Original Article

Microstructure evolution of Al/Mg/Al laminates in deep drawing process

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\textbf{Abstract}
Magnesium based laminates have been successfully prepared by various methods. Their microstructure and mechanical properties have also been fully discussed. However, there are few reports on their formability which is essential to further manufacture and application of laminates. In this paper, hot-rolled Al/Mg/Al laminates were used to conduct deep drawing at various temperatures, and microstructure evolution of three typical regions including bottom, corner and wall taken from the drawn cylindrical part with the largest limit drawing ratio (LDR) was also investigated. No delamination is observed in deep drawing. The value of LDR grows with increasing forming temperature, reaching a peak value of 3.1 at 200 °C, which is higher than that of as-rolled Mg or Al sheet, although there exists brittle intermetallics at Mg/Al interface. The reason is that varying degrees of fracture in intermetallic layers helps to release stored energy and facilitate coordinated deformation. At corner region of cylindrical part drawn at 200 °C, fragment is observed in intermetallics. For cylindrical part drawn at 200 °C, Mg layer at bottom, corner and wall regions all exhibit basal texture, but c-axes of Mg grains gradually change orientation from tilting toward the RD to tilting toward the TD. The increasing extent of DRX greatly refine the Mg grains and weaken the basal texture. Continuous recrystallization changes the texture of Al layer. The corner region shows a random texture with the lowest intensity of 4.14, and the bottom and wall regions both exhibit cubic texture.

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1. Introduction
Mg alloys are attracting extensive attention owing to their excellent properties including low density, high specific strength and stiffness [1,2]. Therefore, the evolution of microstructure and mechanical properties of Mg sheets are also investigated in details [3–5]. Stamping forming are conducted based on these studies, because formability is an important evaluation criterion of metal sheets [6–8].

Deep drawing is one of the frequently-used stamping methods [9,10], and deep drawability is often measured by
limit drawing ratio (LDR). The value of LDR can be described by $LDR = R_0 / r_0$, in which $R_0$ is the diameter of sheet (mm), $r_0$ the diameter of successfully drawn part or the diameter of punch (mm). Researchers have done a systematical study on the effect of formation temperature (punch and die), shoulder radius of punch and die, drawing speed and lubricating conditions on formability, using AZ31 Mg sheet with thickness ranging from 0.8 mm to 1 mm. The main conclusions are as follows: 1) warm deep drawing is necessary to obtain a cylindrical part with LDR over 1.2 by using one-step drawing; 2) AZ31 sheet shows preferable performance when the forming temperature is between 150–270 °C, the shoulder radius of punch and die between 5–9 mm, and polytetrafluoro ethylene (PTFE) lubrication is used; 3) the maximum LDR of AZ31 sheet can reach 3.0 [11,12]. Hence, temperature is the most important process parameter influencing the formability of Mg sheets.

To further improves the corrosion resistance and strength of Mg alloys, various kinds of metal laminates are developed, such as Al/Mg/Al composite [13], Ti/Al/Mg composite [14] and carbon fiber/Mg composite [15]. The microstructure of component sheet or fiber, especially the interfacial structure during processing and/or annealing are the main concerns [16,17].

To sum up, arduous efforts have been made to explore the microstructure, mechanical properties and forming properties of Mg sheets, and investigations on the microstructure evolution of Mg matrix composites are also extensive. However, few reports on the formability of metal composite, with no exception of Al/Mg/Al laminate. Therefore, on the basis of our previous studies on Al/Mg/Al laminate [18,19], its deep drawing behavior will be studied. This paper focuses on: 1) the formability of Al/Mg/Al laminate characterized by LDR; 2) the effect of forming temperature on the microstructure and formability of laminate; 3) texture evolution of different regions of drawn part.

2. Experimental

2.1. Fabrication of Al/Mg/Al laminates

The component sheets are commercial AZ31 Mg sheet and 5052 Al sheet, and the thickness are 2.75 mm and 0.5 mm, respectively. The Al/Mg/Al laminate was fabricated by hot rolling with a rolling reduction of 71%, followed by annealing treatment at 200 °C for 1 h, and the final thickness of laminate is 1 mm. The specific fabrication process, microstructure and mechanical properties have been reported in our previous study [20], and the laminate is the raw material of deep drawing.

2.2. Deep drawing of Al/Mg/Al laminates

Deep drawing was conducted on a home-made equipment designed according to GB 15825.3-2008, which was installed in an electronic universal testing machine (DNS200), as shown in Fig. 1a. The specific structures of the main working parts made by Cr12MoV are illustrated in an enlarged view of Fig. 1b. The diameters of punch and die are 50 mm and 53.6 mm, respectively. Heat sinks in die seat and blank holder seat are used to heat die and blank holder, and they will heat the laminate to a preset temperature, and furnace is used to heat punch. The temperature of laminates ranges from ambient temperature to 230 °C, and punch temperature ranges from 20 °C to 80 °C.

To obtain the accurate LDR, the diameter of specimen varies from 80 mm to 150 mm with an internal of 5 mm. Deep

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**Fig. 1 – Deep drawing process: (a) overall equipment; (b) specific structures of main working parts.**
2.3. Characterization

A quarter of the target cylindrical part was cut out along the rolling direction (RD) and the transverse direction (TD), as shown in Fig. 2. The specific sampling positions are bottom, corner and wall region of cylindrical part along RD and TD, respectively.

The microstructures were characterized on a Tescan Mira 3 Field Emission Scanning Electron Microscope (SEM) equipped with an Oxford EDS and an Oxford electron backscatter diffraction (EBSD) system. The surfaces of EBSD samples were ground in turn with 1000, 2000 and 3000 grit SiC papers. Polishing was explored with a supersaturated MgO solution for 10 min followed by ultrasonic cleaning for 5 min. Finally, samples were polished in ion milling for 10 min at 5 kV. The EBSD measure-
Table 1 – Deep drawing parameters of the cylindrical parts in Fig. 3.

<table>
<thead>
<tr>
<th>Number</th>
<th>Forming temperature/°C</th>
<th>Shoulder radius of punch/mm</th>
<th>Shoulder radius of die/mm</th>
<th>Punch temperature/°C</th>
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<tr>
<td>1</td>
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<td>80</td>
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<tr>
<td>6</td>
<td>230</td>
<td>15</td>
<td>10</td>
<td>50</td>
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</table>

Fig. 5 – OM of Al/Mg/Al laminates deep drawing cylindrical part at 150 °C.

ments were taken at 20 kV with a 15 mm working distance, a tilt angle of 70°, and a scanning step of 0.3 µm.

3. Results and discussion

3.1. Deep drawability of Al/Mg/Al laminates

The poor plasticity of Mg is mainly due to its limited slip systems at room temperature [21], so fractures caused by local instability are readily to appear during forming process [22]. When temperature is over 200 °C, <c+a> slip can be activated and coordinates the strain along the normal direction (ND), which improves the ability to resist thinning. Hence, forming temperature has the most important effect on LDR of Al/Mg/Al laminate, compared with the other processing parameters including drawing speed, die shoulder radius and punch temperature [11]. Rupture or wrinkle are often observed when some of process parameters are not appropriately selected, as shown in Fig. 3.

Target cylindrical parts are obtained under various temperatures is shown in Fig. 4a and b, and the corresponding LDR values are illustrated in Fig. 4c. Table 1 gives the relevant specific parameters. All the cylindrical parts do not show delamination during deep drawing process, indicating hot-rolled Al/Mg/Al laminate has a well-bonded Mg/Al interface, and its bonding strength is enough to achieve parts manufacturing.

It can be seen from Fig. 4c that LDR slightly grows with the increase of forming temperature ranging from 20 °C to 120 °C,
followed by a rapid growth before 170 °C. Then, LDR reaches its peak value of 3.1 at 200 °C after a drastic rise from 170 °C to 200 °C. However, further enhancement of forming temperature (230 °C) brings a reduction in LDR, and the reasons are as follows: 1) thickness of intermetallics grows quickly when temperature exceeds 200 °C [18], and increased intermetallics are detrimental to both strength and elongation of laminate, because hard and brittle intermetallics and component sheets cannot achieve coordination deformation [18,23]; 2) high temperature strengthens soften effect of the laminate, weakening strain hardening effect of component sheets, so rupture or wrinkle appear. Besides, it should be noted that the maximum LDR of Al/Mg/Al laminate is higher than that of as-rolled Mg and Al sheets [11,24], although there exists intermetallics at Mg/Al interface. Therefore, this novel laminate possesses satisfying formability, which has potential to be used in aerospace, automobile and other industries.

3.2. Microstructure evolution of Mg layer and intermetallics

Three regions including wall, corner and bottom of cylindrical parts formed at 150 °C and 200 °C are selected to investigate the microstructure evolution of Mg layer of Al/Mg/Al laminate during deep drawing. Relative optical microscope (OM) are provided in Figs. 5 and 6. For bottom region, both deformation temperature and thickness strain have little influence on the microstructure of Mg layer, neither along the RD or the TD. The reason is the materials in this region has the maximum temperature drop and the smallest thickness strain. As thick-
ness strain increases, Mg grain in corner and wall regions of cylindrical part drawn at 150°C have no significant changes, compared with its bottom region. However, some dynamic recrystallized grains arrowed in Fig. 6 are observed in corner region of cylindrical part drawn at 200°C, indicating temperature rise is facilitate to nucleation of dynamic recrystallization at a certain strain. Besides, equiaxial and fine Mg grains are obtained in corner region, as shown in the enlarged view of Fig. 6. In the wall region, there are a great number of fine grains owing to extensive dynamic recrystallization, especially along the RD.

To explore the evolution of intermetallics at Mg/Al interface, scanning electron microscope (SEM) was conducted in cylindrical parts formed at 150°C and 200°C, as shown in Figs. 7 and 8. Slight difference in the bottom regions formed at 150°C and 200°C, both of which are similar to that of original Al/Mg/Al laminate [20]. During deep drawing process, bottom region first contacts with punch and almost no plastic deformation occurs, so deformation temperature has little effect on its microstructure. By contrast, intermetallic layers in corner region illustrate more cracks at 150°C than the bottom region, and fragment of intermetallics are observed in cylindrical parts drawn at 200°C, indicating corner is subjected to larger strain and intermetallics are compelled to fall apart to accommodate it. For wall region, it can be seen that intermetallics along the TD show much more compressive rupture zones than that along the RD, which helps to release stored energy and facilitate coordinated deformation.

Therefore, Al/Mg/Al laminate shows the largest LDR at 200°C, which can be attributed to fine Mg grains and ruptured intermetallics. Moreover, the deformation temperature and thickness strain has a combined effect on dynamic recrystallization of Mg layer, and intermetallics are not sensitive to temperature and mainly influenced by deformation degree.

### 3.3. Texture evolution of component layers

Fig. 9 presents the EBSD results of three typical regions cut from cylindrical parts formed at 200°C. On the whole, the thickness strain of the bottom region, the corner region and the wall region increases successively, resulting in increased
dynamic recrystallization (DRX) and decreased grain size of Mg and Al layers.

It can be seen that the inverse pole figure (IPF) of bottom region (Fig. 9c) that: 1) Mg layer is composed by equiaxial grains caused by recrystallization during annealing treatment after rolling; 2) Al layer is characterized by deformation bands which are formed in the rolling process and not recovered and recrystallized in annealing; 3) Mg17Al12 and Al3Mg2 layers are distinct and an angle between the intermetallics and the RD exists. Therefore, the microstructure of bottom region is approximate to that of Al/Mg/Al laminate before deep drawing [20], which is consistent with the results showed in Figs. 7 and 8. Mg layer exhibits basal texture with the maximum intensity of 10.68, and c-axes of a large number of Mg grains tilt to the RD around 30° to 40°, as shown in (0002) pole figure (PF). Besides, high angle grain boundaries (HAGBs) (>15°) occupy the largest proportion with a peak around 30° in the bar chart of misorientation angle distribution, indicating low dislocation density and extensive recrystallization [25]. However, for Al layer with cubic texture, low angle grain boundaries (LAGBs) (2°–15°) holds dominant position.

Distinct difference can be observed between the bottom and corner regions. As shown in Fig. 9b, Mg layer still exhibits basal texture, but it rotates nearly 90° around the ND. This phenomenon suggests that a majority of grains tilt their c-axes from the RD to the TD, which decreases the maximum pole intensity to 8.72. Besides, the ratio of HAGBs slightly increases, which is attributed to the activation of non-basal slips at high deformation temperature in the previous literature [26]. By comparison, Al grains of corner region presents clear grain boundaries because of plastic strain-induced grain refinement [27], and in Mg alloys DRX is also considered to be a major process in grain refinement [28]. (111) PF shows a more random distribution and a lower intensity than that of bottom region, which can be explained by weakening and even eliminating of original rolling texture. Actually, Al layer in corner region Therefore, LAGBs decline by half and HAGBs significantly grow.

**Fig. 8 – Mg/Al interface of deep drawing cylindrical parts at 200 °C.**
In the wall region, it is obvious that both Mg and Al grain size greatly reduced by more extensive DRX, as shown in Fig. 9a. For Mg layer, intensity of basal texture slightly decrease, and the titling angle from the ND to the TD shows a slight rise. However, pole intensity of Al grows to 5.78 compared with the corner region (4.14). DRX occurs by growth of newly developed nuclei with different crystal orientations from those of original grains, and the continuous recrystallization changes the texture of Al layer [29].

To further investigate plastic deformation process of Mg layer, schmid factor (SF) of four common slip systems of the original (Mg layer of Al/Mg/Al laminate before deep drawing), bottom, corner and wall regions are calculated, as shown in Fig. 10. When deep drawing force // RD, there is little differ-
ence in SF values of basal slip (0001) <11-20> among the three regions from cylindrical part, all of which are smaller than that of the original Mg layer. A similar trend are found in pyramidal slip {10-11} <11-20>, which is opposite to that of prism slip {10-10} <11-20> and pyramidal slip {11-22} <11-2-3>. These changed SF value of slips are associated with the rotation of the c-axis of grains and the texture evolution [30,31]. However, when deep drawing force // TD, SF of these slips at different regions is almost in the opposite condition, compared with deep drawing force // RD.

4. Conclusion

Deep drawing was conducted at various temperatures ranging from 20 °C to 230 °C, using Al/Mg/Al laminates fabricated
by hot rolling at 400 °C and annealed at 200 °C for 1 h, and the bottom, corner and wall regions were selected to observe the Mg/Al interface and to investigate the microstructure evolution of component layers. The following conclusions can be drawn:

1) No delamination is observed in deep drawing at various temperatures, and forming temperature significantly affects the LDR of Al/Mg/Al laminate. The value of LDR grows with increasing forming temperature, reaching a peak value of 3.1 at 200 °C, followed by a reduction at 230 °C. 

2) The maximum LDR of Al/Mg/Al laminate is higher than that of as-rolled Mg or Al sheet, although there exists brittle intermetallics at Mg/Al interface. The reason is that varying degrees of fracture in intermetallic layers helps to release stored energy and facilitate coordinated deformation. At corner region of cylindrical part drawn at 200 °C, fragment is observed in intermetallics.

3) Al/Mg/Al laminate shows the largest LDR at 200 °C, which can be attributed to fine Mg grains and ruptured intermetallics. The deformation temperature and thickness strain has a combined effect on dynamic recrystallization of Mg layer, and intermetallics are not sensitive to temperature and mainly influenced by deformation degree.

4) For cylindrical part drawn at 200 °C, Mg layer at bottom, corner and wall regions all exhibit basal texture, but c-axes of Mg grains gradually change orientation from tilting toward the RD to tilting toward the TD. The increasing extent of DRX greatly refine the Mg grains and weaken the basal texture.

5) For cylindrical part drawn at 200 °C, continuous recrystallization changes the texture of Al layer. The corner region shows a random texture with the lowest intensity of 4.14, and the bottom and wall regions both exhibit cubic texture.

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