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# Deformation behavior and interface microstructure evolution of Al/Mg/Al multilayer composite sheets during deep drawing

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ABSTRACT

The Al(5052)/Mg(AZ31)/Al(5052) multilayer composite sheets were fabricated via accumulative roll-bonding process at elevated temperatures. The present study aims to investigate the formability of the composite sheets by deep drawing test and orthogonal experimental design. The deep drawing parameters such as punch temperature, punch speed and die curvature radius have been optimized to maximize the limit drawing radio of the composite sheets at temperatures ranging from 150 °C to 230 °C. The limit drawing radio of the composite sheets obviously increased with the forming temperature, and the maximum drawing radio of 3.1 was obtained at 200 °C. After forming at 150 °C and 200 °C, the microstructure evolution of the intermetallic compound layers, consisting of $Al_{12}Mg_{17}$ and $Al_3Mg_2$ layers at the interface at different regions of the drawn cup in rolling direction (RD) and transverse direction (TD), was investigated. At the bottom region which was considered as less deformation, the microstructure of the intermetallic compound layers showed almost no changes both at 150 °C and 200 °C. However, the Al/Mg/Al multilayer composite sheets showed more satisfactory bonding properties when drawing at 200 °C with less cracks appearing at the wall region and corner region of the drawn cup than that at 150 °C.


## 1. Introduction

Metallic multilayer composites, containing different components, have drawn a significant amount of attention due to their prominent characteristics such as striking mechanical, magnetic and electrical characteristics [1,2], which cannot be obtained simply by the individual metallic alloy. There are many methods to fabricate multilayer composites, such as magnetic sputtering [3], vacuum pack treatment [4,5], electroplating [6], physical vapor deposition [7] and jet-vapor deposition [8]. However, most of the above preparing methods require complex processes and expensive equipments, which have hindered their applications in commercial and industrial fields [9]. As a type of severe plastic deformation (SPD) combining same or dissimilar metals, accumulative roll-bonding (ARB) exhibits some advantages in fabricating multilayer composites such as strength increase and structural refinement. Moreover, ARB is a kind of solid-state joining technique which has been extensively used in commercial and industrial fields owing to its low cost and high productivity [10–12]. In recent years, various multilayer composite sheets have been fabricated via both cold and hot roll bonding, including Cu/Si [13], Cu/Zr [14], Al/steel [15], Al/Cu [16], Mg/Al [17], etc. It has been shown that the ultimate tensile strength and yield strength of multilayer composite sheets obtained via ARB process obviously increased compared with these of counterparts [18,19].

Although a variety of alloys can be used to prepare multilayer composite sheets, Mg alloy and Al alloy have received wide attention [20–22], which have a great potential in automotive industry because of their prominent combination of high specific strength from Mg alloy and excellent corrosion resistance from Al alloy [23]. Moreover, as lightweight structural metals, the combination of Mg alloy and Al alloy could reduce the carbon dioxide emissions by decreasing the weight of vehicles in the automobile industry. In the recent research [24,25], Mg alloy and Al alloy were formed as Al/Mg/Al multilayer composite sheet by cladding both sides of Mg alloy with Al alloy via ABR process. Liu et al. [23] reported that the Al/Mg/Al multilayer composite sheets processed by three rolling passes could obviously refine the grain size of the composite and the grains in the Mg alloy and Al alloy layers were reduced to 1.0 and 0.5 μm, respectively. Zhang et al. [26] investigated the effects of different rolling temperatures and reductions on microstructure, bonding strength and thickness fractions of the constituent Al/Mg/Al multilayer composite sheets after hot rolling. The results exhibited that the bonding strength decreased with the increasing rolling temperature and reduction,

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the maximal bonding strength of the multilayer composite was 66 MPa. The thickness fraction of the Mg alloy decreased with the increasing rolling temperature and reduction.

When Al/Mg/Al multilayer composite sheets are fabricated at elevated temperature, it is necessary to investigate the inter-diffusion layer produced between Mg and Al alloy layers because of its remarkable influence on the performance of multilayer composite sheets [22]. Luo et al. [24] investigated the microstructural evolution of brittle Al–Mg intermetallic compound (IMC) at the bond interface of Al/Mg/Al multilayer composite sheets during different annealing conditions, which demonstrated that the growth rate of the IMC increased with the increasing annealing temperature, and no observable IMC was observed at the annealing temperature of 200 °C or below. Lee et al. [27] revealed that the secondary warm rolling significantly reduced the thickness of the IMC layer and greatly improved the mechanical properties of Al/Mg/Al sheet. However, till now the deep drawability of Al/Mg/Al multilayer composite sheets at elevated temperature has not been intensively studied yet. And deep drawing is an important and popular process in the assessment of formability of sheet metals. Hence, it is important to investigate the thermal deep drawing behaviors of Al/Mg/Al multilayer composite sheets.

The study aims to have a comprehensive understanding of the influence of deep drawing parameters on the deep drawability of Al/Mg/Al multilayer composite sheets. The IMC microstructures at the wall region, corner region and bottom region were also investigated. In the present study, the draw parameters such as temperature of punch and die, punch speed and die curvature radius were selected as the factors of orthogonal design. The optimal level constitution of these deep drawing parameters for Al/Mg/Al multilayer composite sheets at specified conditions were also revealed by using range analysis.

## 2. Experimental materials and procedures

Commercially available AZ31 magnesium alloy (3.01Al–0.9Zn–0.5Mn in weight.%) and 5052 aluminum alloy (2.5Mg–0.25Si–0.25Cr–0.4Fe in weight.%) were chosen as laminated plate partners. The initial size of the Mg alloy and Al alloy were $160 \times 90 \times 2.7\ mm^3$ and $175 \times 210 \times 0.38\ mm^3$, respectively. Full annealing was performed on AZ31 sheets at 300 °C for 30 min and on 5052 sheets at 350 °C for 60 min (O state).

ARB process was carried out to manufacture the Al/Mg/Al multilayer composite sheets (Fig. 1). Before the first rolling, proper surface treatment (brushing and degreasing) was used to remove the oxidation layer and contamination on the surface of Al alloy and Mg alloy sheets, and then coat the Mg alloy with Al alloy. The first hot rolling performed by preheating the laminate sheets to 360 °C for 15 min, caused a 33.53% reduction in thickness. The subsequent hot rolling was similar to the first rolling, with preheating at 400 °C for 15 min and the thickness reduction of 26.08%, 29.41% and 16.67%, respectively. The thickness was reduced from 2.3 mm to the final 1 mm. After four hot rolling passes, the Al/Mg/Al multilayer composite sheets were prepared by diffusion annealing at 180 °C for 2 h.

The thermal deep drawing tests were carried out to investigate the deep drawability of Al/Mg/Al multilayer composite sheets. Drawing tests were conducted using circular blanks with various diameters to determine the limit drawing radio (LDR) in a given condition. The LDR is defined as the maximum blank diameter/punch diameter without the appearance of cracks and wrinkles during deep drawing. The initial round blank diameter was set as 85 mm. A similar deep drawing process was repeated in the next blank with the diameter increasing by 5 mm. Fig. 2 shows the diagrammatic sketch of deep drawing process. The temperature of punch, blank holder and die were controlled independently by heating barrel, heating element 1 and heating element 2, respectively. The blank was placed in the testing machine when both the blank holder and die reached the desired temperature. Thermo couples were used in each component to record and monitor the temperature. The blank holder force was set as a constant value of 3 kN provided by a lifting jack with a fixed clearance of 1.05 mm. High-temperature grease PTFE [28] was used to lubricate the lower surface of blank holder and upper surface of die.

The orthogonal design was used to optimize the deep drawing parameters of Al/Mg/Al multilayer composite sheets in this study. It can be used to intuitively obtain the optimal level constitution of deep drawing parameters by using the minimum number of experiments without developing the objective function. The degree of sensitivity of drawing parameters to the deep drawability could also be obtained. The optimal level constitution of deep drawing parameters including punch temperature, punch speed and die curvature radius were determined using deep drawing tests. In this paper, range analysis method was used to quantify the importance of process parameters in deep drawing process. The forming temperature plays the largest role in the formability of Mg alloy [29]. Therefore, the orthogonal design was based on the function of different forming temperatures. Considering Mg alloy and Al alloy exhibit excellent formability between 150 °C and 250 °C [30–32], the forming temperatures of multilayer composite sheets were set as 150 °C, 180 °C, 200 °C, 230 °C, respectively. Two levels were considered for punch temperature, punch speed and die curvature

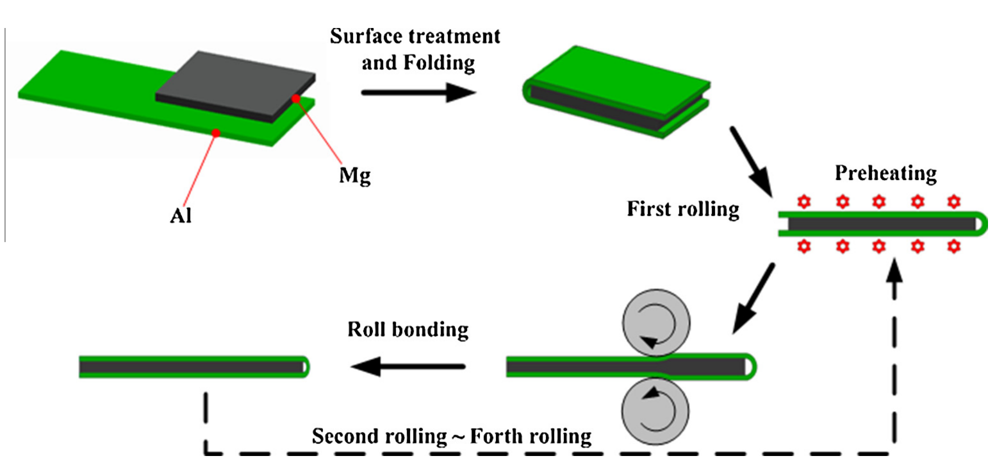


**Fig. 1.** The ARB process for fabrication of Al/Mg/Al multilayer composite sheets.