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Interface Analysis of Annealed Al/Cu Cladded Sheet

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Abstract**—**Effect of aging treatment on microstructural aspects of interfacial layers of the Cu/Al clad sheet produced by differential speed rolling (DSR) process were studied by electron back scattered diffraction (EBSD). Clad sheet of Al/Cu has been fabricated by using DSR, which caused severe shear deformation between Al and Cu plate to easily bond to each other. Rolling was carried out at 100°C with speed ratio of 2, in which the total thickness reduction was 45%. Interface layers of clad sheet were analyzed by EBSD after subsequent annealing at 400°C for 30 to 120min. With increasing annealing time, thickness of interface layer and fraction of high angle grain boundary were increased and average grain size was decreased.

Keywords**—**Aluminum/Copper clad sheet, differential speed rolling, interface layer, microstructure, annealing, electron back scattered diffraction.

I. Introduction

CLAD sheet of aluminum/copper (Al/Cu) offers a 50% reduction in weight, with the equivalent conductivity of a copper alloy. It is also less expensive than a copper alloy, by a factor of 35% [1]. In fact, it is very difficult to meet the wide variety of demands such as superior mechanical and thermal properties for a single material. Therefore, clad metals, consisting of two or more metals, have been developed because of their unique properties [2]. speed rolling (DSR) processes, for which the peripheral velocity or radius of the upper roll may be different from those of the lower roll, have become more and more important in the light of the fact that it can gain such advantages as lower rolling pressure distribution, resulting in less rolling force and less torque.

Several processes have been employed to fabricate bimetal clad sheets, such as explosive welding, diffusion bonding, roll bonding, friction stir welding (FSW), and laser welding. The cold roll bonding is known to be more efficient and economical than the other methods [3]. Differential speed rolling process has shown that the cross shear deformation zone was caused by the displacement of neutral plane of upper and lower roll, providing a severe deformation for materials and lessening the power consumption. In addition, this method improves the interfacial bonding of clad sheet [4], desirable to bond dissimilar component metal, especially for which are difficult to deform.

Fabrication of Cu/Al clad sheet is a great challenge due to the different chemical and physical properties of constituent metals. Since the rolling bond is based on the high deformation, there will be great stress in the metals and their interface. Therefore, the clad sheet must be annealed in order to obtain good formability for the next forming processes such as bending and deep drawing [5].

In the present study, clad Cu/Al sheets were fabricated by DSR process at 100°C with speed ratio of 2. Investigation of interface layer before and after annealing treatment at 400°C for various duration times were carried out to establish the most optimal process condition. Grain size, misorientation angle, and preferred orientation were measured by electron back scattered diffraction method.

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II. Experimental Procedure

The raw materials used in this study were commercial AA3003 with thickness of 2mm and pure copper sheets (C11000) with thickness of 0.3mm in fully annealed condition, of which the specifications are given in Table I. The hot rolling bonding experiments were carried out at 100°C with speed ratio of 2 and the total thickness reduction was 45%. To remove presumably existing oxides, adsorbed ions, greases and dust particles on the surface of raw materials, the metal surface was degreased in acetone for 5min, and then scratched using circumferential brush with 0.3mm diameter stainless steel wires running at 120 rpm. The component metals were stacked together by a soft aluminum wire in the means of copper lying underneath aluminum. The stack combination was fed into the rolling mill without lubrication as schematically illustrated in Fig. 1.

TABLE I
SPECIFICATION OF THE RAW MATERIALS USED IN THIS STUDY

Material	Chemical composition (wt.%)	Tensile strength (MPa)	Elongation (%)
AA3003	98.8Al, 1.2Mn	140	23
C11000	99.9Cu	210	24

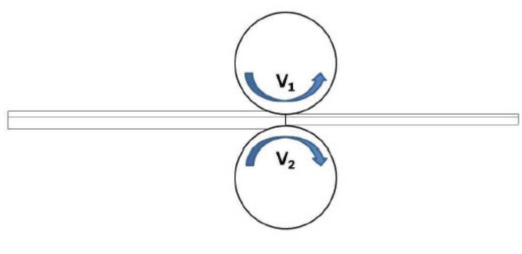

Fig. 1 Schematic illustration of DSR process used in this study

The clad sheets were heat-treated to reduce the residual stress and enhance the effect of precipitation hardening in a furnace at 400°C for 30 to 120min, followed by air cooling as shown in Fig. 2. All specimens were sealed in quartz tube filled with Ar gas to protect oxidization as given in Fig. 3. The cross-section of samples were ground and polished following the standard metallographic procedures, and etched in a solution of 5ml HNO_3, 3ml HCl, 2ml HF, and 190ml H_2O. Microstructure of interfacial layers was analyzed using back scattered electron diffraction (EBSD). Microstructure observation was carried out on TD plane of clad sheets.

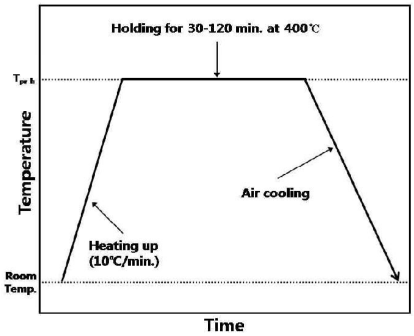

Fig. 2 Schematic illustration of heat-treatment conducted after cladding by DSR process

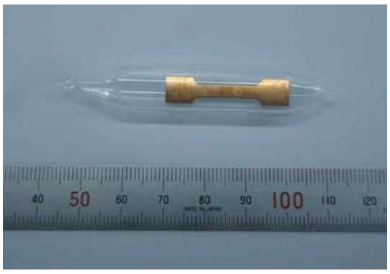

Fig. 3 Appearance of sample for annealing after DSR bonding sealed in quartz tube filled with Ar gas

III. Results and Discussion

Fig. 4 shows appearances of clad sheets hot-rolled at 100^{o}C under the speed ratio of 2:1 with thickness reduction of 45%. Cladding was successfully completed and it is interesting to note that shear deformation of Al sheet is much severer than that of Cu.

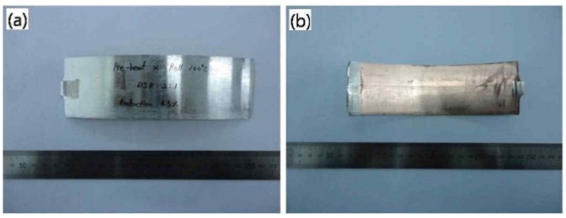

Fig. 4 Appearances of clad sheet processed by DSR at 100^{o}C under the speed ratio of 2:1 with thickness reduction of 45%, showing Al (a) and Cu (b) sides, respectively

Interface observation after cladding revealed that any void or crack could not be observed. Interface area was observed by SEM on the specimens annealed at 400^{o}C for 30 to 120min after hot-rolling at 100^{o}C under the speed ratio of 2:1 with thickness reduction of 45%, and It was found that intermetallic layer of above 3μm thickness was formed and any delamination of interface was not found regardless of annealing times. From EDS analysis, composition gradients were observed through the interface area. By post annealing heat treatment, tensile elongation of cladded sheets were dramatically increased with tensile strengths in the range comparable to Al 3003 raw material.

Figs. 5 and 6 show results of EBSD analysis on pure Cu and Al 3003, respectively, of initial state before annealing treatment. As shown in Fig. 5, initial microstructure of pure Cu layer after DSR process shows elongated grains aligned along rolling direction and average grain size was 3.82μm. The fraction of low-angle grain boundary was measured as 40% and it is apparent that sub-grain structure was dominantly formed by DSR bonding. Preferred orientation of Cu was determined as <101>//ND from the inverse pole figure and maximum pole intensity was as high as 4.177.

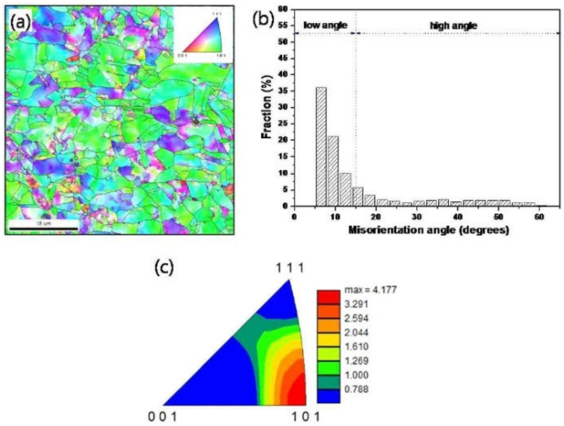

Fig. 5 EBSD analysis results conducted on pure Cu layer before annealing treatment showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

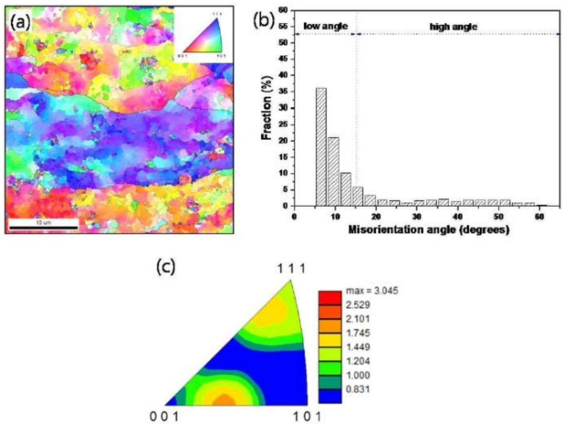

Fig. 6 EBSD analysis results conducted on Al 3003 layer before annealing treatment showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

On the other hand, initial microstructure of Al 3003 layer after DSR process shows bimodal distribution consisting of grains less than 5μm and larger than 20μm, of which the average grain size is 18.6μm, although grains are also elongated aligned along rolling direction. The fraction of low-angle grain boundary was measured as 67%, showing sub-grain structure. Preferred orientation of Al 3003 was determined as <001>//ND.

Figs. 7 and 8 show results of EBSD analysis on Cu and Al layers of clad sheet after annealing treatment at 400^{o}C for 30min. As shown in Fig. 7, microstructure of pure Cu layer after annealing for 30min shows still deformed grains with wide range of grain size from 0.5 to 9μm aligned along <101>//ND and average grain size was 3.9μm. It is apparent that fraction of low-angle grain boundary with misorientation angle less than 10^{o} was still high and measured as 32%.

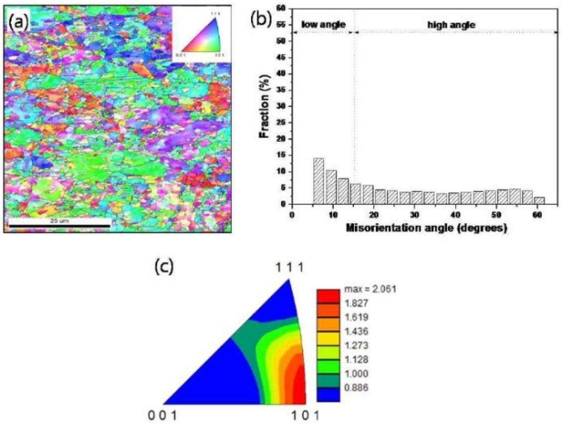

Fig. 7 EBSD analysis results conducted on Cu layer after annealing treatment at 400^{o}C for 30 min, showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

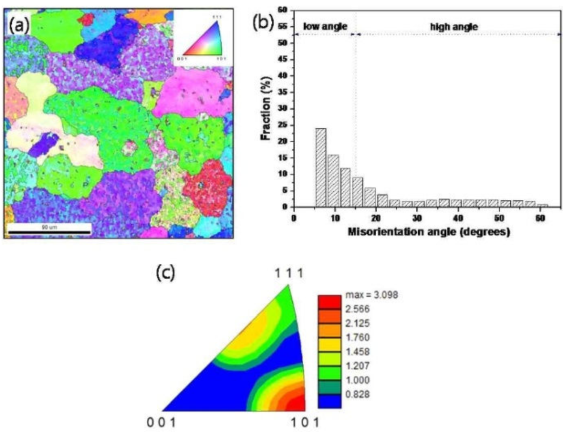

Fig. 8 EBSD analysis results conducted on Al layer after annealing treatment at 400^{o}C for 30 min, showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

Microstructure of Al layer after annealing for 30min given in Fig. 8 shows large grains with preferred orientation of <101>//ND and average grain size was 45μm. It is interesting to note that fraction of low-angle grain boundary was still as high as 53%, showing grain growth and sub-grain formation occurred simultaneously during annealing treatment [6]. Preferred orientation was changed from <001>//ND to <101>//ND.

Figs. 9 and 10 show results of EBSD analysis on Cu and Al layers of clad sheet after annealing treatment at 400^{o}C for 60min. As shown in Fig. 9, microstructure of pure Cu layer after annealing for 60min shows still deformed grains of average grain size of 2.6μm with large amount of elongated grains aligned along rolling direction, of which the preferred orientation was <111>//ND. The fraction of low-angle grain boundary with misorientation angle less than 10^{o} was still high and measured as 30%. Preferred orientation was changed from <101>//ND to <111>//ND.

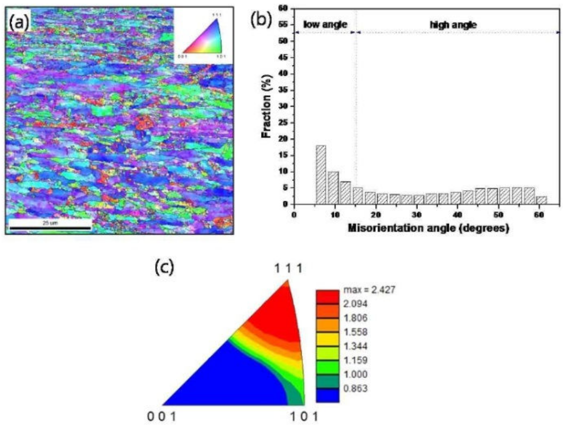

Fig. 9 EBSD analysis results conducted on Cu layer after annealing treatment at 400^{o}C for 60 min, showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

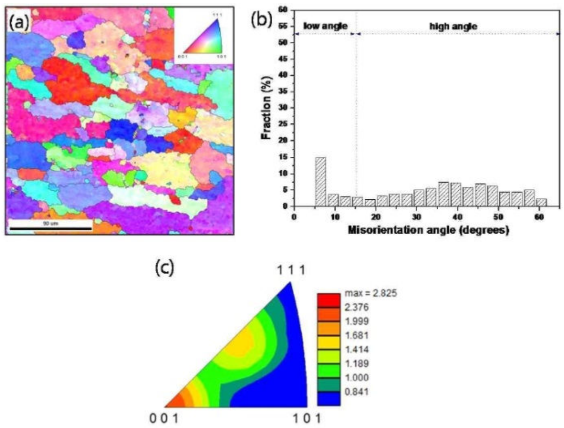

Fig. 10 EBSD analysis results conducted on Al layer after annealing treatment at 400^{o}C for 60 min, showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

Microstructure of Al layer after annealing for 60min given in Fig. 10 shows smaller grains with wide range from 2 to 60μm and average grain size was 39μm. Preferred orientation was again changed into <001>//ND and the fraction of low-angle grain boundary with misorientation angle less than 10^o was still high and measured as 22%.

Figs. 11 and 12 show results of EBSD analysis on Cu and Al layers of clad sheet after annealing treatment at 400^oC for 120 min. As shown in Fig. 11, microstructure of pure Cu layer after annealing for 120min shows deformed grains with sub-grain structure. Average grain size was 3.4μm with range from 0.4 to 7μm and large amount of elongated grains were still aligned along rolling direction, of which the preferred orientation was <111>//ND, which is typical texture of Cu alloy [7]. The fraction of low-angle grain boundary with misorientation angle less than 10^o was still high and measured as 39%.

Microstructure of Al layer after annealing for 120min given in Fig. 12 shows relatively fine grains with average grain size of 24.5μm. Preferred orientation was mainly <111>//ND and fraction of low-angle boundary was much reduced.

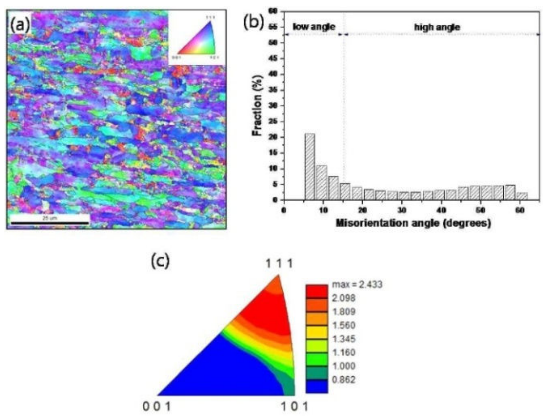

Fig. 11 EBSD analysis results conducted on Cu layer after annealing treatment at 400^oC for 120 min, showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

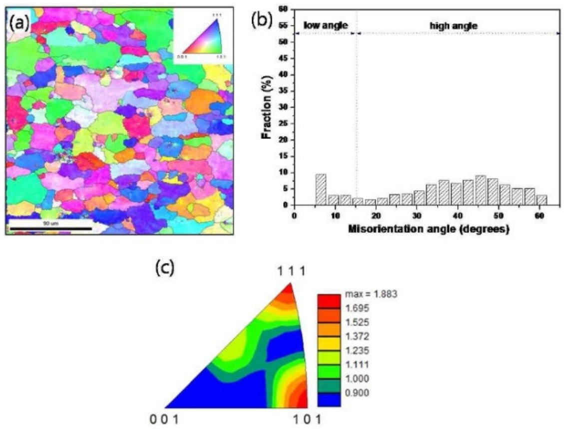

Fig. 12 EBSD analysis results conducted on Al layer after annealing treatment at 400^oC for 120 min, showing (a) orientation image map, (b) distribution of grain boundary misorientation angle and (c) inverse pole figure

IV. Conclusions

In the present study, Al/Cu clad sheets were produced by differential speed rolling at 100^oC under the speed ratio of 2:1 with thickness reduction of 45%. Grain size, misorientation angle, and preferred orientation were measured by electron back scattered diffraction method before and after annealing treatment. Initial microstructure of pure Cu layer and Al 3003 layer after DSR process showed elongated grains aligned along rolling direction with large amount of low-angle boundaries. Preferred orientations of Cu and Al layers were determined as <101>//ND and <001>//ND, respectively. With annealing time increased, fraction of low-angle boundary decreased rapidly in Al layer but remained high level in Cu layer. Preferred orientations of Cu and Al layers were changed into <111>//ND in both cases.

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