Influence of the preheating strategy on the deep drawing of extruded magnesium alloy ME20 sheets

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Abstract. Due to the hexagonal crystal structure of magnesium alloys, a high forming limit can only be achieved at elevated temperatures. For the material characterization of extruded magnesium alloy ME20 sheets, at elevated temperatures, the in-plane torsion test and a multi-layer upsetting test were conducted. Also, FLCs were determined at elevated temperatures. For the deep drawing, two different heating strategies are investigated. In the first method, specimens are placed in an oven at 400 °C for around 10 minutes and then rapidly transferred to the tool. In the second method the specimens are directly heated in the deep drawing tool. In both methods the specimens are painted with Bornitrid lubricant. The effect of the preheating on the coefficient of friction is investigated by using strip tensile tests. FEM simulations for the deep drawing comparing two different material models (Barlat 2000, CPB06) are executed. The results show that specimens heated in the tool show a better formability than oven-heated specimens. The numerical results present that there is no significant difference between Barlat 2000 and CPB06 in an isothermal deep drawing condition. The numerical results are in good agreement with the deep drawing experiments which also indicates that the warm FLCs allow for a good failure prediction.

1. Introduction

The major drawback of using magnesium alloys is poor formability at room temperature (RT) due to the hexagonal crystal structure. Because of cost efficiency and fairly good mechanical properties, rolling is the conventional method for manufacturing of magnesium alloy sheet. However, this method is time-consuming with taking into account a high number of steps for thickness reduction. Furthermore, the achievable thickness in the rolling process is limited as indicated by Friedrich and Schumann [1]. One possibility for decreasing the process time and manufacturing thinner magnesium sheets is an extrusion. By extrusion, there is a possibility of manufacturing thin sheets in only one step. The main restriction of extrusion is the width constraint of the sheets. Gall et al. [2] extruded open tubes and flattened profiles for achieving wider sheets. Norert et al. [3] used the same method for comparing the mechanical properties of the extruded sheets with hot rolling and twin roll casting. The effect of the unbending and flattening of the extruded open-tube magnesium alloys was investigated by Dardaei Joghan et al. [4]. The finite element method (FEM) is a useful tool for prediction of the deformation behaviour of materials in forming processes. For an accurate FEM simulation, the anisotropy needs to properly considered in the material model. Barlat et al. [5]
developed a material model (Barlat 2000) for considering the symmetric response of the material in tension and compression. Later Cazacu et al. [6] introduced advanced macroscopic orthotropic yield criteria for describing the complex behaviour of magnesium and titanium alloys. The Cazacu-Plunkett-Barlat yield function (CBP06) can consider both the anisotropy and the strength differential (SD) effect.

In the following study, the formability of the ME20 extruded magnesium alloy at elevated temperatures is studied. Two different heating strategies, direct heating (tool-heating) and indirect heating (oven-heating) with the application of Bornitrid lubricant are investigated. For the investigation of the preheating effect on the friction coefficient (COF), a strip tensile test is performed. Deep drawing experiments and simulations with Barlat 2000 and CBP06 were performed and the results of the simulations are compared with experiments.

2. Experiments

Magnesium sheets in this study are manufactured by extrusion of ME20 magnesium slabs. To achieve wider sheets, the open tube profiles were extruded and continuously expanded and flattened. The effect of the unbending of the extruded sheets on the flow curves and the evaluation of microstructure are described in details in [4]. The multi-layer upsetting test was performed for determining the biaxial tension point of the yield locus, since the deviatoric stress state in the multi-layer upsetting test is the same as for a biaxial tensile test, which was not available at elevated temperatures. For this, the sheets were laser cut in a square shape with a length of 12 mm and a thickness of 1.5 mm. Ten layers were stacked in the middle of the lower grip in the same extrusion direction (ED) and were aligned with the help of the right measuring angles as illustrated in Figure 1a. No lubricant was used during the experiments. After alignment, the specimens were heated in the oven until the target temperature with the heating rate of 20 K/min. Before performing the experiments, the specimens were kept at the target temperature for 10 minutes for homogenizing the temperature. The experiments were performed at 200 and 250 °C at least three times for each temperature. 

A novel warm in-plane torsion test was executed to study the shear behaviour of the magnesium alloys. For this purpose a new tool was designed and manufactured as shown in Figure 1b and c. The specimens were located by the pins. The upper punch applies the clamping force. Then specimens were heated by thermal conduction in the tool. The strains were measured by the GOM-ARAMIS system.

The deep drawing is performed with the modified tool in a BUP 1000 machine from Zwick GmbH as shown in Figure 2a. The die, blank holder, and the punch were heated to the target temperature with heater cartridges. Both sides of the specimens were fully lubricated with Bornitrid spray. Two different methods were used for heating the specimens. In the direct heating, the specimens were located in the warm tool and waited until the equivalent temperature was reached. In the indirect method, preheating of the specimens were done in an oven. The specimens were heated till 400 °C for 10 minutes and then rapidly transferred to the tool with a transfer time around 5s.

In order to investigate the formability of the extruded magnesium sheets and also using the results for validation of simulations, forming limit curves (FLC) at the three different temperatures (150, 200, 250 °C) were generated. The DIN ISO 12004-2 Nakazima method was employed to determine the FLCs. The same tool set up as shown in Figure 2a for performing the Nakazima tests was used. A new semi-spherical punch with a diameter of 100 mm was manufactured. The offline measurement system GOM-ARGUS was used for measuring the strains. For this purpose, the specimens were painted with circular grid patterns. For heating the specimens, the direct method (heating in the tool) was used. The specimens were formed and as soon as a crack appeared (force drop) the experiments were stopped. Finally, the FLC was determined with the use of the ARGUS system. FLCs were determined in two different directions to the ED (0° and 90°) at 200 °C and in the ED at 150 and 250 °C. For decreasing the friction effect during the Nakazima test, PTFE films and the Bornitrid spray were used. Five specimen geometries were used for the determination of the FLC and for each geometry at least three experiments were repeated.
Figure 1. (a) Experimental setup of sheet multi-layer upsetting test (b) Experimental setup of warm in-plane torsion test (c) Schematic view of the warm in-plane torsion test

The strip tensile tests at 200 and 250 °C were executed for investigating the effect of the preheating on the friction coefficient. The tool setup is shown in Figure 2b. The strip sheets were heated by the inductor to the target temperature before pulling.

Figure 2. (a) Schematic view of deep drawing (b) Setup of the strip tensile test

Due to space restrictions only the upper clamp was heated. For understanding the influence of different process parameters on the friction coefficient, the design of experiments (DOE) method in Minitab software was employed. The number of experiments was optimized by the D-optimal tool. The parameters of the
experiments are mentioned in Table 1. To investigate the effect of the preheating strategy on the friction coefficient, the experiments were performed with the two different methods. In the first method the strips were painted with the Bornitrid spray and then directly heated in the strip tensile testing machine. In the second method the painted strips were preheated in the oven at 400 °C for 10 minutes and then located in the tool. The surface quality of the strips after the experiments was investigated by a Keyence VHX-500F light microscope.

**Table 1. Test plan for strip tensile test**

| Normal Force in N | 500 | 1000 | - |
|-------------------|-----|------|---|
| Sliding velocity in mm/s | 1   | 2    | 4 |
| Temperature in °C | 200 | 250  | - |
| Lubricant | No lubricant (Direct heating) | Bornitrid | - |
| Heating strategy | Indirect heating | Direct heating | - |

**3. Finite Element simulation**

The LS-Dyna software was used for conducting isothermal deep drawing simulations. One quarter of the geometry was simulated for saving computation time. Four-node rigid quadrilateral shell elements were assigned to the tools. The maximum mesh size of 1 mm, based on the results of the convergence of force results, was applied to the blank. The blank was modelled as deformable part using shell elements with 7 through-thickness integration points. For performing the finite element simulations, the two different material models Barlat 2000 and CBP06 were used. The uniaxial compression strength values were exported from Li [7]. Magnesium alloys show a high SD effect as reported by Raphanel et al. [8]. For calibration of the parameters of the CBP06 model, the yield strength in the compression state also is required. For calibration of the parameters of both models the tensile test results of [4] were used. In Table 2 the results of the fitted $\alpha$ values for Barlat 2000 are presented. LS-Opt was used for fitting the eight $\alpha$ values with the inverse identification method.

**Table 2. Barlat 2000 material fitted parameters**

| Temp. in °C | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 200         | 1.200       | 0.8005      | 1.073       | 0.8824      | 0.8963      | 0.9813      | 1.044       | 0.8361      |
| 250         | 1.227       | 0.7518      | 1.038       | 0.8707      | 0.8841      | 0.9536      | 1.024       | 0.8109      |

The CPB06 material model parameters were computed by the ‘minimum of constrained nonlinear multivariable function’ in Matlab. The parameters were calculated based on the results of the tensile test, the multi-layer upsetting and the uniaxial compression. The results of the fitted parameters for the CPB06 are listed in Table 3.

**Table 3. CPB06 material fitted parameters**

| Temp. in °C | $k$ | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{12}$ | $C_{13}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ |
|-------------|-----|----------|----------|----------|----------|----------|----------|----------|----------|
| 200         | 0.1478 | 1.0544   | 1.4642   | 1.0306   | -1.5414  | 1.565    | -1.8092  | -1.1017  |
| 250         | -0.0339 | 0.5637   | 0.4156   | 2.4034   | 2.0543   | 1.0552   | 0.8018   | 1.6253   |

The results of the predicted anisotropy values and yield stresses in the different loading directions for Barlat 2000 and CBP06 at 250 °C are plotted in Figure 3a. The results show that both material models could accurately predict the anisotropy and yield stress values. In Figure 3b, the size and shape of both yield functions are illustrated. The main difference between the two yield functions is in the third quarter of the diagram, where the biaxial in-plane compression point is. Since there is no available experimental result for this point, it could not be decided which yield criterion is more accurate there.
4. Results and discussion

4.1 Experimental results

Figure 4a compares the results of the achieved FLCs at the different temperatures. As expected, by increasing the temperature, the formability increases as well. The most interesting aspect is the low formability of the extruded ME20 sheet at the biaxial stress state which is not the case for rolled magnesium alloys as investigated by Stutz et al. [9]. The results accord with earlier observations by Bohlen et al. [10], which showed that ME21, ZE10 and AZ31 sheets have a poor stretch formability. The main reason for the formability limit in the righthand side of the FLC could be the strong textures and aligned basal planes in the sheet plane [10]. It should be also mentioned that at 250 °C the evaluation of the uniaxial Nakazima specimens was not possible due to the grids distortion and double necking. Therefore, the FLC shown in Figure 4a is drawn based on 4 specimen results.

The anisotropy values of the magnesium alloys are a function of the plastic strain as shown in Figure 4b. The approach for determining the cumulative anisotropy can be found in Ghaffari et al. [11]. By increasing the plastic strain, the cumulative anisotropy values increase. Figure 5 displays the results of the deep drawn specimens with the two different heating strategies. What stands out is that the indirect heating strategy has a negative effect on the drawability of the specimens especially at 200 °C. The maximum achievable
drawability (initial diameter/punch diameter) at 200 °C was 1.75, however with the direct heating, this value increases to 2. The required punch force for drawing the specimen in the indirect heating is almost 50% higher than for the indirect heating at 200 °C. The main reason for this effect could be the friction force. Based on the strip tensile test results, the COF is highly dependent on the type of the heating strategy.

**Figure 5.** Deep drawn specimens at 200 and 250 °C with blank holder force 10 kN

The interaction plot between the process parameters and the COF is plotted in Figure 6a. Since there is no intersection of the lines there is no interaction between the parameters. The lowest COFs are for application of the Bornitrid with the direct heating and the highest values are for the Bornitrid with indirect heating. The COF of the dry surface is even lower than that of the indirect heating with Bornitrid.

**Figure 6.** (a) Interaction plot for mean of COF (b) Surface quality of the strips after the experiments

The reasons for this behaviour could be explained by an investigation of the surface of the strips after the experiments. The light microscopy pictures for the specimens of the two different heating strategies with Bornitrid are presented in Figure 6b. The scratches and striations can be seen in both specimens. However, in the indirect heating case, the scratches are more significant and the surfaces contain also abrasion of the plowing type. Moreover, for both indirect lubrication and no lubrication there was an accumulation of the material at the end of the of the contact zone. The scratches for indirect heating are deeper but in the direct heating the scratches were superficial. It can thus be concluded that the Bornitrid loses its properties in the oven and acts as an abrasive material. Therefore, the COF increases sharply.

**4.2 Simulation results and comparison**

Deep drawing simulations for both heating strategies (practically meaning different COF) were executed with the Barlat 2000 and CBP06 material models. The result of the thickness distribution for the simulation and experimental results are presented in Figure 7. It is revealing that both material models predict almost the same thickness distribution. It can be seen that neither the Barlat 2000 nor the CBP06 material model are able to predict accurately enough the thickness at the middle of the wall to the flange of the cup. This
contrast could be explained by two main reasons. One reason could be explained by Figure 4b. The dependency of the anisotropy values on plastic strain is not considered in both material models.

![Image](https://example.com/image.png)

**Figure 7.** Thickness distribution comparison for indirect heating and direct heating

Therefore, in this area the prediction of the thickness is not exact and lower than the experimental results. The second reason could be the inhomogeneity of the temperature distribution in the experiments. Consequently, there is no constant strength during the deep drawing process which was also found by Palaniswamy et al. [12]. Moreover, it can be seen that there is a difference between the predicted thicknesses for the two models especially in the wall area mainly at indirect heating. This difference could be explained by considering the biaxial stress state of the deep drawing in the wall area. As Figure 3b shows the main contrast in both models is in biaxial stress states. It could be concluded that the yield function Barlat 2000 could accurately enough model the deep drawing simulations. Due to the simplicity of the Barlat 2000 in comparison to CPB06, it was used for further simulations. Since fractures happened at 200 °C, FLCs were determined in the two directions, ED and TD, as shown in Figure 8a. As an instance of simulation accuracies, the deep drawing simulation results at 200 °C with the indirect heating and at 250 °C with the direct heating with considering the results of the warm-FLC are presented in Figure 8. Since an FLC shows the initiation of localized necking but not necessarily the fracture strains of a material, an offset of the FLC is used as a fracture line (FL), as also used by Lee et al. [13] for magnesium AZ31 alloy. Mitukiewicz et al. [14] show that the fracture points are in a range of less than 10% above the warm FLC for magnesium AZ31 alloy. However, Isik et al. [15] show, for aluminum AA1050-H111, that the fracture line may not look like a constant offset of the FLC. In this work, the 10% offset of the FLC is considered as a failure criterion (as also implemented in commercial codes, like LS-Dyna). From the results, as shown in Figure 8a, it can be seen that the FL in TD could predict the fracture. At 250 °C, it is clear that the distance between the strain paths and the FLC is long enough to remain in the safe strain region. Overall, it can be concluded that the simulations are in good agreement with the experimental results.

5. Conclusion

The present work was designed to study the effect of the preheating strategy on the drawability of extruded magnesium alloy ME20 sheets. It was concluded that heating the specimens directly in the tool shows a lower COF and consequently a higher formability could be achieved. Moreover, numerical simulation results show that there is no significant difference between the Barlat 2000 and CBP06 material model for the deep drawing of the magnesium alloys, and Barlat 2000 could accurately enough simulate the deep drawing process.
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