Kovove Mater. 55 2017 7–12
DOI: 10.4149/km_2017_1_7

Strength and electrical conductivity of roll-bonded Cu/Al-Mg-Si/Cu clad composite

W.-N. Kim, S. I. Hong*

Department of Advanced Materials Engineering, Chungnam National University, Daejeon, Republic of Korea

Received 25 May 2016, received in revised form 8 December 2015, accepted 18 January 2016

Abstract

Tri-layered Cu/Al-Mg-Si/Cu clad composite was cold roll-bonded, and its mechanical/electrical properties were studied. In the roll-bonded and aged Cu/Al-Mg-Si/Cu clad composite, neither interfacial reaction layer nor interface defects were observed. The strength as high as 415 MPa with the conductivity of 82 % IACS was attained in 3-ply light-weight Cu/Al-Mg-Si/Cu clad composite. The ductility and conductivity of clad composite are increased appreciably with heat treatment at 175 °C. After mechanical testing, the interface crack propagation and fracture in the well-bonded interface between metallic Cu and Al occurred in softer Al matrix. The increase of detached Al lumps onto the separated Cu side in clad composite heat-treated at 175 °C strongly supports that the interface bonding can be enhanced during aging of Al-Mg-Si alloy layer in Cu/Al-Mg-Si/Cu clad composite. The increased ductility in the aged Cu/Al-Mg-Si/Cu clad composite can be attributed to the enhanced interface bonding and precipitation in Al-Mg-Si layers.

K e y w o r d s: composites, clad, roll bonding, interface, strength, conductivity

1. Introduction

The clad metals, consisting of two or more metallic layers, have advantages compared to individual metals and alloys for a variety of applications. The performance of clad composite materials is determined by the design and selection of component materials to be joined, the stacking structure and thickness of different materials. Roll bonding is the most cost-competitive process to produce clad or hybrid metal sheets because of fast and efficient production rate [1–5]. Since bonding at the interface between similar and dissimilar metals is obtained during roll-bonding, variations of the strain state in the roll gap, reduction ratio and rolling temperature are of great importance.

Cu/Al clad composites have attracted the interest of many investigators, because of their merits associated with low density, good electrical conductivity and cost-competitiveness compared to Cu and Cu alloys. Bi-layered Al/Cu clad composite sheets could almost reduce the weight by 40 %, with the electrical and thermal conductivity equivalent to those of Cu alloys. Furthermore, the material expenses can be decreased by 40 % compared to those of Cu alloys. Aluminum clad copper is frequently used as busbar conductor joint, electrical wires, communication wires and cables, armored cables, yoke coils, electronics chassis and cookwares [6, 7]. In many applications Cu/Al clad can directly replace solid copper or aluminum.

Producing Cu/Al clad sheet, however, is a great challenge due to the different chemical and physical properties of copper and aluminum. The formation of the brittle intermetallic layers at the interface during high-temperature heat treatments seriously weakens the interface strength. The nature and properties of interfacial intermetallic layers in as-roll-bonded and annealed Al/Cu are not completely understood [3]. The properties and reliability of clad composite are dependent on the interface properties. The ductility of clad does not increase in case the interface bonding strength is low because of the interface flaws, voids and brittle intermetallics [8, 9].

In this study, 3-ply Cu/Al-Mg-Si/Cu plates were fabricated by a roll-bonding process, and the mechanical performance and electrical properties were studied. The influence of aging on the electrical conductiv-

*Corresponding author: tel.: +82-42-821-7637; e-mail address: sihong@cnu.ac.kr

ity and hardness of Cu/Al-Mg-Si/Cu clad metal were studied. The objective of the present work was to examine the effect of aging on mechanical and electrical properties of tri-layered Cu/Al-Mg-Si/Cu clad composite to find a way to enhance the properties of layered clad composites.

2. Experimental

In the present study, stacked copper and Al-Mg-Si plates were roll-bonded at room temperature. Materials used for roll-bonding in the present study were pure OFHC copper and Al-1.0wt.%Mg-0.6wt.%Si-0.25wt.%Cu-0.2wt.%Cr. Al-Mg-Si plates were solution treated, and Cu plates were annealed at 800 ℃ for 1 h before roll-bonding. Stacked Cu/Al-Mg-Si/Cu plates were rolled at a reduction ratio of 78.7 % at room temperature. Al-Mg-Si alloy sheet with 2 mm thickness and Cu sheet with 1 mm thickness were stacked and rolled. The post-roll-bonding thickness of whole clad composite plate was measured to be 0.85 mm, and that of the copper layer and Al-Mg-Si layer was 0.2 and 0.45 mm, respectively. Some clad Cu/Al-Mg-Si/Cu composites were aged at 175 ℃ for 3 and 6 h to examine the effect of aging in Al alloy on the overall performance of clad materials. The interface structures of Cu/Al-Mg-Si/Cu clad composites were observed by a scanning electron microscope (SEM) and an optical microscope (OM). The hardness of each layer in as-roll-bonded and heat-treated clad composites was measured using a micro-Vickers hardness tester to examine the effect of heat treatment on the hardness of Al alloy and Cu layers. In this study, the mechanical properties and interface behavior were studied in tensile testing to examine the interface behavior during extensive tensile forming. The mechanical testing was performed using a Universal Materials Testing Machine (UNITED, US/SSTM) at room temperature at the strain rate of 1×10^{-3} s^{-1}. The gauge width and gauge length for tension testing specimens were 1.5 and 3.19 mm, respectively.

3. Results and discussion

Figure 1 shows the optical micrographs of Cu/Al-Mg-Si interfaces of tri-layered Cu/Al-Mg-Si/Cu clad composite, as-rolled (a), aged at 175 ℃ for 3 h (b), 6 h (c). No intermetallic compound layers were observed at the interface in the as-roll-bonded and aged composites. As-roll-bonded and aged Cu/Al clad composites exhibited no interfacial cracks and defects. It suggests that the bonding interface between Al-Mg-Si and Cu is intact. Kim and Hong investigated [1] the interface structure of tri-layered Cu/Al/Cu clad composite and demonstrated the presence of Cu_9Al_4, Cu_3Al_2 and

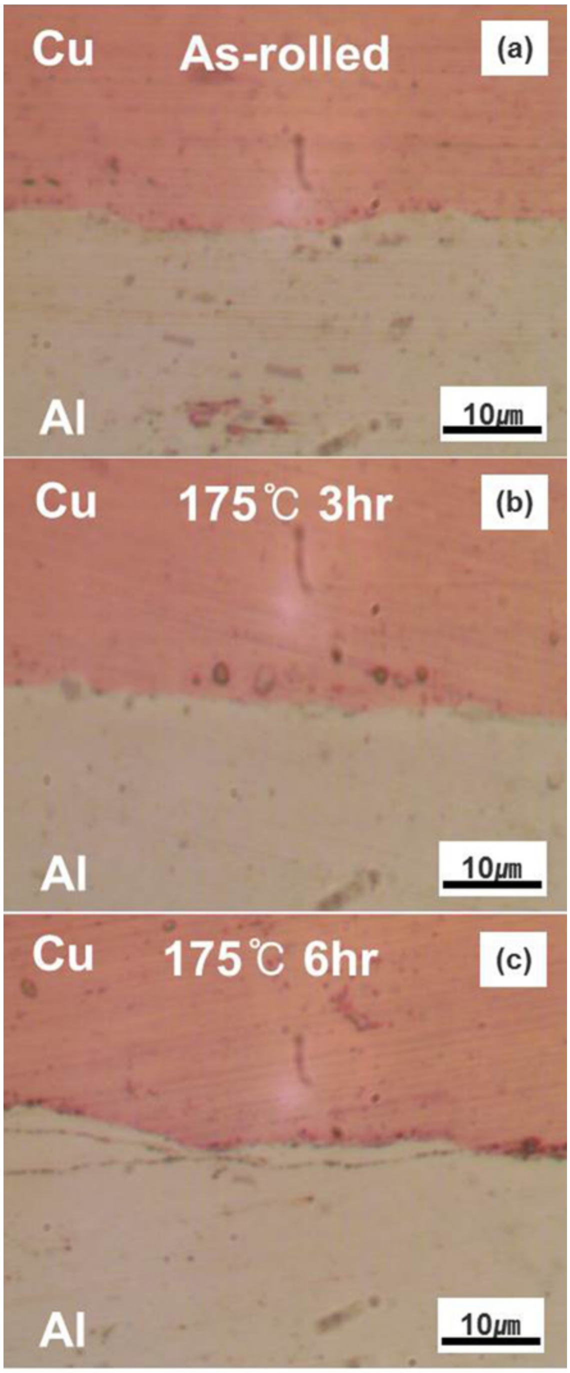

Fig. 1. Optical micrographs of Cu/Al-Mg-Si interface region in Cu/Al/Cu clad metals (a) as-roll-bonded, aged at 175 ℃ for 3 h (b), 175 ℃ for 6 h (c).

CuAl intermetallic layers heat-treated above 300 ℃. They reported [1], however, that no visible intermetallic layers were observed at the Cu/Al interface by optical microscopy after annealing at 200 ℃. It has also been shown that the intermetallic layer with the thickness smaller than 10 μm does not deteriorate the mechanical reliability of interface in clad composites [1, 2,

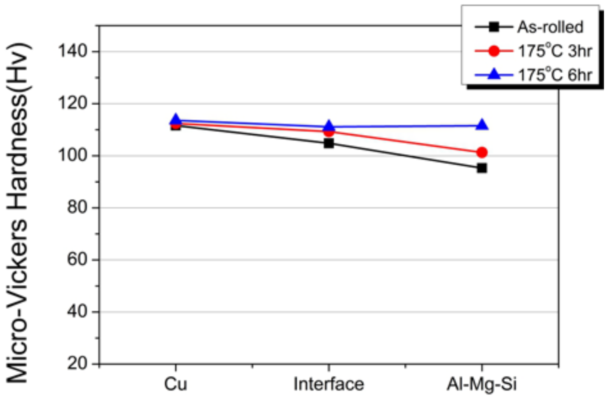

Fig. 2. Vickers hardness of as-roll-bonded and aged Cu/Al-Mg-Si/Cu clad composites.

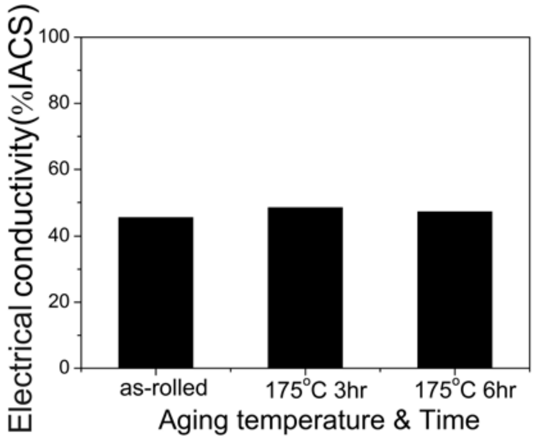

Fig. 3. The electrical conductivity of as-roll-bonded and aged Cu/Al-Mg-Si/Cu clad composites.

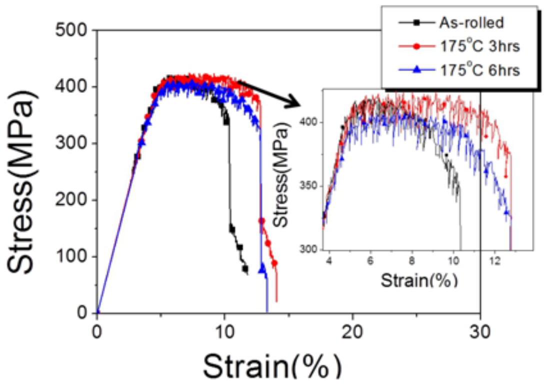

Fig. 4. Stress-strain curves of as-roll-bonded and aged Cu/Al-Mg-Si/Cu clad composites.

10–12]. Sheng et al. [13] also reported the presence of intermetallic layers in Cu-Al bimetal composite heat-treated at 300 ℃ after cold-roll-bonding. They, however, reported [13] that no intermetallic layers formed at the Cu/Al interface in Cu/Al clad heat-treated at 150 ℃ for 1 h. They [13] observed the $CuAl_2$ intermetallic layer with the thickness of approximately 100 nm when Cu-Al was heat-treated at 150 ℃ for 20 h. It is, therefore, reasonable to assume the absence or negligible effect of the intermetallic layer in the as-rolled and aging-treated (at 175 ℃) tri-layered composite in the present study.

Micro-Vickers hardness values of the clad metal in Cu layer, Al-Mg-Si layer and the interface region of 3-ply Cu/Al-Mg-Si/Cu clad composite are shown in Fig. 2. The microhardness at the Cu/Al-Mg-Si interface is the average of microhardness values at the Cu and Al-Mg-Si layers. The hardness of Cu layer is not appreciably changed by heat treatment at 175 ℃ because the heat treatment temperature is far lower than the typical recovery temperature (~ 450 ℃) of Cu [14]. The microhardness of Al alloy layer in the as-rolled condition is smaller than that of Cu layer. However, the microhardness of Al alloy layer (95 HV) before aging heat treatment was found to be greater than that (80 HV) typically observed in solution-treated 6061 Al because of deformation and deformation-induced precipitation during roll-bonding [15]. Figure 2 shows that the microhardness of Al-Mg-Si layer increased up to 113 HV by aging at 175 ℃. The microhardness of as-rolled Al-Mg-Si aged at 175 ℃ for 6 h was similar to that of Cu layer. The increase of hardness with aging at 175 ℃ is mainly due to the precipitation in Al-Mg-Si alloy [16–18].

Figure 3 shows electrical conductivity of as-rolled and aged Cu/Al-Mg-Si/Cu clad composite. The electrical conductivity of as-rolled Cu/Al-Mg-Si/Cu clad composite was measured to be approximately 80 % IACS. After aging heat treatment, the electrical conductivity of Cu/Al-Mg-Si/Cu clad composite increased slightly to ~ 83 % IACS. The insensitivity of conductivity to the aging treatment of Cu/Al-Mg-Si/Cu clad composite is thought to be associated with precipitation by aging during roll-bonding and large volume fraction of Cu. Kim and Hong [3] suggested that the temperature during roll-bonding could reach ~ 80 ℃, which may promote precipitation during roll-bonding. The higher hardness value and insensitivity of conductivity to the aging treatment in the roll-bonded Cu/Al-Mg-Si/Cu clad composite support the possible precipitation during the roll-bonding process.

In Fig. 4, stress-strain curves of the as-roll-bonded clad plate and aged clad plate at 175 ℃ are exhibited. As-rolled Cu/Al-Mg-Si/Cu clad composite and aged Cu/Al-Mg-Si/Cu clad composite at 175 ℃ for 6 h showed similar yield strength and ultimate tensile strength. The strengths of as-rolled and aged Cu/Al-Mg-Si/Cu clad composites were found to be as high as 415 MPa. The strength of 3-ply Cu/Al-Mg-Si/Cu clad composite was not observed to be greatly influ-

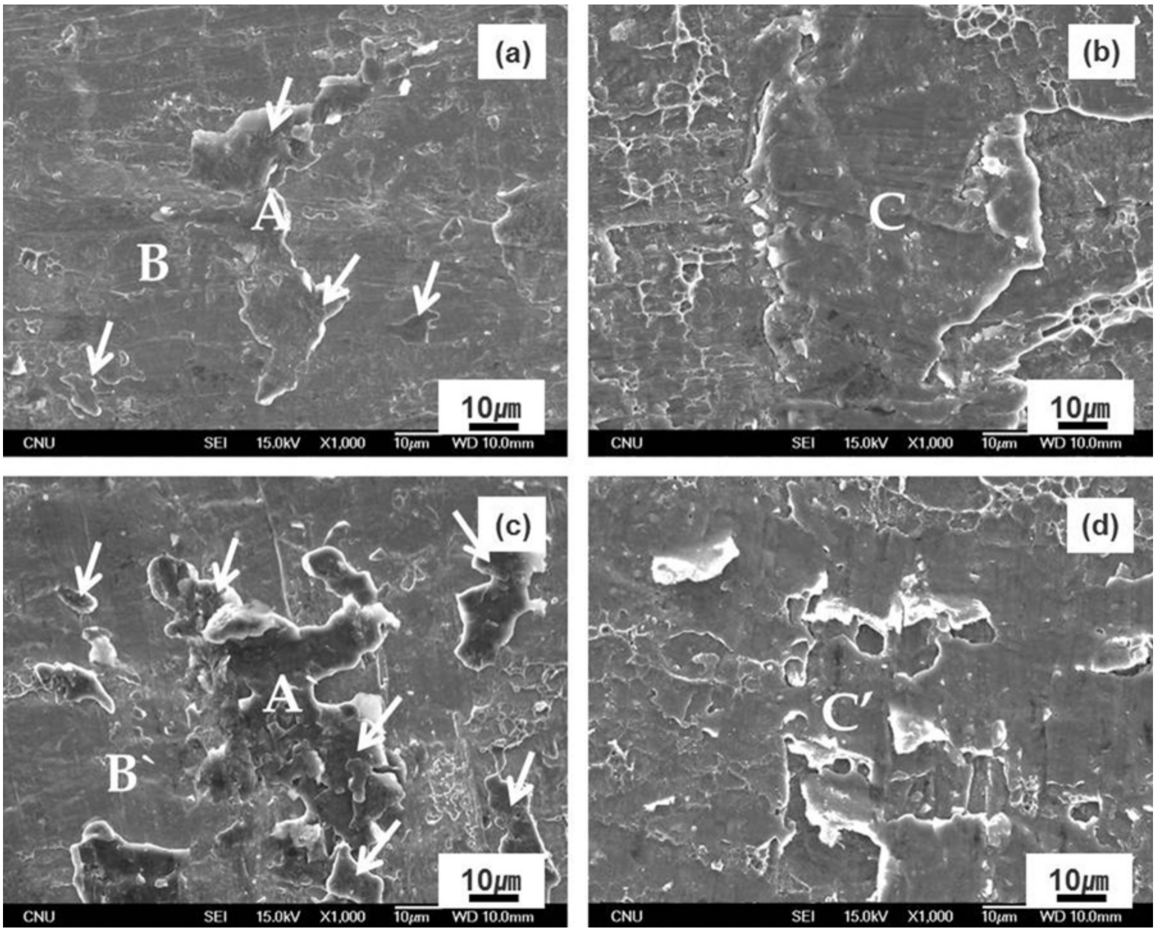

Fig. 5. SEM images of separated interface fracture surfaces of peeled-off Cu plate (a, c) and Al-Mg-Si plate (b, d) of Cu/Al-Mg-Si/Cu clad composites; as-roll-bonded (a, b) and heat-treated at 175 ℃ for 6 h (c, d).

enced by aging because of the greater contribution of Cu to the overall strength. In the Cu/Al-Mg-Si/Cu clad composite aged at 175 ℃ for 3 h, the yield stress, and ultimate tensile strength increased slightly. In the as-roll-bonded Cu/Al-Mg-Si/Cu clad composite, the strain softening occurred after yielding, resulting in the lower ductility. In the aged Cu/Al-Mg-Si/Cu clad composite, extended stress saturation behavior probably caused by the balance between Cu and Al-Mg-Si layers due to precipitation hardening in Al is observed in Fig. 2. In Fig. 4, sudden stress drops due to the premature fracture of Cu layer are exhibited in all Cu/Al-Mg-Si/Cu clad composites, and subsequent fracture of Al layers ensued after 1–2 % extra elongation.

In order to examine the effect of heat treatment at 175 ℃ on the interface bonding nature in Cu/Al-Mg-Si/Cu clad composite, the Cu/Al-Mg-Si interface was deliberately peeled off, and the separated interface fracture surfaces were observed. Figures 5a–d exhibit SEM images of separated interface fracture surfaces of peeled-off Cu plate (a, c) and Al-Mg-Si plate (b, d) of as-roll-bonded (a, b) and heat-treated (c, d) (at 175 ℃ for 6 h) Cu/Al-Mg-Si/Cu clad composites. The peeled-off interface fracture surface of Cu side revealed irregular island-shaped regions, which have the chemical composition different from Cu as is shown in Fig. 6.

Element	Atomic%
Mg K	0.92
Al K	98.91
Cu L	0.18
Totals	100

Element	Atomic%
Cu L	100.00
Totals	100

Element	Atomic%
O K	4.39
Mg K	0.99
Al K	94.04
Si K	0.58
Totals	100

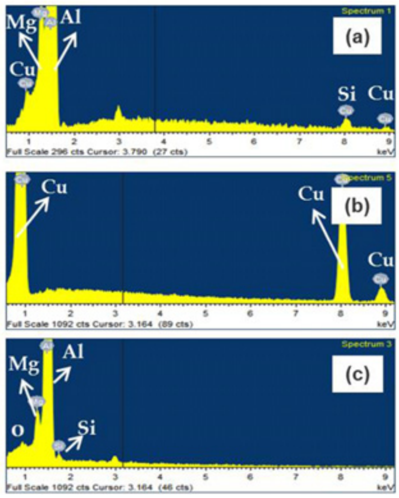

Fig. 6. EDX spectra from the point marked with A', B' (a, b) on the separated fracture surface of Cu plate (Fig. 5c) and those from the point marked with C' on the separated fracture surface of Al plate (Fig. 5d).

The island-shaped regions increased appreciably after heat treatment at 175 ℃ for 6 h. Figures 6a–c display the energy-dispersive X-ray spectroscopy (EDX) spectra from the points marked with A', B' on the separated fracture surface image of Cu plate in Fig. 5c and those from the point marked with C' on the separated fracture surface image of Al plate in Fig. 5d. The EDX spectra from points marked with A, B, and C in Figs. 5a,b are similar to those shown in Fig. 6 and will not be shown. It is interesting to note that the EDX spectra in Fig 6a from region A' (an island--shaped region in Fig. 5c) show the presence of mainly Al ($\sim$ 99 wt.%), suggesting the island-shaped region is detached from Al plate and joined onto the Cu surface [3]. The EDX spectra from region B' (Fig. 5c) exhibited mainly Cu peak (100 wt.%), which may represent the unbonded or weakly bonded region. On the other hand, the EDX spectra from region Al plate (marked with C' in Fig. 5d) show the presence of only Al. The comparison of the fracture surface and EDX spectra of Cu side with those of Al side suggests that the island-shaped region on Cu fracture surface (Figs. 5a,b) was formed during the final detachment and separation of island-shaped Al lump attached to the copper layer.

Kim and Hong [3] reported that the crack propagation and fracture would occur in softer Al matrix away from the well-bonded interface between metallic Cu and Al, resulting in the Al lumps on Cu and no Cu lumps on Al, supporting EDX spectra analysis results in Fig. 6. The increase of island-shaped region (detached Al lumps onto Cu) on the Cu side interfacial fracture surface in clad composite heat-treated at 175 ℃ for 6 h strongly supports that the interface bonding would also be enhanced during aging heat treatment of Al-Mg-Si alloy layer in Cu/Al-Mg-Si/Cu clad composite. Therefore, the increased ductility after aging in Fig. 4 can be attributed to the accumulation of dislocations in the presence of precipitates in Al-Mg-Si layer and the enhanced interface bonding [8].

Hong and his coworkers [8, 19, 20] suggested that the ductility of clad composite could be enhanced if the interface bonding strength were enhanced. They [8, 19] suggested that the local necking of one metal layer could be suppressed by the facing joined layer if the interface bonding were strong, resulting in the promotion of homogenous plastic deformation caused by the interactive constraint imposed by the attached facing layer. They [8, 19] reported that constraint and interaction by the adjacent attached facing metal layer could be made by the transfer of stress and strain through the joined interface. It is not clear if the interface bonding is enhanced during aging heat treatment at 175 ℃, but the increased ductility of clad composite after heat treatment may support the enhanced interfacial bonding as suggested by Kim and Hong [19]. Figure 7 showed the SEM images of the fractured tensile specimens, (a) as-rolled and aged at 175 ℃ for 3 h (b) and 6 h (c). Cu layers at the outer surfaces were found to be well-bonded to the Al-Mg-Si plate even after final fracture, indicating an excellent bonding between Al-Mg-Si and Cu in the as-rolled and aged clad composites at 175 ℃.

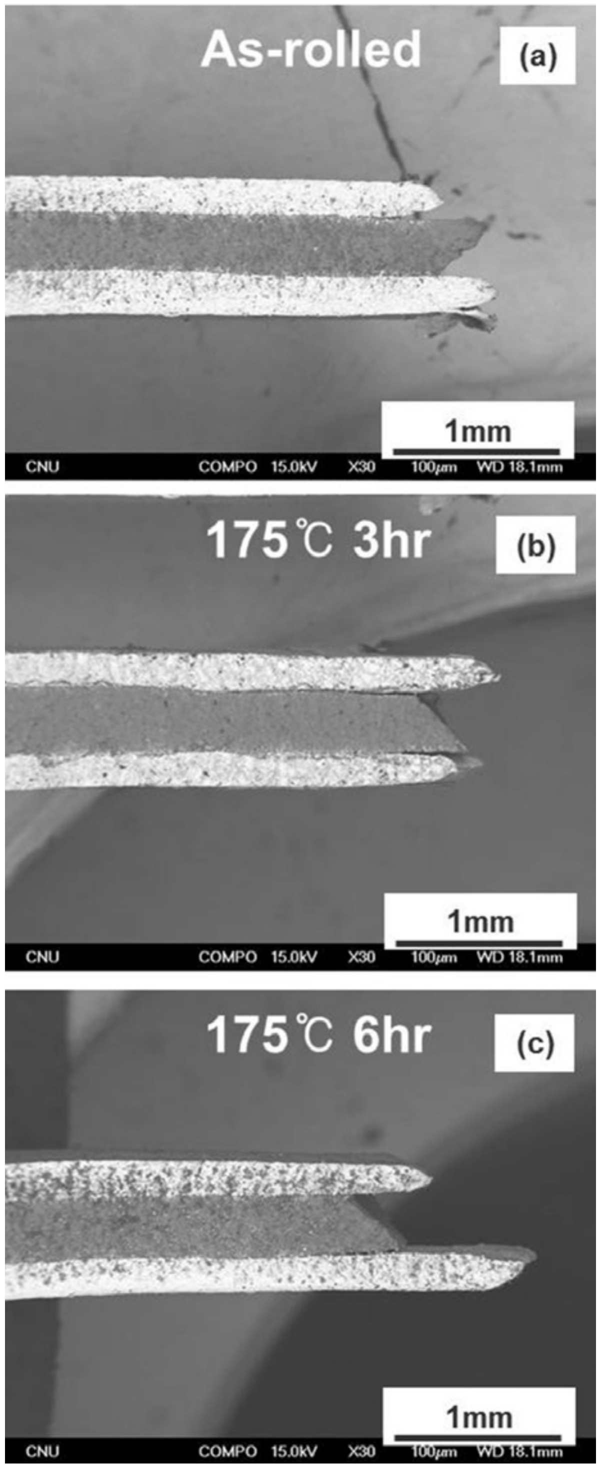

Fig. 7. An edge view of the tensile specimens after tensile fracture.

4. Conclusions

In this study, mechanical and electrical properties in Cu/Al-Mg-Si/Cu clad metals were studied. The following important observations were made:

1. In this study, light-weight conducting clad materials with high strength and excellent conductivity were developed. The strength as high as 415 MPa with the conductivity of 83 % IACS was attained in tri-layered Cu/Al-Mg-Si/Cu clad composite.

2. The comparison of the peeled-off interface fracture surface and EDX spectra of Cu side with those of the Al side suggests that the interface crack propagation and fracture in the well-bonded interface between metallic Cu and Al occurred in softer Al matrix, resulting in the detached Al lumps on Cu.

3. The increase of detached Al lumps on the Cu side in clad composite heat-treated at 175 ℃ for 6 h strongly supports that the interface bonding can be enhanced during aging heat treatment of Al-Mg-Si alloy layer in Cu/Al-Mg-Si/Cu clad composite.

4. The increased ductility in the aged Cu/Al-Mg--Si/Cu clad composite can be attributed to the accumulation of dislocations in the presence of precipitates in Al-Mg-Si layers and the enhanced interface bonding, resulting in the overall increase of ductility of clad composite.

5. Sudden stress drops due to the premature fracture of Cu layer were observed in all Cu/Al-Mg-Si/Cu clad composites, and subsequent fracture of Al layers ensued after 1–2 % extra elongation.

6. Cu layers at the outer surfaces were found to be well-bonded to the Al-Mg-Si plate even after final fracture, indicating an excellent bonding between Al--Mg-Si and Cu in the as-rolled and aged clad metals at 175 ℃.

Acknowledgement

The authors are grateful for the support from the 2nd phase of the Fundamental R&D Programs for Core Technology of Materials funded by Ministry of Trade, Industry and Energy (2014–2015).

References

[1] Kim, I. K., Hong, S. I.: Mater. Design, *47*, 2015, p. 590. doi:10.1016/j.matdes.2012.12.070
[2] Kim, I. K., Hong, S. I.: Metall. Mater. Trans. A, *44*, 2013, p. 3890. doi:10.1007/s11661-013-1697-8
[3] Kim, I. K., Hong, S. I.: Mater. Design, *57*, 2014, p. 625. doi:10.1016/j.matdes.2014.01.054
[4] Khosravifard, A., Ebrahimi, R.: Mater. Design, *31*, 2010, p. 493. doi:10.1016/j.matdes.2009.06.026
[5] Kim, I. K., Hong, S. I.: Mater. Design, *49*, 2013, p. 935. doi:10.1016/j.matdes.2013.02.052
[6] Ha, J. S., Hong, S. I.: Mater. Design, *51*, 2013, p. 293. doi:10.1016/j.matdes.2013.04.068
[7] Kim, H., Hong, S. I.: Mater. Design, *67*, 2015, p. 42. doi:10.1016/j.matdes.2014.11.005
[8] Jin, J. Y., Hong, S. I.: Mat. Sci. Eng. A, *596*, 2014, p. 1. doi:10.1016/j.msea.2013.12.019
[9] Konieczny, M.: Kovove Mater., *48*, 2010, p. 47. doi:10.4149/km_2010_1_47
[10] Abbasi, M., Karimi, T. A., Salehi, M. T.: J. Alloy Compd., *319*, 2001, p. 233. doi:10.1016/S0925-8388(01)00872-6
[11] Honarpisheh, M., Asemabadi, M., Sedighi, M.: Mater. Design, *37*, 2012, p. 122. doi:10.1016/j.matdes.2011.12.045
[12] Peng, X. K., Wuhrer, R., Heness, G., Yeung, W. Y.: J. Mater. Sci., *34*, 1999, p. 2029. doi:10.1023/A:1004543306110
[13] Sheng, L. Y., Yang, F., Xia, T. F., Lai, C., Ye, H. Q.: Compos. Part B-Eng., *42*, 2011, p. 1468. doi:10.1016/j.compositesb.2011.04.045
[14] Hong, S. I., Hill, M. A.: Acta Mater., *46*, 1998, p. 4111. doi:10.1016/S1359-6454(98)00106-2
[15] Kim, J. K., Jeong, H. G., Hong, S. I., Kim, Y. S., Kim, W. J.: Scripta Mater., *45*, 2001, p. 901. doi:10.1016/S1359-6462(01)01109-5
[16] Hong, S. I., Gray, G. T., Wang, Z.: Mat. Sci. Eng. A, *221*, 1996, p. 38. doi:10.1016/S0921-5093(96)10483-4
[17] Yigit, R.: Kovove Mater., *52*, 2014, p. 29. doi:10.4149/km_2014_1_29
[18] Ozenc, M., Sekercioglu, T. : Kovove Mater., *52*, 2014, p. 1. doi:10.4149/km_2014_1_1
[19] Kim W. N., Hong, S. I.: Mat. Sci. Eng. A, *651*, 2016, p. 976. doi:10.1016/j.msea.2015.11.062
[20] Ha, J. S., Hong, S. I.: Mat. Sci. Eng. A, *651*, 2016, p. 805. doi:10.1016/j.msea.2015.11.041