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EFFECT OF INTERFACE STRUCTURE ON THE STRESS-STRAIN RESPONSES AND FRACTURE BEHAVIORS IN TRI-LAYERED CU/AL/CU CLAD COMPOSITE

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Abstract: *Stress-strain responses and fracture behavior of roll-bonded and post-roll-bonding heat treated tri-layered Cu/Al/Cu clad composite were investigated. In this study, the effect interface bonding and intermetallic layers on the fracture behaviors were also studied. A brittle interfacial reaction layer formed at the Cu/Al interfaces at and above 400 °C. The thickness of the reaction layer increased with increase of annealing temperature above 300 °C. The strength of tri-layered Cu/Al/Cu clad composite decreased and the ductility increased with heat treatment up to 400 °C. Above 400 °C, the interfacial intermetallics have the detrimental effect on the bonding strength of the Cu/Al/Cu clad composite and the ductility of clad composite, resulting in the rapid drop of ductility. Pronounced interfacial debonding developed along the brittle intermetallic layer above 400 °C, attributing to the decrease of the ductility. No strain incompatibility and cracks were observed across the interface in the as roll-bonded clad composite and, for annealed clad composites at 300 °C, some appreciable strain incompatibility developed, starting to form interface microcracks. For annealed clad composites at 500 °C, the interface crack opened wide up with strain because the separated Cu and Al plate deform, developing their independent necks and fracture independently.*

Keywords: *interface fracture, intermetallic, clad, annealing, Cu/Al/Cu, nanoindentation*

INTRODUCTION

Recently, the demand for advanced composite and clad materials with enhanced properties and functions increased. It is getting more difficult to satisfy the combination of various properties such as superior mechanical and electrical properties in a single material. To meet these demands, clad composite material in which different metals and alloys with various properties were joined have been developed and commercialized in various industrial fields (Hug, & Bellido, 2011; Kim, & Hong, 2015; Matsumoto, Watanabe & Hanada, 2005; Kim, & Hong, 2016; . Siti Mariam, Zuhana & Nizam Abd, 2015). The clad metals, consisting of two or more metals, are attractive because of their unique combination of properties. The properties of clad composite material are determined by the selection of component metals to be joined, the stacking structure and thickness of component metals (Kim,

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& Hong, 2013) and interface structure and properties between bonded metals (Hug, & Bellido, 2011; Ha, & Hong, 2016; Lee, Kim & Jeon, 2016).

Rolling is one of the most useful cost-competitive processes because of its excellent productivity (Jin, & Hong, 2014; Kim, & Hong, 2013). Copper and aluminum clad composites have been widely studied, because of their advantages associated with low density and cost-effectiveness over copper and copper alloys. For example, a two-layer clad sheet of aluminum/copper can almost reduce 40% in weight, with the equivalent electrical and thermal conductivity as a copper alloy. But the cost can be reduced to the 60% of a copper alloy. For these reasons, Al/Cu clad is frequently used for armored cables, yoke coils in TV sets, air-cooling fin and bus-bar conductor joint. However, the formation of brittle intermetallic compound at elevated temperature weakens seriously the interfacial bonding. In this study, the roll-bonded Cu/Al/Cu clad metals were annealed up to 500! for 3hrs in order to induce the formation of the interfacial reaction layer intentionally and its effects on the mechanical properties and fracture behavior were studied. The objective of this research was to examine the interface properties and fracture behavior of annealed clad metals in relation to.

EXPERIMENTAL

The Cu/Al/Cu clad was manufactured using roll bonding of copper and aluminum of the commercial purity. Cu/Al/Cu clad Thickness of 2.0mm and that of Cu and Al plate was 0.2mm and 1.6mm. The clad was annealed from 200 °C to 500 °C for 3hrs and tensile-tested using a Universal Materials Testing Machine (UNITED, US/SSTM) at room temperature. The gauge length and width were 15mm, 3.4mm respectively. The cross-head speed was 0.9mm/min, corresponding to and initial strain rate of 1×10-3/sec. Cu/Al interface microstructure was observed by an optical microscope (OM) and a scanning electron microscope(SEM).

RESULTS AND DISCUSSION

Fig. 1 shows the stress-strain curves of as-rolled and annealed clad metals at various temperatures. The as-rolled clad and that annealed at 200 °C showed the similar behavior, high yield stress followed by a rapid strain softening. On annealing at and above 300 °C, the decreases of the yield strength and the increases of fracture strain can be attributed to the softening associated with recovery/recrystallization in Cu/Al/Cu clad. On annealing at and above 400 °C, the lower yield strength and the gradual work hardening were observed. The fracture strain decreased with increasing annealing temperature from 400 °C to 500 °C, suggesting the increased intermetallic layer has a harmful effect on the ductility.

Fig. 2 shows the reaction layer thickness with various annealing temperatures. As shown in Fig. 2 reaction layer was formed on the specimen annealed above 400

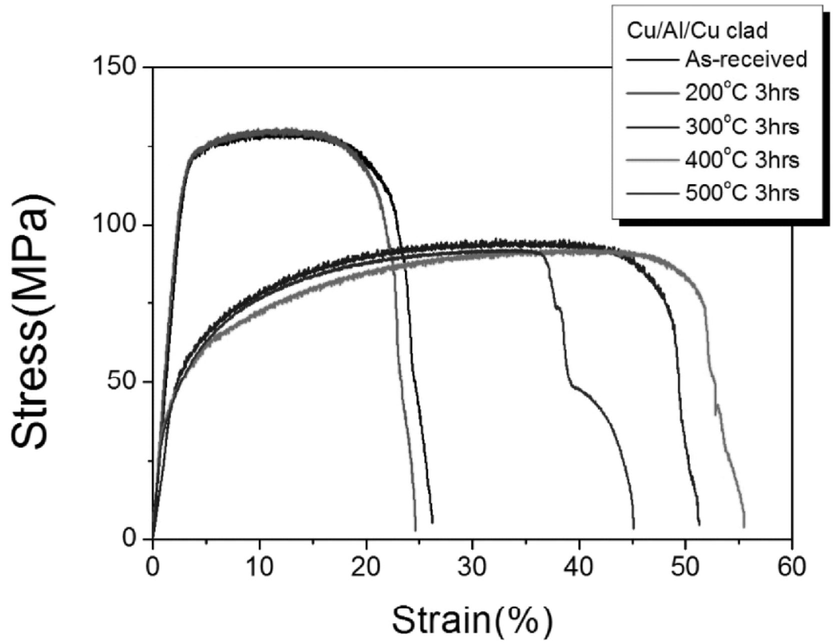

Figure 1: Stress-strain responses of as-roll-bonded clad metals annealed at various temperatures

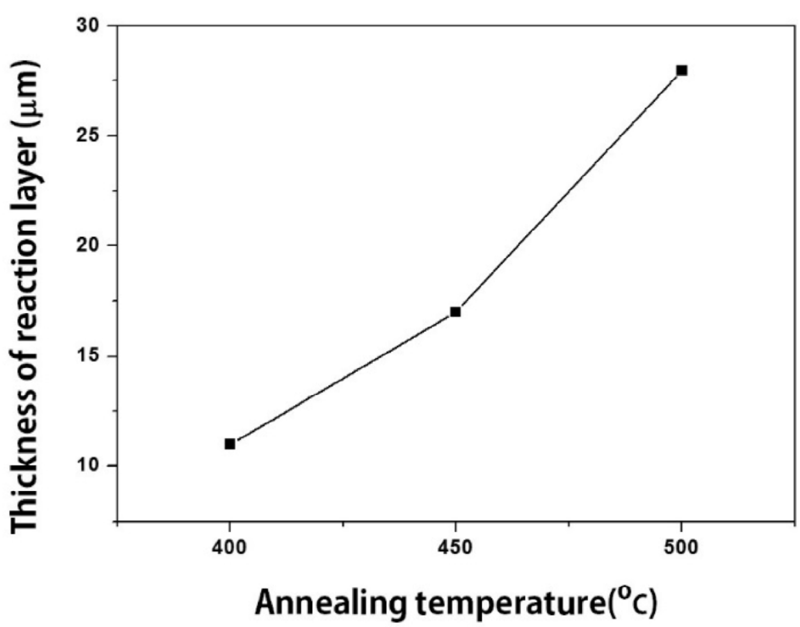

Figure 2: Reaction layer thickness with various annealing temperatures

°C. At the annealing temperature of 400 °C, intermetallic reaction layer thickness was 12µm and increase of annealing temperature 450 °C and 500 °C, the reaction thicknesses are 17 µm, 28 µm respectively.

Fig. 3 shows the interface structure consisting of several intermetallic layers between Al and Cu matrices in Cu/Al/Cu clad composite and nano-indentation results from Cu, Al substrates and various intermetallic layers. Cu/Al/Cu clad were annealed at 500 °C for 64hrs, to grow the each intermetallic layers thick enough for accurate measurements. Kim and Hong (Kim, & Hong, 2013) demonstrated the presence of Cu9Al4, Cu3Al2 and CuAl (Cu3Al4) on the Cu side and CuAl2 and CuAl. Chen and Hwang (Chen, & Hwang, 2007) reported that four layers of intermetallic compounds, were formed at the interface of Cu/Al at 500 °C. In Fig. 3, layer 1, layer 2, layer 3, layer 4 are auumed to be Cu9Al4, Cu4Al3, CuAl, CuAl2. As expected, the hardness values of Cu and Al substrates are low. It appeared that the maximum hardness was attained in layer1 (Cu9Al4) and the hardness decreased gradually step-wise from 1 to layer 2, layer 3 and layer 4. This result is compatible with the suggestion of Kim and Hong (Kim, & Hong, 2014) that Cu9Al4 is most brittle.

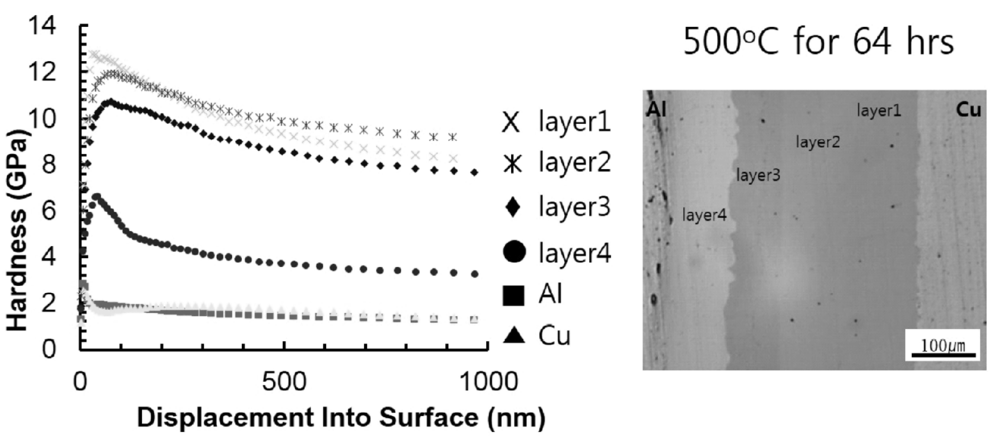

Figure 3: Various intermetallics hardness Cu/Al/Cu clad annealing at 500 °C for 64hrs

Fig. 4 shows the SEM images of the fractured tensile specimens, (a) as-rolled and (b) ~ (e) annealed at 200 °C~500 °C for 3hrs. Despite the necking formation for the all specimens, Cu layer at the outer surfaces were not detached from the Al layer, indicating an excellent bonding between Al and Cu in the as rolled and annealed clad composites at and below 300 °C. This result is consistent with the observation that no intermetallics were formed after annealing at and below 300 °C. Therefore, the Cu and Al layers behave as if they are a single material. This may be due to the enhanced bonding between Cu and Al in the clad annealed at

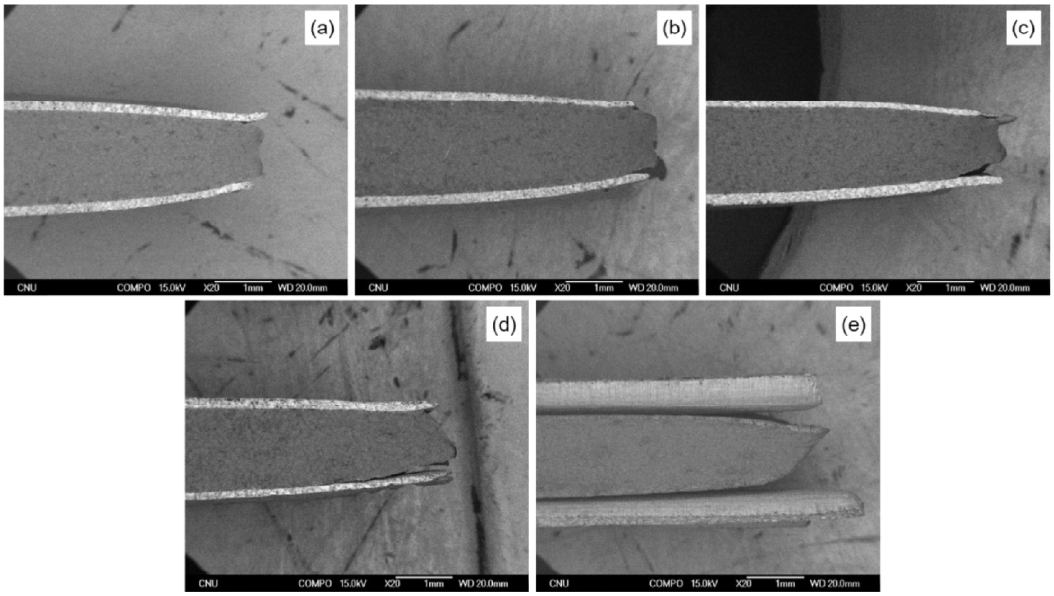

Figure 4: SEM images of the fractured tensile specimens, (a) as-rolled and (b) ~ (e) annealed at 200 °C(b), 300 °C(c), 400 °C(d)~500 °C(e) for 3 hrs.

300 °C (Matsumoto, Watanabe, & Hanada, 2005). The delamination was observed at the Cu/Al interface of the clad metals annealed at and above 400 °C, and it initiated from the intermetallic reaction layer formed at the Cu/Al interface. The length of the delaminated region increased with increasing heat treatment temperature, consistent with the increase of the intermetallic layer with increasing heat treatment temperature. The intermetallic reaction layer has a detrimental effect on the bonding strength of the Cu/Al/Cu clad metal.

Fig. 5 displays the high magnification images, after tensile testing, of the Cu/Al interface region for the rolled clad plate (a) and those annealed at 300 °C (b), 400! (c), and 500 °C (d) for 3hrs respectively. No strain incompatibility and cracks were observed across the interface in the as roll-bonded clad composite, compatible. For annealed clad composites at 300 °C, some appreciable strain incompatibility developed, starting to form interface microcracks. For annealed clad composites at 400 °C, interface cracks grew appreciably and the cracks started to open up from the surface. For annealed clad composites at 450 °C, the interface crack opened wide up with strain because the separated Cu and Al plate deform, developing their independent necks and fracture separately. The periodic secondary cracks were formed on the intermetallic layer perpendicular to the tensile direction because of the strain mismatch between metal layers and the reaction compound layer. It appears clearer that the localized slip developed both in Cu and Al emanating from the open cracks in the intermetallic layer as shown in Fig. 5(c) and 5(d). These

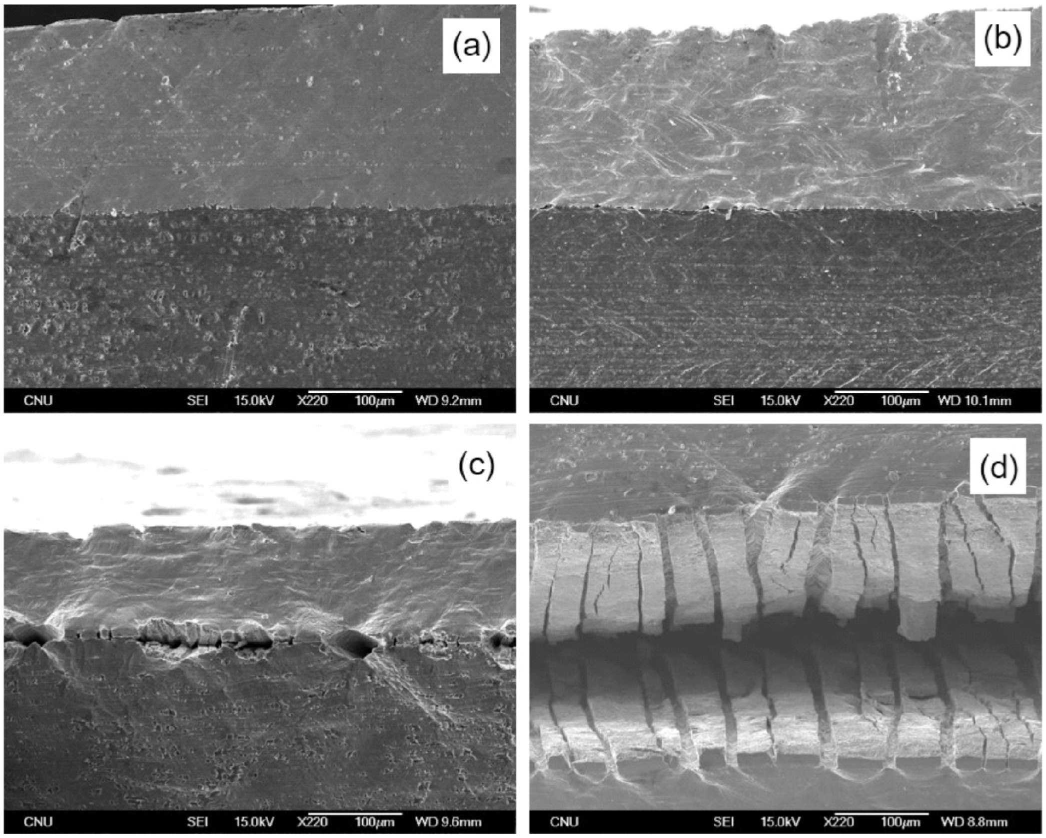

Figure 5: High magnification image of Cu/Al interface region after fracture (a) as-rolled, annealed at (b) 300 °C, (c) 400 °C, (d) 500 °C.

slip localization is likely to induce premature crack formation in Cu and Al layer, resulting in the decreased clad metal fracture strain.

In Fig. 6, fracture surfaces of Cu/Al/Cu clad are exhibited. Fig. 6(a), 6(c), 6(e) shows the fracture surfaces Cu/Al/Cu composite at a low-magnification. Fig. 6(b), 6(d), 6(f) exhibited the fracture surfaces of center Al substrate at a high magnification. Dimples in Al substrate are observed in as-rolled Cu/Al/Cu composite (b) and that annealed at 300! (d). But dimples are not observed in Cu/Al/Cu composite (f) annealed at 500! because of severe thickness-wise deformation and neck formation of Al substrate. The thickness-wise deformation and neck formation of Al substrate increased pronouncedly because Cu layer was detached from Al substrate due to the presence of thick brittle intermetallics. Independent deformation of freed Al substrate from Cu layer due to the brittle intermetallics render severe thickness-wise deformation and neck formation of Al substrate, resulting in the shear-type fracture of Al substrate.

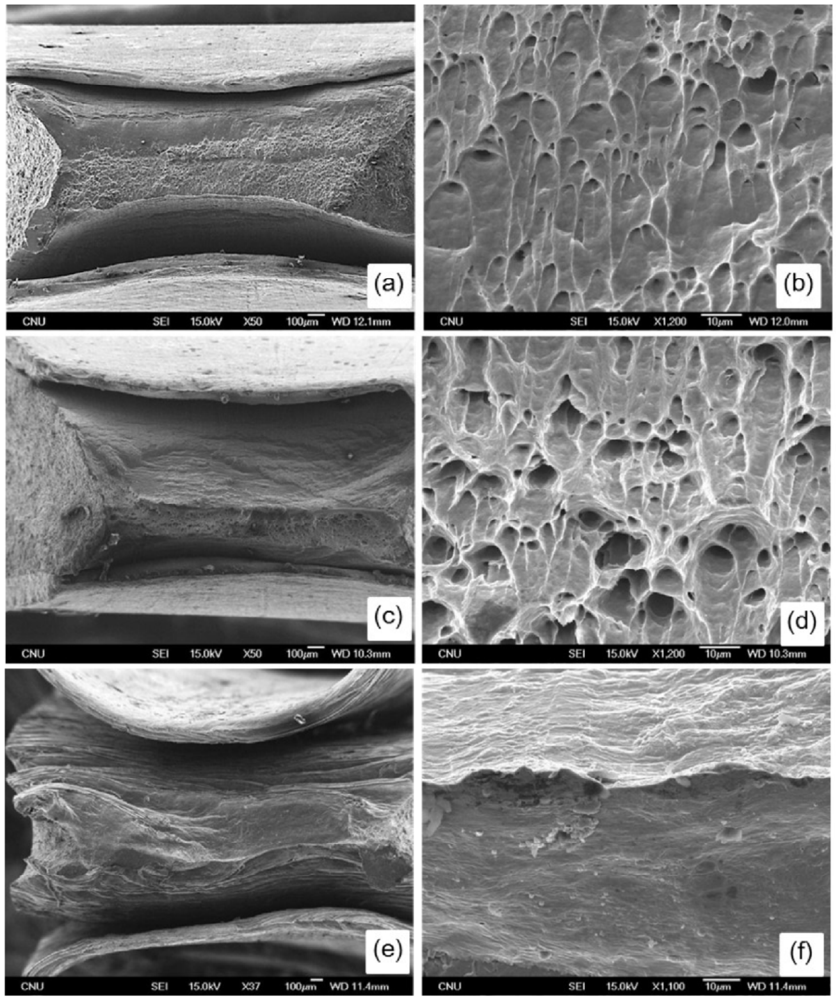

Figure 6: SEM micrographs of fracture surface as-rolled(a, b), annealed at 300! 3hrs(c, d), annealed at 500 °C 3hrs(e, f)

SUMMARY

As a result of the study on the fracture of the roll-bonded Cu/Al/Cu clad metal, the following conclusions were obtained;

1. For as-rolled Cu/Al/Cu and those heat-treated up to 300!, a good combination of strength and ductility was observed with intact bonding along the interface even after the final fracture.
2. Cracks and delamination in reaction layer between Cu and Al were observed after annealing at and above 400 °C, resulting in the reduction of ductility. As the heat treatment temperature increased above 400!, the

ductility decreased. The intermetallic reaction layer has a detrimental effect on the bonding strength of the Cu/Al/Cu clad metal.

3. The maximum hardness was attained in Cu9Al4 layer and the hardness decreased gradually step-wise from Cu9Al4, to Cu4Al3 layer, CuAl layer, and CuAl2 layer. This result is compatible with the suggestion that Cu9Al4is most brittle.
4. The delamination was observed at the Cu/Al interface of the clad metals annealed at and above 400 °C, and it initiated from the intermetallic reaction layer formed at the Cu/Al interface. The length of the delaminated region increased with increasing heat treatment temperature, consistent with the increase of the intermetallic layer with increasing heat treatment temperature.
5. The slip localization at the interface induced premature interface crack formation and delamination at 500!, resulting in the decreased clad metal fracture strain.

Acknowledgments

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