High performance of mechanical and electrical properties of Cu-Cr-Zr alloy sheets produced by ARB process and additional thermo-mechanical treatment

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Abstract. The additional cold rolling and the aging process were applied to Cu-0.85Cr-0.07Zr alloy sheets processed by ARB, and mechanical properties and structural information were investigated for the purpose of further improvement of the mechanical properties and the electrical conductivity. From the results of the tensile test and the measurement of electrical conductivity, ARB/aged/CR was most appropriate processing in order to achieve technical advantages. The high tensile strength of 745 MPa and the high electrical conductivity of 68 %IACS were obtained simultaneously. In addition, the improvement of incomplete boundaries generated during ARB processing was possible by thermo-mechanical treatment.

1. Introduction
Fine-grained metals achieve very high yield strength in accordance with Hall-Petch relation. Accumulative roll bonding (ARB) processing [1] was taken up in this study to get fine-grained thin sheets, which are expected to be used as electrical parts. On the other hand, conventional thermo-treatment like age hardening has been used in order to improve some mechanical properties of metallic materials until today. It is expected that such materials would obtain more excellent properties with thermo-mechanical treatments, i.e., the severe plastic deformation (SPD) and the thermo-treatment. However, materials given huge strain by SPD have a problem of unstabilization of thermal stability in the viewpoint of recrystallization and recovery.

In our previous study, the improvement of mechanical properties of ARBed Cu-Cr-Zr alloy after extra annealing processes was reported [2]. As a result, the high tensile strength of 625 MPa, the large total elongation of 15 % and the high electrical conductivity of 79 %IACS were obtained by ARB and subsequent aging treatment. However the average crystal grain size of 240 nm in ARB/aged material was larger than that of 210 nm in ARB/5cycles materials due to recrystallization by heat treatment. Therefore subsequent mechanical plastic deformation processing would affect a refinement of grains, and higher strengthening is expected simultaneously.

In this study, the additional cold rolling and the aging process were applied to Cu-Cr-Zr alloy sheets processed by ARB, and mechanical properties and structural information were investigated for the purpose of further improvement of the mechanical properties and the electrical conductivity.
2. Experimental

The Cu-0.85Cr-0.07Zr (in mass %) alloy was used in the present investigation. It was quenched in the 5 % water solution of NaCl after heating at 1000 °C for 2 hours for the purpose of solution heat treatment. Samples having dimensions of 50 x 300 x 1 mm³ for the ARB processing were cut from the 80 % cold-rolled plate (As-rolled material). The ARB processing was carried out up to 5 cycles (As-ARBed material). In the ARB processing, a plate of 1 mm thick was cut into two pieces and they were stacked with brushed surface. Stacked plates were subjected into the roll bonding process with reduction of 50 % per one cycle. In addition, the aging treatment to ARBed materials was conducted at 450 °C for 2ks in the salt bath (ARB/aged material). The most excellent strength-electrical conductivity combination could be accomplished by this aging time and temperature [3]. As mentioned in the introduction section, further improvement about strength is expected by additional mechanical treatment to the ARB/aged material. Therefore, the additional cold roll (CR) processing was carried out to the As-ARBed (ARB/CR material) and the ARB/aged (ARB/aged/CR material) samples respectively. The thickness of two kinds of CRred materials was reduced from 1.0 mm to 0.2 mm by the additional cold rolling. An explanation drawing of each processing is shown in Fig.1.

Mechanical tensile test with the specimens of 3 mm in width and 10 mm in gage length was performed by tensile test machine at the strain rate of 10⁻³ sec⁻¹. Vickers hardness on the ND-RD section was also measured at the load of 2.94 N for 15 sec. Electrical conductivity of all specimens was measured by using eddy-current method.

Electron backscatter diffraction pattern (EBSD) images on the ND-RD section were obtained by the orientation imaging microscopy (OIM) system attached to FE-SEM. The average grain size, the fraction of high angle grain boundaries (HAGBs) and the grain boundary image were analyzed from EBSP data sets. Then, SEM micrographs on fracture surface of each specimen after tensile test were compared.

3. Results and Discussion

3.1. Mechanical and Electrical Properties

Some mechanical properties obtained from present specimens are summarized in Table 1. The ARB processing improved the strength of the Cu alloy without deterioration of the electrical conductivity. Moreover, the elongation was improved simultaneously. In general, it is known that metallic materials have a trade-off relation between strength and ductility. Nevertheless, the result in this experiment was different from our knowledge. It is very interesting phenomenon. Subsequently, both the strength and the elongation were improved in the ARB/aged processing. It is noted in particular that high electrical conductivity could be achieved at the same time. Ordinarily, the dissolution of precipitation from solid solution and the elimination of dislocation with recovery occur by heat treatment, and they would affect the strength, the elongation and the electrical properties of this material. On the other hand, the ARB/CR processing could not improve the strength, and besides, it decreased the elongation and the
Finally, although the electrical conductivity of the ARB/aged/CR processing diminished slightly in comparison with that of the ARB/aged processing, the most superior result about the tensile strength in all specimens was obtained by the ARB/aged/CR processing.

| Specimen       | Vickers hardness (HV) | Yield stress (MPa) | Tensile strength (MPa) | Total elongation (%) | Electrical cond. (%IACS) |
|----------------|-----------------------|--------------------|------------------------|----------------------|--------------------------|
| As-rolled      | 141                   | 460                | 464                    | 7.5                  | 35                       |
| As-ARBed       | 170                   | 540                | 585                    | 10.0                 | 35                       |
| ARB/aged       | 209                   | 605                | 625                    | 15                   | 79                       |
| ARB/CR         | 170                   | 600                | 626                    | 6.9                  | 39                       |
| ARB/aged/CR    | 217                   | 700                | 745                    | 7.0                  | 68                       |

### 3.2. Microstructure and Related Data by EBSD

Boundary maps by EBSD are shown in Fig.2. The average grain sizes and the fraction of HAGBs analyzed by EBSD are summarized in Table 2. The lamellar structure consisting of grains like pancakes was created by the ARB processing, and this structure hardly changed by subsequent aging treatment. Refined grains about 200nm by the ARB contribute to the strength of specimens. Figure 3 shows a TEM micrograph of the ARB/aged specimen. Some precipitations that seem compounds Cu$_5$Zr in a grain can be recognized. The additional aging can induce the dissolution of precipitate without serious coarsening of grain size of matrix materials. Since grain refinement was promoted by additional cold rolling after additional aging treatment, the ARB/aged/CR specimen obtained the highest strength of all specimens. It is supposed that the ARB/aging/CR processing would induce extreme refinement of crystal grains due to the pile up of dislocations associated with small precipitations generated by the aging treatment ahead of the cold rolling. In addition, the strain-induced solid solution formation could occur because the electrical conductivity after additional CR was lower.

![Fig. 2](image-url)

**Figure 2.** Boundary maps of specimens obtained by EBSD. Gray lines and black lines indicate High angle grain boundaries (HAGBs: 2-14°) and Low angle grain boundaries (LAGBs: 15-180°) respectively.

| Specimen       | Lamella intervals (nm) | Fraction of HAGBs (%) |
|----------------|------------------------|------------------------|
| As-rolled      | ~ 6x10³                | 31                     |
| As-ARBed       | 230                    | 75                     |
| ARB/aged       | 260                    | 81                     |
| ARB/aged/CR    | 130                    | 84                     |
3.3. Influence of Bonding Boundary in ARB on Strength
There is a possibility that the sheets processed by ARB include some incomplete bonding boundaries. Indeed, some such faults were found in all specimens from the observation of the fracture surface in tensile specimens. Two SEM pictures of fracture surface around bonding boundaries are shown in Fig. 4. There were equiaxial dimples on the fracture surface, and it means indicating the typical ductile fracture. Some faults caused by incomplete bonding were found out among dimples. It could be observed that faults in the ARB/aged/CR specimen were pretty smaller than that in the ARB/aged specimen. The additional thermal and mechanical treatments were able to improve the condition of incomplete bonding boundaries. It is supposed that atomic migration takes place by additional heat treatment and subsequent plastic deformation segmentalizes remained faults. Although it is unclear whether the crack initiation corresponds with the incomplete bonding boundary, reduction of such faults would improve the mechanical properties.

Figure 3. TEM micrograph of ARB/aged specimen.

Figure 4. Incomplete bonding boundaries on fracture surface by tensile test. White arrows point to some of faults in specimens.

4. Conclusions
The ultrafine-grained Cu-Cr-Zr alloy processed by ARB was investigated with respect to the strength, the electrical conductivity and the grain size after additional aging and subsequent cold rolling. Major improvements from As-ARBEd material are summarized as follows;

- The ARB/aged processing extremely improved not only the mechanical properties but also the electrical conductivity.
- The ARB/aged/CR processing achieved the highest strength of all specimens without sacrificing much of the electrical conductivity.
- The additional aging and CR processing was able to reduce incomplete bonding boundaries generated during ARB processing.

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