Non-Isothermal Simulation of Warm Circular Cup Deep Drawing Processing of an AZ31 Magnesium Alloy Sheet

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Due to their low density, high specific strength, and electromagnetic interference shielding, magnesium alloy sheets are increasingly used in automotive and electronics industries. However, magnesium alloy sheets are usually formed at an elevated temperature due to poor formability at room temperature. For the industrial use of magnesium alloy sheets, the mechanical properties at elevated temperatures and appropriate forming process conditions need to be developed. In this study, the warm deep drawing process of AZ31 sheets is numerically studied by non-isothermal simulation. The difference between the isothermal and non-isothermal simulation results and the progress of warm forming is also discussed. The drawn depth and thickness distribution obtained from non-isothermal simulation agreed well with experimental results.

Keywords: AZ31 magnesium alloy sheet, deep drawing, non-isothermal simulation, warm forming

1. Introduction

The development of lightweight materials is a very important issue in automotive, aerospace, and electronics industries. The product weight can be effectively reduced using lightweight materials such as magnesium alloys, which have excellent mechanical properties such as low density, high specific strength, and electromagnetic interference shielding. The dominant technique in manufacturing magnesium alloy components is die-casting,¹ ² but the parts have limited mechanical properties, for example, endurance strength, ductility, and limited thin-walled casting. The sheet forming process is an alternative process for magnesium alloys, which produces good mechanical properties and a fine-grained microstructure. However, sheet forming of magnesium alloys is restricted by the crystalline structure.

The crystal structure of magnesium alloy is hexagonal closed-packed, which limits deformation at room temperature. Therefore, magnesium alloys show limited formability at room temperature. In general, the formability of magnesium alloys is effectively improved by increasing temperature with the activation of non-basal slip systems and twinning. Although most studies investigated the formability of magnesium alloy sheets with square or circular deep drawing, several papers on the warm forming of magnesium alloy sheets indicated that the formability of magnesium alloys was significantly improved at temperatures up to approximately 200°C.³ ⁴ ⁵ ⁶ Several research papers conducted FE simulation for the warm forming of magnesium alloy sheets³ ⁴ ⁵ ⁶ ⁷ ⁸ using isothermal conditions with PAM-STAMP or non-isothermal conditions with DEFORM, MARC, and ABAQUS/standard. However, few papers have been published on the FE simulations for the warm forming of magnesium alloy sheets using non-isothermal conditions.

In this study, the warm deep drawing processing of magnesium alloy sheets was studied using both the non-isothermal simulation and the experimental approach. In order to verify the warm forming process, tensile tests and warm circular cup deep drawing experiments were conducted. In the FE simulations, the difference between the isothermal and non-isothermal simulation results and the progress of warm forming are also discussed. At the same time, thickness distribution and major strain distribution in the sheet obtained in experiments were compared with non-isothermal FE simulation results.

2. Experiment

2.1 Tensile test

To determine the mechanical properties, uniaxial tensile tests on AZ31 were conducted at temperatures ranging from room temperature to 300°C. AZ31 magnesium alloy sheet specimens with a thickness of 0.8 mm were prepared according to ASTM E8. Tensile specimens had a gauge length of 25 mm and width of 6 mm. The specimens were elongated at nominal strain rates of 0.16/s.

As shown in Fig. 1, the true stress-strain behavior of the AZ31 sheet at elevated temperatures indicated increased elongation and decreased stress. Figure 2 shows the stress-strain relations of the AZ31 at 25°C and 250°C from specimens cut along 0°, 45°, and 90° angle with respect to the rolling direction. During flow stress at 250°C, the strength of the transverse direction samples was greater than the rolling direction samples, and the strain of the rolling direction samples was greatest due to the anisotropy of magnesium.

2.2 Circular cup deep drawing

To evaluate the formability of the AZ31 sheets, warm circular cup deep drawing tests were conducted using a 200
ton servo press at temperatures ranging from room temperature to 250°C, as shown in Fig. 3. To increase the blank temperature, the blank was heated inside the preheated tool. The tooling systems were heated to the forming temperature using cartridge heaters. The main tool dimensions were as follows; punch diameter of 40 mm, punch and die shoulder radius of 6.25 mm, and a die hole diameter of 41.92 mm. The blanks used in the deep drawing tests were rolled magnesium alloy AZ31 sheets with an initial diameter of 100 mm. The punch speed and temperature were approximately 5 mm/sec and 15°C, respectively. The blank holding forces varied from 5 to 6.8 kN and graphite powder was used as a lubricant.

The experimental and simulation relationships between the forming temperature and drawn depth are shown in Fig. 4, indicating the drawn depth increased with increasing temperature. The circular cup deep drawing experimental results are shown in Fig. 5. To restrict the wrinkling of the blank, the blank holding force was increased. In Fig. 5, however, wrinkling was observed, as the deep drawing experimental setup did not have sufficient blank holding force.

3. Simulation of Warm Circular Cup Deep Drawing

3.1 Simulation model

Non-isothermal simulation of circular cup deep drawing of the magnesium alloy AZ31 at elevated temperatures was conducted using PAM-STAMP (2007.0.1). Only a quarter of the geometries were modeled due to their symmetric boundary conditions, as shown in Fig. 6. Tools were treated as rigid bodies with isothermal and elastic mechanical properties. The 4-node shell element was adopted to construct the mesh for the blank. The material properties of the AZ31 sheet obtained from the tensile test were used in the simulation. The flow stress curves were interpolated and extrapolated using the available input data and a constant tool temperature was assumed. This study did not consider heat convection, material anisotropy, and strain rate effect. The simulation inputs are shown in Table 1. Simulation parameters were as follows: punch velocity of 5 mm/sec, punch temperature of 15°C, blank heating times of two seconds, and punch strokes of 40 mm.

The warm forming PAM-STMAP simulation had two inputs: thermal contact thickness and velocity scale factor (VELSCF). The thermal contact thickness indicates the distance from the contact face and VELSCF controlled the simulation time step for the heat transfer. The thermal contact thickness of the blank and the VELSCF of 0.001 were derived from many simulations.
3.2 Simulation results and discussions

The simulation drawn depth of circular-cup deep drawing is shown in Fig. 4. The study assumed that the blank would rupture when the thinning ratio exceeded 25%. The blank triangle, $\Delta$, indicates the isothermal condition simulation results using a flow stress curve at room temperature and $200^\circ$C. Figure 4 indicates that the drawn depth increases with increasing temperature for both the simulation and experiment.

There is considerable discrepancy of the drawn depth between the non-isothermal and isothermal condition simulations at a tool temperature of $200^\circ$C. The drawn depth of the non-isothermal simulation was 40 mm. The cup wall was cooled by the punch in the non-isothermal simulation. The blank can be more easily drawn from a high-temperature than a low-temperature location as the flow stress increases with decreasing temperature. Alternatively, the drawn depth of the isothermal simulation was approximately 9 mm because the flow stress at high temperature was lower.
Figure 7 and 8 show the drawn shapes and thickness distribution from the experiment and simulation at 200°C, respectively. The simulation thickness distribution agrees with the experimental results. The simulation temperature distribution and percentage thinning distribution are shown in Fig. 9. Maximum thinning was observed at the cup wall where the strength of the cup wall was not uniform. As seen in Fig. 9, the temperature was lower at the punch corner and increased towards the die corner. Therefore, compared with the punch corner, the higher temperature at the cup wall induced low flow stress, which caused thinning at the cup wall.

The experimental major strain contour resembled the simulation of the drawing depth of 40 mm at 200°C as shown in Fig. 10. A discrepancy between the experimental and simulation results was due to different grid sizes.

4. Conclusions

The evaluation of the formability of the magnesium alloy sheet AZ31 was studied using both experimental approaches and numerical modeling. The tensile tests indicated that the flow stress curves decreased with increasing temperature. With a flow stress of 250°C, the strength of the transverse direction samples was greater than the rolling direction, and the strain of the rolling direction samples was greatest. The warm circular-cup deep drawing indicated that the drawn depth increased with increasing temperature. A discrepancy between the drawn depth of the non-isothermal and iso-thermal conditions was observed in the simulation results due to heat transfer effects. The drawn depth obtained from non-isothermal simulation agreed with the experimental results and the non-isothermal simulation thickness distribution was in good agreement with the experimental results. Future work will focus on determining the process conditions of warm deep drawing, such as tool radius, friction between the tool and blank, punch velocity, and tool temperature, using non-isothermal simulations.

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