the recrystallization texture are only less than a half of those on TD. Besides, there appear less fractions of components close to ideal orientations.

#### 3.3. Change in microstructure through RD-compressive shear and step heating

3.3.1. RD-compressive shear test. A shear strain  $\gamma$ =0.50 was imposed in RD-compressive shear test. Grain size before the test was measured as 53.7µm. The square in the central area of the S-shaped specimen deformed into a parallelogram with rotated RD and TD by 6.9° and 33.5°.

3.3.2. In-situ analysis during heating. Figure 6 displays changes in fractions of  $<111> \perp RD_{o}$ ,  $<110>//RD_{o}$ ,  $<111> \perp TD_{o}$  and  $<110>//TD_{o}$ . Even In RD-compressive shear specimen the shear textures on RD,  $<111> \perp RD_{o}$  and  $<110>//RD_{o}$ , do not evolve remarkably. The fractions after shear deformation are only 10.2% and 15.7%, and moreover, less than 10% after the heating at 607K. In contrast to this, the fractions of  $<111> \perp TD_{o}$  and  $<110>//TD_{o}$  rise up to 19.5% and 23.8%, respectively after shear deformation in the RD-compressive shear specimen also. The fractions of the shear recrystallization texture increase acceleratingly during step heating and reach 35.9% and 35.3% at 607K. Recrystallization proceeds somewhat lately compared with in TD-compressive shear specimen.

## 3.4. Evolution of $E_{TD}$ {111}<110> through compressive shear and step heating

Evolution of  $E_{TD}{111}<10>{\text{shear plane}}<\text{shear direction> on TD (or TD shear analysis) is supposed from the results in clauses 3.2 and 3.3. Orientation E {111}<10> [12] was examined as one of shear texture components in asymmetric rolling process. Figure 7 shows orientation maps of <math>E_{TD}$  with its fraction during step heating in both of TD- and RD- compressive shear specimens. Orientation  $E_{TD}{111}<10>$  grew up to more than 25% in annealing after attaining fraction of 10% by shear deformation.



Fig. 4 IPF and KAM maps representing microstructural changes during step heating after TD-compressive shear deformation. KAM lowers from 1.95, 1.38, 1.11, 0.99 and 0.83 degrees.



Fig. 5 Evolutions of shear preferred orientations before and after shear deformation and subsequent step heating: fractions of (a) <111> $\perp$  TD<sub>0</sub>, (b) <110>//TD<sub>0</sub>, (c) <111> $\perp$  RD<sub>0</sub> and (d) <110>//RD<sub>0</sub> in TD-compressive shear specimen.

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IOP Conf. Series: Materials Science and Engineering 375 (2018) 012017 doi:10.1088/1757-899X/375/1/012017



Fig. 6 Evolutions of shear preferred orientations before and after shear deformation and subsequent step heating: fractions of (a) <111> $\perp$ RD<sub>0</sub>, (b) <110>//RD<sub>0</sub>, (c) <111> $\perp$ TD<sub>0</sub> and (d) <110>//TD<sub>0</sub> in RD-compressive shear specimen.



Fig. 7 Evolution of  $E_{TD}$ {111}<110> during step heating after TD- and RD- compressive shear deformation. Fractions of  $E_{TD}$  increase from 6.2% to 26.2% and from 13.0% to 28.0%.

#### 4. Conclusions

In the present study, preferred orientation formation with shear deformation and annealing in Al-3mass%Mg alloy rolled sheet has been investigated by SEM/EBSD technique. The obtained results are summarized as follows:

1. Grain orientation with its slip plane parallel to shear one or its slip direction parallel to shear one tends to evolve through shear deformation and subsequent annealing.

2. For both of TD- and RD- compressive shear specimens, remarkable increases in shear texture components on TD plane are found, which indicates that both shear systems are active equivalently for preferred orientation formation and the components on TD have predominance.

3. Orientation  $E_{TD}$ {111}<110> grows up to more than 25% in annealing after attaining fraction of 10% by shear deformation.

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