Formability of AZ31 Mg alloy sheets within medium temperatures

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Abstract

The stretching tests of the commercial AZ31 Mg alloy were conducted at 130 °C, 170 °C, 210 °C, at the forming speeds of 10 mm/min and 50 mm/min, respectively. The formability of AZ31 sheets at high temperature was evaluated by forming limit diagrams (FLD). The fracture morphologies were analyzed using a scanning electron microscope. The results show that the FLD of AZ31 Mg alloy is affected by the forming temperature, in another word, the formability increases with the increasing of the forming temperature. That may be because the non-basal slip system starts to move by thermal activation at high forming temperature. It is also demonstrated that the formability of the AZ31 Mg alloy is on the decline with the increasing of the forming speed. The slipping performs thoroughly to release the stress during the deformation if the forming speed decreases. In addition, the higher the forming temperature is, the more obvious the effect of the forming speed is. The forming temperature is the main dominating factor on the formability of AZ31 Mg alloy.

Keywords: AZ31 Mg alloy; The warm formability; Forming temperature; Forming speed

1. Introduction

Magnesium alloys, the lightest metal structure material for engineering applications, have taken a great research interest in the automotive, aerospace, weapons, electronic and other fields, because of their low density, high specific strength and stiffness, good damping characteristics, as well as excellent castability. Especially in the field of automobile industry, magnesium alloys have replaced the steel, cast iron and even aluminum alloys, because they can reduce the weight of vehicles, so that significantly contribute to fuel economy and reducing CO₂ emissions [1–6]. Nowadays, magnesium alloy products have been mainly manufactured by the die casting process, but the traditional casting magnesium alloys are unable to meet the growing industrial demands due to various casting defects and poor mechanical properties of the casted material. The wrought magnesium alloys synthesized by the plastic processing technologies such as rolling, extrusion, and forging etc., have taken serious attentions, since they have the higher mechanical properties. Thus, the sheet forming processes achieved by using wrought magnesium alloys can be feasible alternative methods and they can assure higher productivity and final strength. Therefore, sheet forming processes of magnesium alloys have become the important development direction [7–10]. However, sheet forming processes of magnesium alloys are seriously restricted by the limited ductility at room temperature. This is because, only the basal slip system can start in the hexagonal close-packed (HCP) crystal structure of magnesium alloys. Although non-basal slip planes can also move, they are not active because their critical resolved shear stresses (CRSS) are much higher than those of the basal one at room temperature, resulting in plastic deformation relying more on the coordinated action of the slip and twin. According to the reasons described above,
the plastic deformation ability of magnesium alloys is so poor and these alloys are prone to emerge deformation defects such as cracks [8,10–12]. Usually, with the increasing of the deformation temperature, the activities of non-basal slip systems increase, therefore the ductility of magnesium alloys is obviously improved. However, if the deformation temperature is too high, the grain size will significantly grow up, and at the same time, complex high temperature forming tool systems, high cost and poor surface quality limit the production of wrought magnesium alloy sheets [12,13]. As a matter of fact, a lot of deformation request of the magnesium alloy stamping is not high, and its stamping deformation can realize within the range of 100～170 °C, so that there is no need for stamping at higher temperatures. In addition, the magnesium is a very rate-sensitive material especially at elevated temperatures [7].

Research on the formability of magnesium alloy sheets has been actively conducted for recent years. Japanese scholars Takuda and El-Morsy [14,15] have given their warm stamping research results, and they have determined that the temperature range is 150～250 °C. S. H. Zhang [16] has put forward warm forming process of magnesium alloy sheets, indication that the range is 120～170 °C, which is suitable for production requirement due to high production efficiency and good formability. Naka et al. have obtained the forming limit diagram (FLD) of an Al–Mg alloy sheet at different temperatures and forming speeds [17]. But until now, the factors influencing on the formability of the Mg alloys haven’t been explored clearly. Therefore, the formability of the Mg alloy within medium temperatures at different forming speeds was observed using FLD in the present study and the effects of forming temperature and forming speed on the formability of AZ31 alloys were examined, in order to provide the reference for industrial production.

2. Experimental

2.1. Experimental material

The AZ31 magnesium alloy sheets in fully annealed state after hot rolling with the thickness of 1.0 mm were used for the present study. The chemical composition of AZ31 magnesium alloys is shown in Table 1.

2.2. Experimental principle

In order to determine the FLD of AZ31 sheet, the stretching test was performed. Fig. 1 shows the schematic diagram of stretching tests. The sample with circular grid was put between the die and the blank holder, and the edge of the sample was pressed by the blank-holder force to ensure the material does not flow. During the tests, a bulge would form at the middle of the sample under the punch force, and the experiment would stop until the sample had neck or slight rupture.

2.3. Stretching test

2.3.1. Sample preparation

All specimens were prepared along the rolling direction. Samples with different widths (40 mm, 60 mm, 120 mm,
140 mm, 180 mm) were machined to obtain different straining conditions required for the determination of the forming limit curves. The dimension of FLD specimens is shown in Fig. 2.

2.3.2. Grid printed

Before FLD test, the electrochemical corrosion method was adopted to print 2.5 mm-diameter circles, because the FLD test would be carried out under heating condition. The grid printed sample is shown in Fig. 3.

2.3.3. Experimental condition

The stretching tests were carried out on a BCS-50AR testing machine. The punch diameter was 100 mm. Table 2 presents the experimental parameters.

2.3.4. Draw the FLD

An automatic strain measuring system was used to evaluate the major ($\varepsilon_1$) and minor strains ($\varepsilon_2$) to built the FLDs.

2.4. Microstructural observation

The fractured surface morphology was analyzed by JSM-6510A scanning electron microscope (SEM).

3. Results and discussion

3.1. The influence of deformation temperature on the formability

Fig. 4 shows the deformed specimens, with different widths, tested at different temperatures. It can be seen that the different degree deformation have occurred in different parts of the samples, and finally, the rupture or necking phenomenon appeared.

The forming force—displacement curves, shown in Fig. 5, were obtained from the samples with the width of 60 mm tested at various temperatures. It clearly reveals that as the temperature increases, the forming force decreases and the stamping height increases gradually.

Fig. 6 implies the FLDs of AZ31 alloy at different temperatures. As shown in Fig. 6, for a given minor strain, a higher major strain is obtained with increase in temperature. Thus, the formability of the AZ31 magnesium alloy increases as temperature increases. Furthermore, it can be seen that the curves are asymmetric, in another words, the curves in the negative part of the $\varepsilon_1$ versus $\varepsilon_2$ diagram are higher than those in the positive part. The minor strain on the left part is less than 0, meaning that the sample is under the pull-compressive stress state, while the minor strain in the right part is greater than 0, implying that the sample is under the pull—pull stress state. Actually, materials under the pull—pull stress are more likely to rupture, so the forming limit curve on the right side is lower than the left.

Macroscopic morphologies and microscopic morphologies of fracture surface obtained from the samples with the width of 60 mm at different temperatures are shown in Figs. 7 and 8,
respectively. It is clear that the morphology of fracture is strongly affected by the forming temperature. From Fig. 7(a), it can be seen the macroscopic surface is flat at 170°C, while the surface is broken at 210°C in Fig. 7(b). From further microscopic morphologies in Fig. 8, the dimple can be observed, and with increase in temperature, the dimple is becoming bigger and deeper, which means the formability is improved.

Generally, the formability of AZ31 magnesium alloy sheet increases with the rising of forming temperature. That is because the temperature is the key factor influencing the slip of magnesium alloy and plastic deformation capacity. That means if the temperature is different, the started slip system is not the same. At low temperature, the plastic deformation of magnesium alloys is given priority to basal slip and twinning, while as the temperature increases, the activities of the atoms are enhanced, and the difference of critical resolved shearing stress between the basal slip system and the non-basal slip system decreases. As a result, the potential slip systems such as prismatic surface and taper surface can be activated by heat, so that the plastic deformation of magnesium alloy ability is improved greatly.

3.2. The influence of forming speed on the formability

Fig. 9 shows the FLDS tested at different forming speeds. It is observed that with increase in forming speed, the FLDS become lower. Thus, the formability of the AZ31 magnesium alloys increase as the forming speed decreases. But, in the actual production, in order to acquire the greater productivity, the forming speed should be as high as possible on the premise of guarantee the formability. The effect of the forming speeds is more obvious to the positive part of the forming limit curves.
Comparing Fig. 9(a)–(c), it can be seen that the higher the temperature is, the more evident the influence of the forming speed is. At 130 °C, the temperature is the main limiting factor for plastic deformation of AZ31 magnesium alloy, therefore, the effect of forming speed is not obvious, but the effect of forming speed on the pull—pull area is larger than that on the pull-compressive area. When the forming temperature increases, the temperature is no longer the restricting factor for the plastic deformation of magnesium alloy, and at this time, the effect of forming speed on the formability becomes more obvious, meanwhile, the effect on the pull—pull area becomes consistent with the effect on the pull-compressive area.

Microscopic fracture surface morphologies obtained from the samples with the width of 60 mm at different forming speeds are shown in Fig. 10. With the forming speed decreases, the dimple is becoming bigger and deeper, which indicates that the formability is much greater when the forming speed is lower.

In spite of the effects of the forming temperature on the formability, the forming speed of AZ31 magnesium alloy also has certain influences. But the effect of forming speed is more complex. In general, the plasticity of pure magnesium and most magnesium alloys is improved by decreasing the strain rate at room temperature, while super-plastic forming at high temperature is difficult to get big forming efficiency if the speed is too high or too low. The influence of forming speed on the formability mainly attributes to the following two aspects. First one is the thermal effect. The thermal effect can affect the slip and other hot deformation behavior and is advantageous to the plastic deformation, especially at a low temperature and large forming speed. Therefore the influence of thermal effect cannot be neglected. Secondly, forming speed influences
hardening behavior and dislocation motion of magnesium alloys. It takes time to slip during plastic deformation, so decreasing the deformation speed is good for slipping. If the forming speed is too high, the spread of slip between adjacent crystal grains is not conductive and continuous, so it’s easy to cause large stress concentrations near the grain boundary. At this time, simple slip is difficult to release stress, thus the slip must rely on twin or crack initiation and propagation to coordinate deformation and release the stress. Thus, if the forming speed decreases, the slipping performed thoroughly to release stress during the deformation, and this is favorable to the forming process of AZ31 Mg alloy.

4. Conclusions

(1) The influence of forming temperature on the FLD of AZ31 Mg alloy is obvious. The formability can be improved with the increase in temperature. Non-basal slip system started by thermal activation is considered as the main reason why the plastic deformation of magnesium alloys can be greatly improved with the increasing of temperature.

(2) It is also demonstrated that the formability of AZ31 Mg alloy is on the decline with the increasing of forming speed. The slipping performed thoroughly to release the stress during the deformation if the forming speed decreases.

(3) The higher the forming temperature is, the more obvious the effects of the forming speed is. The forming temperature is the main dominating factor on the formability of AZ31 Mg alloy.

References