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Mechanical Behavior of Deep-Drawn Cups with Aluminum/Duralumin Multi-Layered Clad Structures

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***Abstract*—**This study aims to investigate mechanical behavior of deep-drawn cups consisting of aluminum (A1050)/ duralumin (A2017) multi-layered clad structures with micro- and macro-scale functional gradients. Such multi-layered clad structures are possibly used for a new type of crash-boxes in automobiles to effectively absorb the impact forces generated when automobiles having collisions. The effect of heat treatments on microstructure, compositional gradient, micro hardness in 2 and 6-layered aluminum/ duralumin clad structures, which were fabricated by hot rolling, have been investigated. Impact compressive behavior of deep-drawn cups consisting of such aluminum/ duralumin clad structures has been also investigated in terms of energy absorption and maximum force. Deep-drawn cups consisting of 6-layerd clad structures with micro- and macro-scale functional gradients exhibit superior properties in impact compressive tests.

***Keywords*—**Crash box, functionally graded material (FGM), Impact compressive property, Multi-layered clad structure.

I. Introduction

THE safety of vehicles mostly depends on behavior of frontal automotive structures during crash. These structures, defined as crash boxes, are the main energy absorbers of the crash. Crashworthiness of crash boxes depends on their dimensions and materials. They are particularly designed for the absorption of the energy during the impact to reduce injury of car passengers in high speed-collisions and the damage of car in low-speed collisions [1]. Conventionally, the car crash box is made from homogeneous steel sheet or aluminum extrusions, but recently the application of aluminum-based alloy clad materials to crash boxes in automobiles has been proposed with a new concept of functionally graded materials (FGMs) [2].

The clad materials are multilayered structures possessing various properties which surpass those of single metal sheets. Most clad materials not only preserve the original characteristics of the individual layer metals but also provide additional functional properties [3]. Highly functional compound clad sheets and sandwich sheets are being widely manufactured for increasing industrial needs. Generally, with different material combinations, clad materials can have advantageous characteristics such as good thermal conductivity, anti-corrosion properties, wear resistance and surface quality.

FGMs are advanced multi-phase composites that are engineered to have a smooth spatial variation of material constituents. This variation results in an inhomogeneous structure with smoothly varying thermal and mechanical properties. The advantages of FGMs as an alternative to two dissimilar materials (ceramics and metal) joined directly together include smoothing of thermal stress distributions across the layers, minimization or elimination of stress concentrations and singularities at the interface corners and increase in bonding strength [4,5]. Multifunctional inhomogeneous materials such as FGMs have been considered to be used in car crash boxes.

For impact behavior of crash boxes, numerical and experimental studies have been made so far [6,7]. A classical analysis of plastic folding of a thin cylindrical shell under axial crush loading goes back to the work of Alexander in 1960 [8]. A theoretical analysis of the plastic deformation of a prismatic column undergoing static compression load was developed by Wierzbicki and Abramowicz, [9]. The experimental validation of the proposed theory was performed by Abramowicz and Jones, [10]. In their work, they also studied the dynamic crushing strength of columns. For a specific material, complete static and dynamic axial crushing tests of square thin-walled aluminum extrusion were conducted by Langseth et al. [11].

In this study, the effect of heat treatments on microstructure, micro-Vickers hardness and deep-drawing formability of 2 and 6-layered aluminum/ duralumin clad structures have been investigated. Impact compressive behavior of deep-drawn cups consisting of the multi-layered clad structures with micro- and macro-scale functional gradients has been investigated in terms of energy absorption and maximum force.

II. Experimental Procedure

A. Materials and Hot Rolling

Aluminum (A1050) sheets and duralumin (A2017) sheets with a thickness of 1mm were prepared for hot rolling. Duralumin contains 3~5 wt. % Cu. Both sheets were heat-treated at 450^{o}C for 2hours, initially. These sheets were hot-rolled into layered clad structures with a reduction rate of 50%. The roll diameter and rolling speed are 100mm and 12

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m.p.m., respectively. Before hot rolling, the aluminum and duralumin sheets were degreased by swabbing with acetone and drying in air. The surfaces of ingredient materials sheets were scratched by brushing. The hot-rolled clad samples have a thickness of around 1mm ± 0.1mm. The hot rolling fabrication process is illustrated in Fig. 1. Heat treatments for hot-rolled multi-clad structures include three types. The first is as rolling (AR) (no heat treatment), the second is to be annealed at 400°C followed by cooling in furnace (HT400), and the third is to be homogenized at 500°C followed by water quenching and aging at room temperature (HT500) (T4 heat treatment). The sample descriptions of 2- and 6-layered clad structures are shown in Table I.

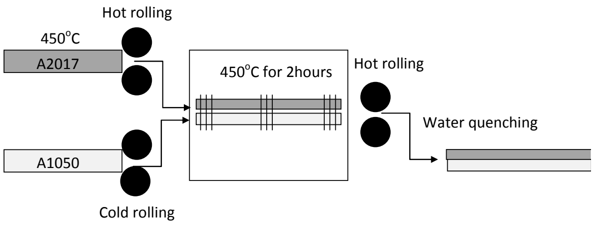

Fig. 1 Hot rolling process of multi-layered clad structures

TABLE I
SAMPLE DESCRIPTIONS OF 2- AND 6-LAYERED CLAD STRUCTURES AND DEEP-DRAWN CUPS

2LAR	AS-ROLLED (NO HEAT TREATMENT) 2-LAYERED CLAD STRUCTURES
2LHT400	400°C HEAT-TREATED 2-LAYERED CLAD STRUCTURES
2LHT500	500°C HEAT-TREATED 2-LAYERED CLAD STRUCTURES
6LAR	AS-ROLLED (NO HEAT TREATMENT) 6-LAYERED CLAD STRUCTURES
6LHT400	400°C HEAT-TREATED 6-LAYERED CLAD STRUCTURES
6LHT500	500°C HEAT-TREATED 6-LAYERED CLAD STRUCTURES

B. Microscope Examinations and Mechanical Property Tests

A microstructure observation was conducted using optical microscope (OM) and scanning electron microscope (SEM, JSM-5900LV, JEOL, Japan) with an acceleration voltage of 15 kV. The composition in the samples was identified using the SEM energy-dispersive X-ray spectroscopy (EDS, JED-2200). The samples for microscope observation and indentation tests were prepared by embedding the pieces cut from clad sheets into the resin. Micro-Vickers hardness tests were conducted with the load of 245.2mN for 15sec using Shimazdu Micro-Vickers Tester.

Deep drawing formability tests were carried out at room temperature (RT) using the electric servo press, ZENFormer MPS675DS (Hoden Seimitsu Kako Kenkyusyo Co.Ltd.). The fabricated clad sheets were cut to a circular plate with a diameter of 60mm. The punch diameter is 25mm. The drawing rate is 40mm/sec. The produced cup consisting of clad structures, in which A1050 is outside and A2017 is inside, has an internal diameter of 25mm and external diameter of 27.5mm. The height of the cup is around 18 to 25 mm.

Impact compressive tests were conducted using a drop weight impact tester of IM10T-20HV (IMATEK Pty.Ltd.). The test conditions include the dropped mass of 14.63kg, dropping height of 1m to produce 143.4 J kinetic energy. A high-speed capturing video camera systems were set for observing the high speed fracture behavior of the samples. The tested deep-drawn samples have dimensions of height of 18mm and outer diameter of 27.5mm. For 2- and 6-layered-samples, some heat-treatment was carried out to make macro-scale functional (hardness) gradients in the deep-drawing direction in the samples as shown in Fig. 2. The heat-treatment procedure includes HT400 to make the closed part softer and HT500 to make the open part harder in the cup samples.

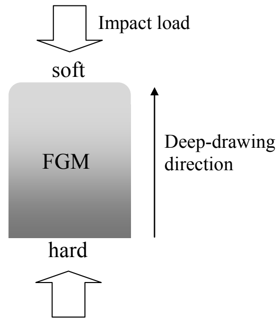

Fig. 2 Macroscopic functional gradation in a cup sample

III. EXPERIMENTAL RESULTS

2- and 6-layered clad structures were soundly fabricated using hot-rolling methods. The OM images of the 2- and 6-layered aluminum/duralumin clad structures are shown in Fig.3. It is seen that as-rolled samples (2LAR and 6LAR) show clear boundaries between neighbor layers, while heat-treated samples (2LHT400, 2LHT500, 6LHT400 and 6LHT500) show unclear boundaries because heat treatments are considered to promote diffusion of Cu, which is basically contained in duralumin. Figs.4 and 5 show SEM images with EDS analysis results of Cu for 2- and 6-layered clad structures, respectively. It is seen that in the same way as OM images shown in Fig. 3, as-rolled samples (2LAR and 6LAR) show clear boundaries between neighbor layers, while heat-treated samples (2LHT400, 2LHT500, 6LHT400 and 6LHT500) show unclear boundaries. It can be seen from EDS analysis that Cu content gradually varies from a high level at the duralumin side to a low level at the aluminum side, which means that heat treatments can make gradient distributions of Cu at the interface like functionally graded materials. Such a gradient can produce gradient distributions of various properties such as mechanical, thermal, electrical and other properties, which can be controlled by heat treatment procedures.

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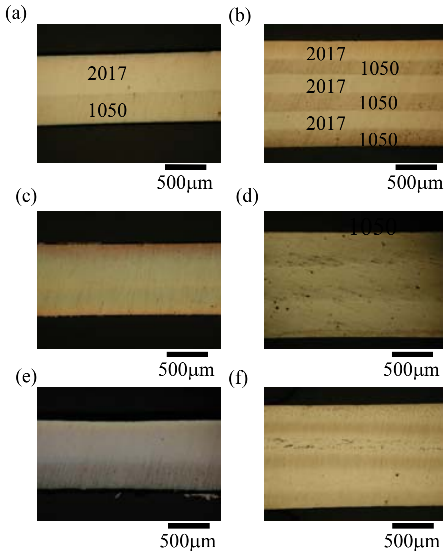

Fig. 3 OM images of 2- and 6-layered clad structures, (a) 2LAR, (b) 6LAR, (c) 2LHT 400, (d) 6LHT 400, (e) 2LHT500, (d) 6LHT 500

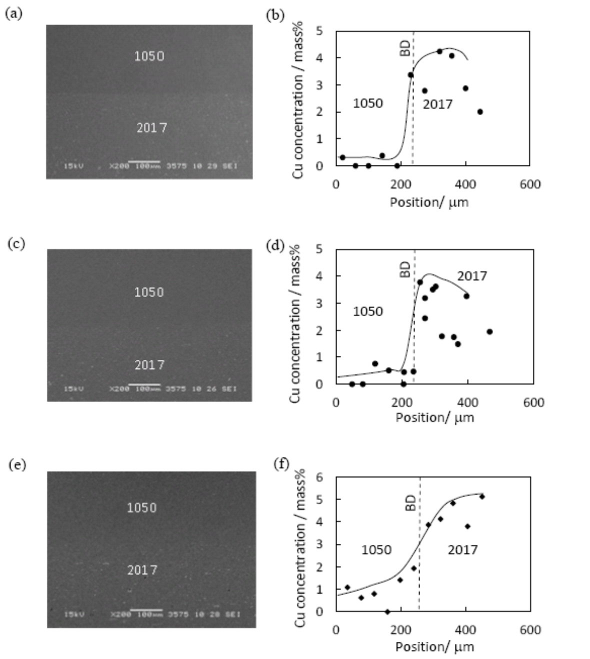

Fig. 4 SEM images and EDS analysis results for Cu of 2-layered clad structures, (a) 2LAR SEM image, (b) 2LAR EDS, (c) 2LHT400 SEM image, (d) 2LHT400 EDS, (e) 2LHT500 SEM image, (d) 2LHT500 EDS

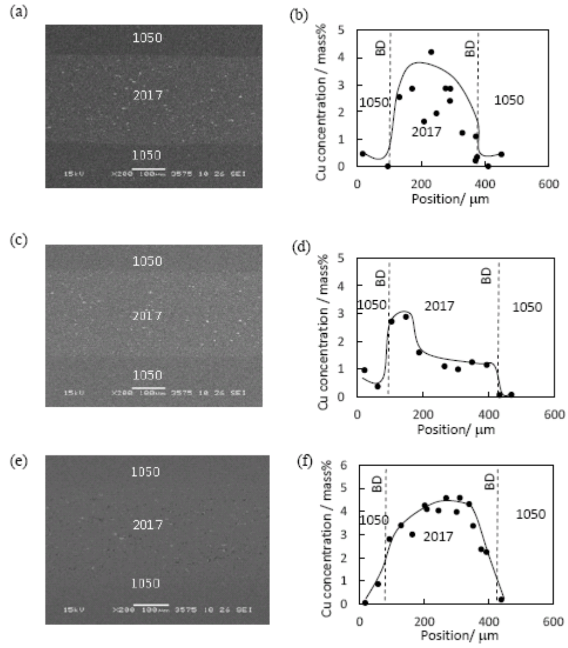

Fig. 5 SEM images and EDS analysis results for Cu of 6-layered clad structures, (a) 6LAR SEM image, (b) 6LAR EDS, (c) 6LHT 400 SEM image, (d) 6LHT 400 EDS, (e) 6LHT500 SEM image, (d) 6LHT500 EDS

Fig. 6 shows the distribution of the micro-Vickers hardness in 2- and 6-layered clad structures. It can be seen that hardness distribution indicates considerable distinguish features among the samples suffering different heat treatments. Both A2017 and A1050 in 2LHT400 and 6LHT400 are much softer than those in others. 2LHT500 and 6LHT500 show extremely high hardness in A2017.

Fig. 7 shows the deep drawing formability in 2- and 6-layered clad structures. Only 400^{o}C heat-treated samples (2LHT400 and 6LHT400) can be successfully deep drawn, which means that 400^{o}C heat-treated samples has highest formability among all the samples investigated. According to the hardness test results shown in Figs. 6 to 8, A2017 in only 400^{o}C heat-treated (HT400) samples shows low hardness, which imply that this heat treatment (HT400) is effective for the clad structures to be deep-drawn and processed by other techniques.

Fig. 8 shows the absorbed energy and maximum force during the weight dropping. Here, “G” placed at the last part of the sample name means that the deep-drawn caps have macro-scale functional gradients in the drawing direction with upper (closed) side softer and lower (open) side harder (Fig. 2). It is seen in Fig. 8 (a) that aluminum (1050HT500) shows very low absorbed energy, and 6layered-clad structure shows high absorbed energy. It is also seen in Fig. 8 (b) that aluminum shows very low maximum force, and 6layered-clad structure shows high maximum force. Therefore, aluminum plates are less effective for crash boxes, while 6layered-clad structure are most suitable for crash boxes among the tested samples.

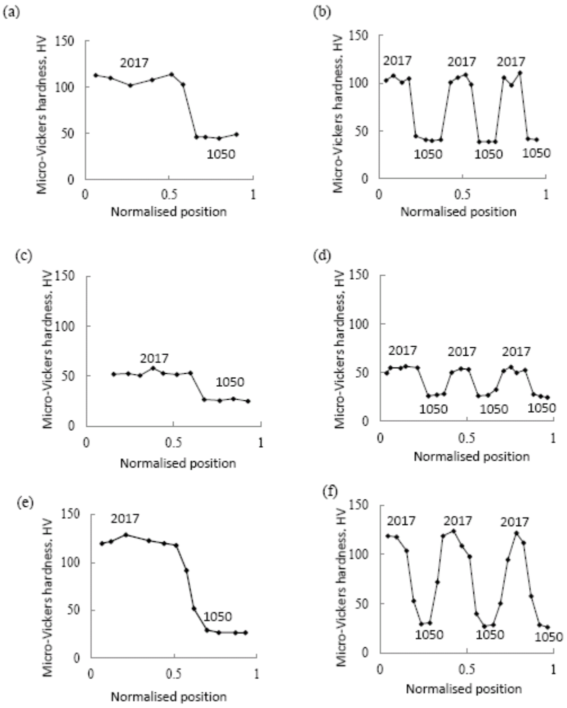

Fig. 6 Micro-Vickers hardness distribution in the clad structures, (a) 2LAR, (b) 6LAR, (c) 2LHT400, (d) 6LHT400, (e) 2LHT500, (d) 6LHT500

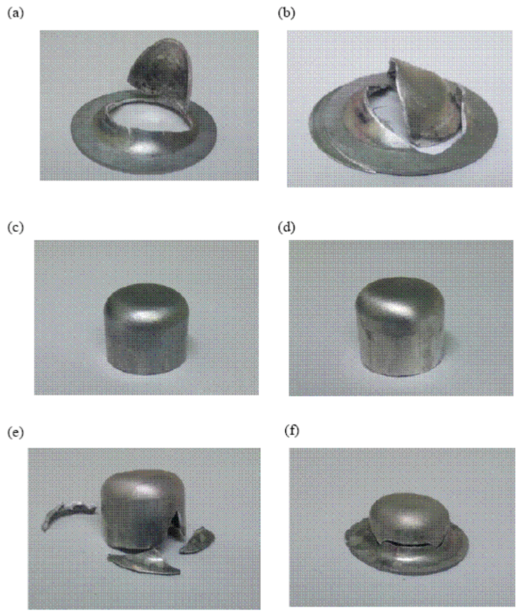

Fig. 7 Sample appearance after deep drawing, (a) 2LAR, (b) 6LAR, (c) 2LHT400, (d) 6L400HT, (e) 2LHT500, (d) 6LHT500

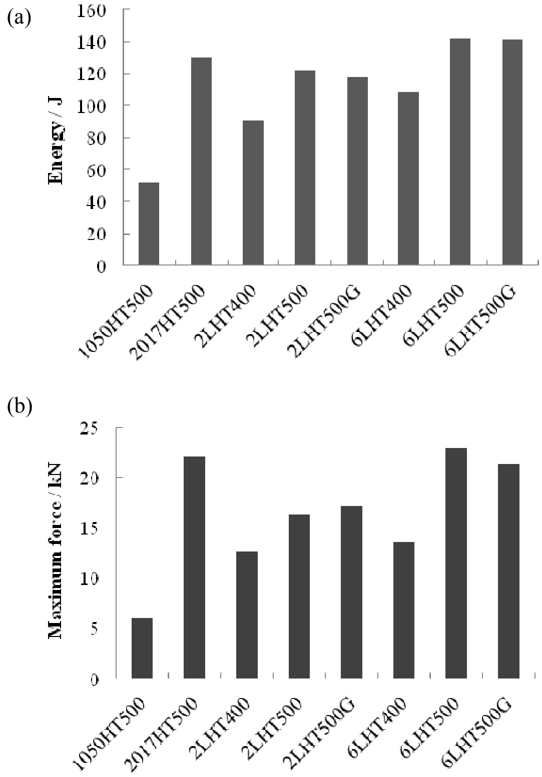

Fig. 8 Impact compressive properties of deep-drawn cups with aluminum (A1050)/ duralumin (A2017) multi-layered clad structures, (a)Absorbed energy, (b)Maximum force

IV. Discussion

2- and 6-layered clad structures were successfully fabricated using a hot-rolling method. It is expected that such clad structures can be applied to crash boxes in automobiles. Therefore, it is important to understand how heat treatments affect the microstructure, mechanical properties, deep-drawn formability of multi-layered clad structures and impact strength of the cups. For aluminum (A1050)/ duralumin (A2017) clad structures, heat treatments largely affect the mechanical properties of A1050 and A2017, and Cu concentration around the interface. Cu distributions can be also related to nano- and micro-scale mechanical property distributions around the interface. Micro-Vickers hardness hardness varies according to Cu concentration around the interface. Higher Cu concentration corresponds to higher hardness because Cu can produce intermetallics by reacting with Al during the aging process, which leads to strengthening the materials with dispersed intermetallic precipitations. Nanoindentation elastic modulus and hardness are also affected by nano-scale microstructure and Cu-Al intermetallics, so these properties can be controlled by heat treatments.

For deep drawing formability, 400^{o}C annealed samples (2LHT400 and 6LHT400) show superior formability compared to others. This result is reasonable based on the nanoindentation and micro-Vickers hardness results. For making the crash boxes, it will be better to apply such heat treatments to aluminum-based multi-layered structures before forming and processing.

For impact compressive behavior, aluminum is less effective for crash boxes, while 6-layered aluminum/ duralumin clad structures are most suitable for crash boxes among the tested samples. Macro-scale functional gradients provided not so much effect on impact compressive properties. Difference between 2- and 6-layered structures in impact compressive properties is relatively large even though the volume ratio of aluminum and duralumin in their structures are the same. The effect of heat treatment (HT400 and HT500) on impact compressive properties is very large, in which HT500 can make impact compressive properties much better than HT400.

V. Conclusion

This study investigated mechanical behavior of deep-drawn cups consisting of aluminum (A1050)/ duralumin (A2017) multi-layered clad structures with micro- and macro-scale functional gradients. The following conclusion can be drawn from this work.

1. 2- and 6-layered aluminum (A1050)/ duralumin (A2017) clad structures were soundly fabricated using hot rolling methods.
2. Boundaries between layers with different materials (aluminum and duralumin) are clearly seen in as-rolled (AR) samples, while heat-treated samples (HT400 and HT500) show unclear boundaries, which imply that diffusion of Cu occurs at the boundaries during heat treatment processes.
3. Micro-Vickers hardness varies around the interface between layers in heat-treated samples according to gradient distribution of Cu.
4. 400°C heat-treatments (HT400) make the samples softer, while 500°C heat-treatments (including water quenching and aging) (HT500) make duralumin much harder.
5. 400°C heat treatments (HT400) make deep drawing formability of the clad samples higher.
6. 6-layered aluminum/ duralumin clad structures show superior impact compressive properties.
7. The effect of heat treatment (HT400 and HT500) on impact properties is very large, in which HT500 can make impact properties much better than HT400.

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