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Fabrication of Al/Cu Clad Sheet by Shear Extrusion

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Abstract**—**Aluminum/Copper clad sheet has been fabricated using asymmetric extrusion method, which caused severe shear deformation between Al and Cu plate to easily bond to each other. Interfacial microstructure and mechanical properties of Al/Cu clad were studied by scanning electron microscope equipped with energy dispersive X-ray detector, micro-hardness, and tension tests. The asymmetric extrusion bonding was very effective to provide a good interface for atoms diffusion during subsequent annealing. The strength of bonding was higher with the increasing extrusion ratio.

Keywords**—**Aluminum/Copper clad sheet, Asymmetric extrusion, Interfacial microstructure, Annealing, Tensile test.

I. INTRODUCTION

COPPER/ALUMINUM (Cu/Al) clad sheet has drawn a growing interest for cost reduction, especially combining the advantages of high specific conductivity and good resistance to corrosion. The sheet shows high formability, electrical and thermal conductivity, making it a promising material for specific application in automobile and electronics industries. However, fabrication of Cu/Al clad sheet is a great challenge due to the different chemical and physical properties of constituent metals. The formation of brittle intermetallic phase, known to be formed at elevated temperature (Cu_xAl_y), deteriorates significantly the interface bonding [1].

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 [2]. The cold roll bonding is known to be more efficient and economical than the other methods [3]. A sound bonding is achieved when surface deformation breaks up the contamination layers and roll pressure causes the extrusion of material through any cracks present in fractured surface [4].Asymmetric rolling method 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 [5], consequently regarded desirable to bond dissimilar component metal, especially for which are difficult to deform.

Circular and special-shaped hollow sections have been used extensively in engineering applications. In many cases, their insides and outsides are exposed to different environments or are required to possess different characteristics. For example, one side of a hollow section may be used under conditions of high temperature or corrosive atmospheres, while the outer side may be required to possess ductility and resistance to impact as a structural component. It is obvious that it is difficult for individual homogeneous materials to satisfy durability and reliability requirements. It is necessary to compound or join different materials to fulfill the desired requirements of providing different properties. Various bimetallic pipes, such as those of stainless steels or high-alloy steels or superalloys clad onto carbon or low-alloy steels, have been utilized in boilers, heat exchangers, nuclear power plants, petroleum, and chemical industries [6, 7] to offer superior resistance to corrosion, oxidation or wear.

Extrusion is an important processing technique in manufacturing elongated products with various cross-sectional shapes. It can also be applied to form powders or poor-processing materials, since heavy deformation can be achieved under a high hydrostatic pressure. In the fabrication of hollow extruded sections, the porthole die method and the mandrel method are often used. For porthole die method, a solid billet is divided into several parts, followed by joining in a welding chamber and then forming a hollow extrudate by employing an appropriate extrusion die. The products extruded by this method exhibit good dimensional accuracy, but high strength dies are required and the extrudable materials are restricted because the dies are subjected to high pressures during the division process of a billet [8].

In the present study, Cu/Al clad sheets were fabricated by cold rolling and asymmetric shear extrusion (ASE) method. Hollow tubes with Cu in their inside and Al outside were also manufactured by the multi-billet extrusion (MBE), which is very similar to the porthole extrusion method. Interfacial microstructures and mechanical properties of clad sheets and tubes were studied in this study.

II. EXPERIMENTAL PROCEDURES

TABLE I
SPECIFICATION OF THE RAW MATERIALS USED IN THIS STUDY

Material	Chemical composition (wt.%)	Tensile strength (MPa)	Elongation (%)
AA1060	99.6Al	35	38
C11000	99.9Cu	50	45

The raw materials used in this study were commercial pure aluminum sheets (AA1060) with thickness of 4 mm and pure copper sheets (C11000) with thickness of 2 mm in fully annealed condition, of which the specifications is given in Table I. The cold rolling bonding experiments were carried out using a four-high mill with a loading capacity of 20 tons. To remove presumably existing oxides, adsorbed ions, greases and

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dust particles on the surface of raw materials, the metal surface was degreased in acetone for 5 min, and then scratched using circumferential brush with 0.3 mm diameter stainless steel wires running at 120 rpm. The scratching process was essential to remove surface oxides as well as to create a work-hardened surface layer [9]. 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.

Feedstock for asymmetric shear extrusion was prepared in the same procedure for cold rolling bonding. In the case of asymmetric shear extrusion, bonding was carried out at 300°C with lubrication by graphite spray. Reduction ratio in the process was 0.2 and shear deformation was restricted to aluminum side. To fabricate hollow tubes with Al outside and Cu inside, multi-billet extrusion (MBE) was employed in this study. There are several insertion holes in the container, in this method. The billets, which are inserted into these holes beforehand, are simultaneously extruded into the welding chamber of a die, where the materials coming from different holes are joined to each other. Then subsequently a product is extruded out from the die hole. Since there is no division process of billets as in porthole die extrusion, the limits on the die strength and materials to be extruded are eliminated [1].The extrusion experiments were performed at 500°C.

The clad sheets and tubes were treated to reduce the residual stress in a furnace without protective atmosphere at 400°C for 1 hr. The cross-section of samples were ground and polished following the standard metallographic procedures, and etched in a solution of 5 ml HNO_3 + 3 ml HCl + 2 ml HF + 190 ml H_2O. Interfacial microstructure and chemical composition were analyzed using scanning electron microscope (SEM) equipped with energy dispersive X-ray detection (EDX). For clad samples, tensile test was carried out at room temperature under the strain rate of 5×10^{-4} s^{-1}. The peeled surface and fracture of clad sheets were also observed in this study.

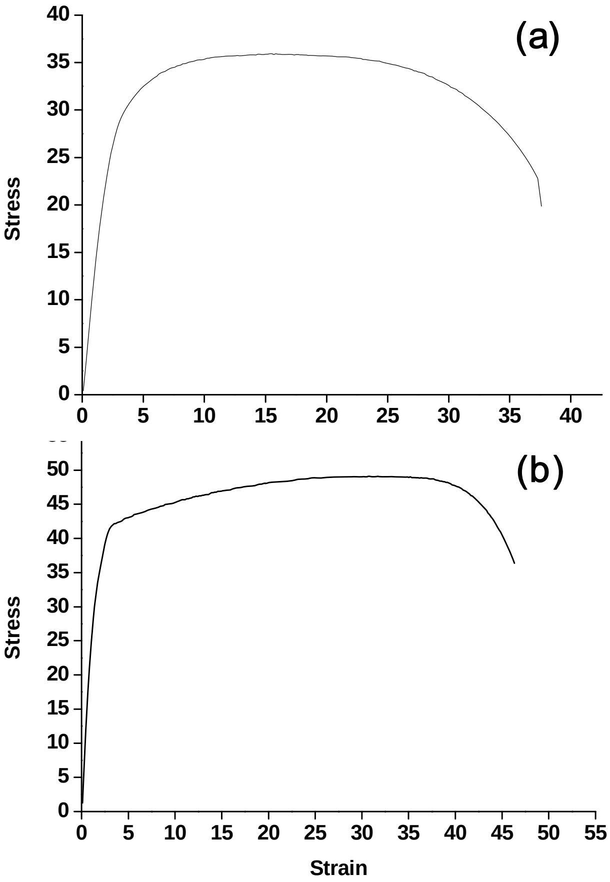

Fig. 1 Stress-strain curves of aluminum (a) and copper (b) used in this study

III. RESULTS AND DISCUSSION

Fig. 1 shows stress-strain curves obtained from tensile tests on the raw materials. Flow stresses of raw materials are somewhat low because the materials are in the fully annealed state. Appearances of bimetallic samples fabricated in this study were illustrated in Fig. 2. As shown in the figure, Al/Cu clad sheets and tubes were successfully fabricated.

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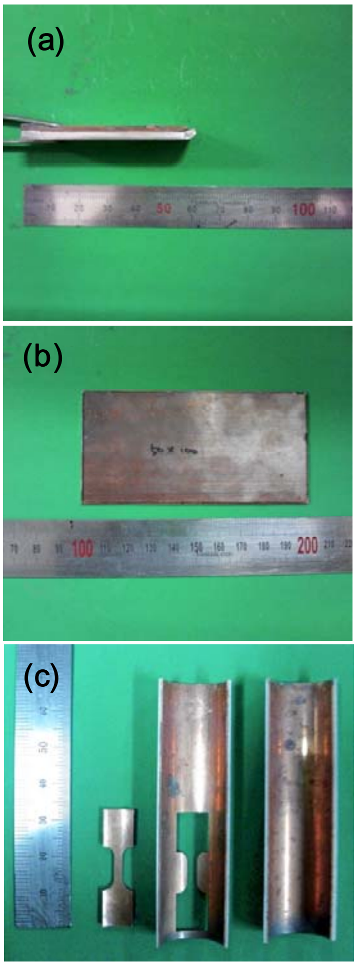

Fig. 2 Appearances of bimetallic samples fabricated in this study by asymmetric shear extrusion (a), cold rolling bonding (b), and multi-billet extrusion (c), respectively

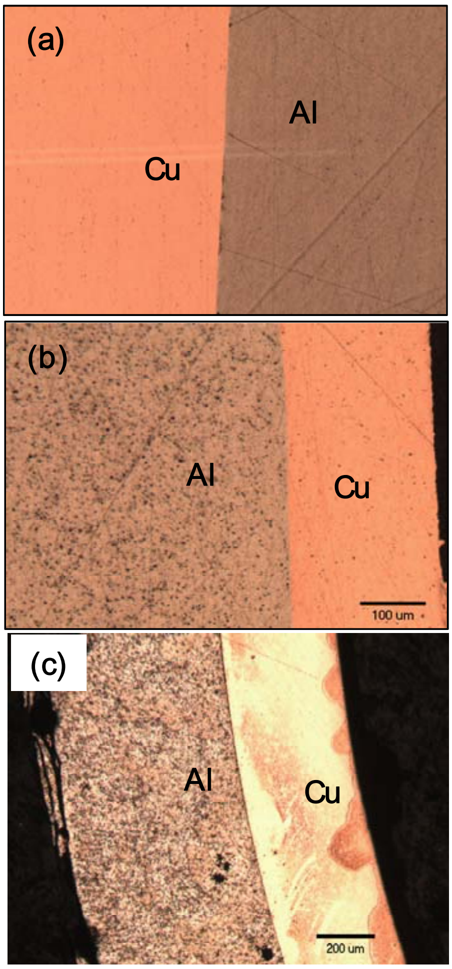

Fig. 3 Optical microstructure of bimetallic samples obtained by asymmetric shear extrusion (a), cold rolling bonding (b), and multi-billet extrusion (c), respectively

Fig. 3 shows the interfacial microstructure of Cu/Al clad sheets and hollow tube obtained by asymmetric shear extrusion with reduction of 0.2 at 300°C, cold rolling bonding, and MBE, respectively. As shown in Fig. 3(a), interface gap is clear between Al and Cu constituent, while interface gap vanishes and interfacial layer appears on some positions. The adsorbed layer as well as hardened layer caused by scratch on metal surface fractures due to the deformation in asymmetric shear extrusion. Then a mechanical mesh can be obtained under enormous pressure. However, the mechanical bonding through mesh depending on the van der Waals force of metal atoms is weak [3]. For the samples obtained by asymmetric shear extrusion, cold rolling and multi-billet extrusion, interfacial microstructures were also observed by SEM and illustrated in Fig. 4. Similar results were obtained and the interface of bimetallic tube obtained from MBE was very clear and sound bonding was obtained as shown if Fig. 5, which is because the process was conducted at high temperature of 500°C. In the case of cold rolling bonding, a good interface was also produced as shown in Fig. 4.

Researches on the effect of annealing on interfacial bonding proposed a mechanism termed as the Energy Theory [3, 10], in which the interfacial microstructure of clad product annealed at high temperature exhibit some cracks. The atom diffusion in the interfacial zone is promoted by annealing, and the interfacial layer grows quickly. The distribution of oxides in interfacial zone is also spread and lead to the crack. In the present study, annealing treatment at 500°C for 2hr caused the cracks in the interfacial zone in all samples.

On the bimetallic clad samples, tensile tests were conducted at room temperature under the strain rate of 5×10^{-4} s^{-1}. The results were summarized in the Fig. 5. It is very interesting to note from the figure that the tensile strength of the clad samples are higher than that of raw aluminum and lower than that of raw copper. Tensile strength of the sample fabricated by asymmetric shear extrusion is higher than those produced by cold rolling and MBE method. Elongations of clad samples are very similar to one another and observed as about 40%. Peeling was not observed before tensile specimens were fractured in any sample.

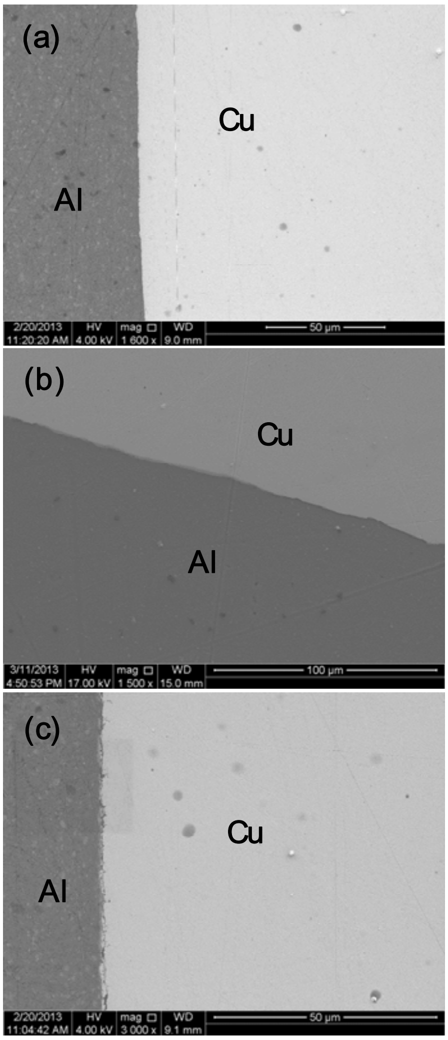

Fig. 4 SEM micrographs of bimetallic samples obtained by asymmetric shear extrusion (a), cold rolling bonding (b), and multi-billet extrusion (c), respectively

Fractured surfaces were examined by SEM and the results obtained from a hollow tube sample are illustrated in Fig. 6. As shown in Fig. 6(b), fracture surface of the sample exhibits typical aspects of ductile fracture. Even after fracture, no evidence for interface separation can be seen. According to fractured microstructure, the stress-strain curves in Fig. 5 with only one strain hardening exponent value can be explained. There was no evidence for interface debonding in any case.

Generally, copper layer is first fractured in tensile test due to the lower plasticity, and then aluminum layer continues to deform until fracture occurred [11], which gives rise to the stress-strain curves with two stages. In the present study, however, elongation of raw copper is much higher than that of raw aluminum as shown in Table I. Copper layer could be deformed, in this regards, until the facture occurred.

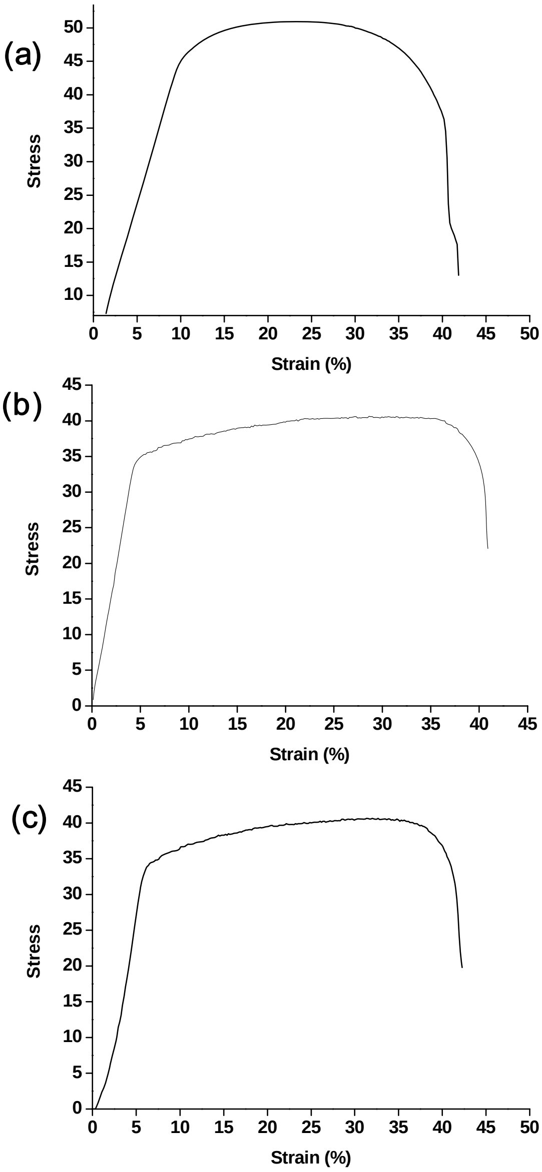

Fig. 5 Stress-strain curve obtained from tensile tests conducted on the clad samples fabricated by asymmetric shear extrusion (a), cold rolling bonding (b), and multi-billet extrusion (c), respectively

IV. CONCLUSIONS

In the present study, Al/Cu bimetallic clad sheets and tubes were successfully fabricated by asymmetric shear extrusion, cold rolling bonding, and multi-billet extrusion methods. Hollow tubes with Al outside and Cu inside were also successfully produced by multi-billet extrusion. Microstructure observation revealed that interface gap was clear between Al and Cu constituent, while interface gap vanished and interfacial layer appeared on some positions. Annealing treatment at 500^{o}C for 2hr caused the some cracks in the interfacial zone in all samples. Tensile strength of the Al/Cu clad sheets produced by asymmetric shear extrusion was higher than those obtained by cold rolling and MBE method. Elongations of clad samples are very similar to one another and observed as about 40%.Fracture surface of the bimetallic clads exhibits typical aspects of ductile fracture. Even after fracture, no evidence for interface separation can be seen.

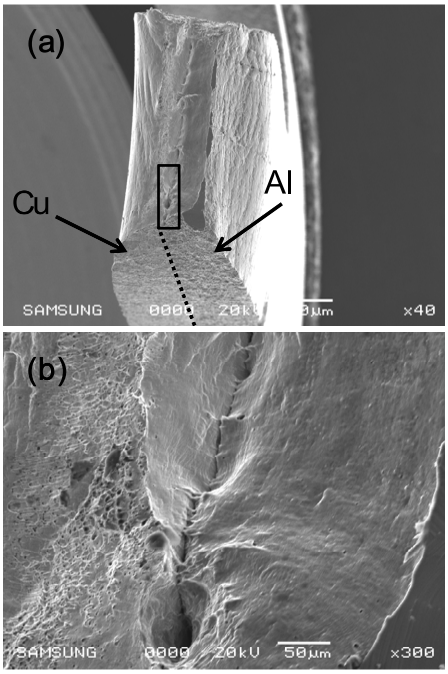

Fig. 6 SEM fractograph of Al/Cu clad taken after tensile test (a) and enlarged image denoted by the box (b)

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