Change in intragranular misorientation during stress relaxation in Al-Cu-Mg-Mn alloy subjected to continuous cyclic bending

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Abstract. Change in intragranular misorientation during stress relaxation in Al-Cu-Mg-Mn (2024) alloy sheet subjected to continuous cyclic bending (CCB) has been investigated by electron back scatter diffraction (EBSD) technique. EBSD analysis revealed that kernel average misorientation (KAM) value was heightened not only in the sheet worked by CCB but also during stress relaxation test. Grain orientation spread (GOS) value, another misorientation parameter, was also calculated and compared with KAM value of each sample. Both of KAM and GOS values varied with four stages about stress and stored strain: (a) unloaded before stress relaxation test (SRT), (b) loaded before SRT, (c) loaded after SRT and (d) unloaded after SRT. Change in KAM value was likely corresponding to sum of applied and residual stresses. Quantitative relationship between increase and decrease in KAM value between the stages was divided into two types according to dynamic restoration mechanisms.

1. Introduction
Copper wires with high electrical conductivity are generally used for wiring harnesses in automobiles. In recent years, for the purpose of reducing the weight of vehicles, aluminum alloys which are close to copper in terms of electrical conductivity but with half of the weight are being used. When the aluminum alloys are used as current-carrying members, their stress relaxation characteristics are required to be known for assuring contact reliability. Takayama and Szpunar [1] investigated crystallographic orientation distribution in the surface layer of an Al-Mg alloy sheet subjected to continuous cyclic bending to clarify the relationship between the KAM value corresponding to the local accumulated strain or stored strain energy and the Taylor factor (TF) assuming a plane strain state. As a result, the KAM value generally increased with increasing TF and increased somewhat in the region where TF was close to the minimum value of 2. On the other hand, Norhafiza et. al. [2] and Takayama et. al. [3] reported that the intragranular orientation difference also increased during a softening process, that is, stress relaxation. In addition, the increase of intragranular orientation difference with high temperature deformation has been reported by several studies [4-6].

In the present study, change in intragranular misorientation during stress relaxation in an aged-hardened Al-Cu-Mg-Mn alloy sheet subjected to continuous cyclic bending (CCB) was investigated by electron back scatter diffraction (EBSD) technique. The stress relaxation process was analyzed by using the intragranular misorientation in microstructure of the alloy at each stage of (a) unloaded before stress relaxation test (SRT), (b) loaded before SRT, (c) loaded after SRT and (d) unloaded after SRT. Further,
the relationship between the changes in the KAM (kernel average misorientation) and GOS (grain orientation spread) values and the stress relaxation was investigated [5].

2. Experimental Methods

2.1. Materials and specimens

An Al-Cu-Mg-Mn alloy (2024 Al-T3) sheet was received as a starting material. The chemical composition of the 2024 Al alloy is listed in Table 1. The received sheet was solution-treated at 768 K for 30 min, and then machined into the stress-relaxation specimen of 24mm long in rolling direction (RD), 7mm wide in transverse direction (TD) and 1.5mm thick in normal direction (ND).

Table 1. Chemical composition of material (mass%)

|   | Si   | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Zr+Ti | Ti  | Al   |
|---|------|-----|-----|-----|-----|-----|-----|-------|-----|------|
|   | 0.07 | 0.18| 4.55| 0.48| 1.58| 0.02| 0.09| 0.03  | 0.02| Bal. |

2.2. Continuous cyclic bending

The CCB processing equipment was used to work 40pass and 160pass specimens at a roll drive speed of 40 rpm, indentation of 0.5 mm, and an ambient temperature. These specimens are hereafter referred to 40pass and 160pass materials. The front side and the back side of the specimen was not changed during CCB process.

2.3. Aging process

The starting material was aged at 463K after solution treatment (ST). The optimal aging time was determined for each sample by using the Vickers hardness-aging time relationship. The specimen without CCB was aged for 8 hours, which was hereinafter referred to "aged specimens." Some of specimens were subjected to CCB passes before aging. 40pass and 160pass CCBent specimens were aged for 7 and 10 hours, referred to 40p/Aged and 160p/Aged, respectively.

2.4. Stress relaxation testing

Stress relaxation test was performed using a special specimen holder with which the specimen was allowed SEM/EBSD analysis in four stages: Stage I, unloaded before SRT, Stage II, stress loading (elastic strain), Stage III, stress relaxation (elastic strain + plastic strain) and Stage IV, unloaded after SRT (plastic strain). The analysis area was sited in the center and on the front and back sides of CCB on the TD plane and sized as the RD180μm × ND240μm, respectively. Top and Bottom mean top and bottom sides of the specimen, and besides, correspond to tensile and compressive strain for bending in the stress relaxation test. During the stress relaxation process the permanent strain occurs when the loaded deflection is released. The stress relaxation ratio is expressed as the ratio of the permanent deflection displacement produced to the initial deflection displacement loaded. The stress relaxation rate is calculated by the following equation.

\[
\text{stress relaxation ratio} (\%) = \frac{\delta_t}{\delta_0} \times 100
\]

\(\delta_t\): Permanent deflection displacement of the specimen caused by stress unloading after the test (mm)

\(\delta_0\): Initial deflection displacement of the test specimen at a given stress load (mm)
3. Experimental results and discussion

Figure 1 shows change in stress relaxation ratio for five kinds of specimens. As the stress relaxation ratio is lower, the stress relaxation characteristics is superior. 160p/Aged has the best stress relaxation resistance among them.

The grains were extracted one by one from the inverse pole figure (IPF) map obtained by EBSD analysis, and their KAM values were analyzed one by one (figure 2). There is a strong correlation in KAM difference between Stage II to Stage III and Stage I to Stage II CCB and aged specimens, and the data of aged specimens are more scattered than those of CCB (figure 3). In the case of CCB and aged specimens, the dislocations shifted from Stage I to Stage II are restored by the same amount before and after the relaxation from Stage II to Stage III, which may be related to the slip deformation of dislocations. The correlation of 160p/Aged was not observed in the aged specimens. In both specimens, the dynamic restoration process proceeded because they were held at high temperature under the external force in Stage II during the stress relaxation test. Therefore, the stress relaxation phenomena of 2024Al alloy can be divided into two types: one is the change in the KAM value due to dynamic restoration, as in the case of aging, and the other is the change in the KAM value, which is strongly related to the slip deformation of dislocations, as in the case of 160p/Aged, when CCB and aging are combined.

![Stress relaxation ratio of five kinds of specimens.](image1)

![160p/Aged Stage I Top IPF map](image2)
Therefore, the line profiles of misorientations taken for arbitrary grains of 160p/Aged with the superior stress relaxation ratio and the aged specimen with the inferior stress relaxation ratio are shown in figure 4. Point to point (red graph) shows the misorientation from the neighboring measurement point, and point to origin (blue graph) shows the misorientation from the first measurement point. Focusing on the point to origin, it can be seen that the misorientation increases as the distance from the origin point increases for the 160p/Aged, whereas for the aged material the change in misorientation does not change much with distance. This indicates that 160p/Aged is an extensive change in orientation, whereas the change in orientation is localized for the aged specimen.

Next, the grains were extracted one by one from the IPF map and their KAM and GOS values were analyzed one by one, and the mean values of KAM and GOS for each stage are shown in figure 5. The black and red lines represent the GOS and KAM values, respectively. The KAM value, which is the local misorientation value, refers to the adjacent measurement points, while the GOS value, which is the intragranular misorientation average, refers to all the measurement points within the grain, so that the KAM value corresponds to the local misorientation change and the GOS value corresponds to the change in misorientation due to a wide area. These results suggest that the two phenomena of dislocation slip deformation and dynamic restoration lead to the intragranular misorientation.
Fig. 5 Changes in average KAM and GOS values in each stage of SRT.
4. Conclusions
In the present study, change in intragranular misorientation during stress relaxation in an aged-hardened Al-Cu-Mg-Mn alloy sheet subjected to CCB has been investigated by EBSD technique. The stress relaxation process was analyzed by using the intragranular misorientation in microstructure of the alloy at each stage of (a) unloaded before SRT, (b) loaded before SRT, (c) loaded after SRT and (d) unloaded after SRT. Further, the relationship between the changes in the KAM and GOS values and the stress relaxation was investigated. The obtained results are summarized as follows.

1. 160p/Aged specimen has the best stress relaxation resistance among five materials.

2. Stress relaxation phenomena can be divided into two types: those that show a change in the KAM value due to dynamic recovery, as in the case of aged materials, and those that show a change in the KAM value, which is strongly related to the slip deformation of dislocations, by combining CCB and aging, as in the case of 160p/Aged.

5. References
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