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# Achievements in deep drawing of magnesium alloy sheets

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**Abstract.** Magnesium alloy sheets bear significant potential in replacing conventional materials such as aluminium and steels in ultra lightweight designs. High specific strength and stiffness, combined with the lowest density of all structural metals make magnesium alloy sheets candidates to face the challenges of reducing vessel weight in the transportation industry and thus, green house gas emissions. For forming components from sheet metal, deep drawing is a well established and commonly applied process. Due to the limited formability of magnesium sheets at room temperature, deep drawing processes have to be conducted at elevated temperatures. In the present study, hot deep drawing experiments on an industrial scale hydraulic press were successfully conducted. Forming was done at moderately low temperatures from 150°C to 250°C. Sheets of the magnesium alloy AZ31B (Mg-3Al-1Zn-Mn) were drawn to symmetrical cups according to Swift. For AZ31, distinct basal type textures are formed during hot rolling. The influence of texture on earing is displayed. The microstructural evolution of the material is dominated by the formation of twins and dynamic recrystallisation. By optimising the process, a drawing ratio of 2.9 was achieved for AZ31 sheet, outperforming conventional materials at ambient temperature.

## Introduction

Magnesium sheets will play an important role for ultra lightweight designs in the transportation industry. The low density of magnesium alloys (1.74 g/cm$^3$) coupled with mechanical properties that are comparable to aluminium alloy sheets make magnesium alloy sheets candidates to solve the task of reducing vessel weight and fuel consumption [1]. Applying magnesium sheets for formed components requires profound knowledge about process limits and parameters. This study deals with the deep drawing of magnesium sheets AZ31B (Mg-3Al-1Zn-Mn) as the most common wrought magnesium alloy used for sheets. Due to the limited formability of conventional magnesium alloy sheets at ambient temperatures, forming processes have to be conducted at elevated temperatures. Magnesium alloy sheets usually feature a sharp basal type texture which hampers strain especially in thickness direction of the sheet and results in a low work hardening potential [2]. Above 225°C for pure magnesium, formability increases significantly due to thermal activation of non basal slip systems [3]. Thus, the main concern of this study is the influence of temperature on the drawability of magnesium sheets and resulting properties of the deformed sheet metal. Deep drawing experiments on cylindrical cups according to Swift can yield information about the formability. Supplementary forming limit tests are reported in former publications [4].

## Experimental

The deep drawing behaviour of a conventional magnesium alloy AZ31 sheet was investigated in this study. The initial thickness of the sheet was 1.52mm. The sheet was supplied in annealed condition with the initial microstructure consisting of equiaxed grains with an average grain size of 10µm.

The deep drawing experiments were conducted on a industrial scale press Müller-Weingarten ZE-315 with a maximum drawing force of 3MN. A custom deep drawing tool with a cylindrical punch with a diameter of 75mm was used. The blankholder was heated up to 150°C, 200°C and 250°C, respectively, the punch temperature was kept at 80°C. A comparable cold punch was found to be beneficial for the deep drawing process by Dröder [5]. Circular blanks with increasing diameter were cut from the sheet in order to determine the drawing limit ratio. The drawing limit ratio as defined in equation 1 is a reasonable measure for the drawability of sheet metal. In order to minimize friction, oiled PTFE foil of 50µm thickness was used as lubrication system.

$$\beta_{0max}=D_{0max}/d_0 \qquad (1)$$

$\beta_{0max}$: drawing limit ratio, $D_{0max}$: maximum blank diameter, $d_0$: punch diameter

Successfully drawn cups were sectioned and the wall thickness was measured with an outside micrometer from the bottom of the cup to the onset of earing along the rolling direction and at 85% maximum wall height around the circumference. In order to gather information about the earing tendency of the material, the profile height was measured around the circumference. The hardness of the deformed cups was measured according to Vickers (HV5) from the bottom of the cup to the top in order to determine a hardness profile. Micrographs of the microstructure of deep drawn cups were taken at the centre of the wall, using standard preparation techniques based on picric acid etching [6].

## Results

The drawing limit ratio as defined in equation 1 of the investigated magnesium alloy AZ31 sheet vs. testing temperature is show in Fig. 1. While the drawability is rather low at 150°C, cups with a high drawing ratio of 2.9 were drawn successfully at 200°C and 250°C respectively. Applying higher drawing ratios resulted in failure of the sheet metal during forming.

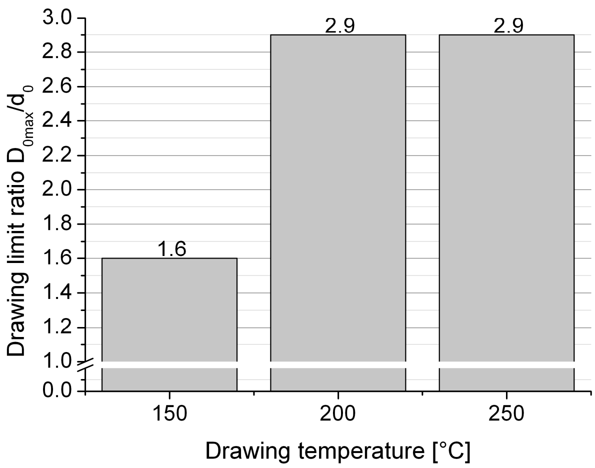


Figure 1: Drawing limit ratio of AZ31 sheet vs. drawing temperature

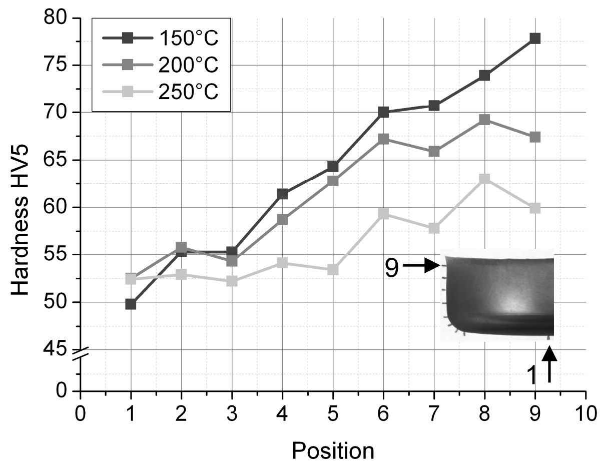


Figure 2: Hardness profile of cups, drawing ratio β=1.6

Figure 2 shows the hardness profile from the bottom to the onset of earing of cups drawn with a drawing ratio of 1.6. Compared to the initial hardness of the sheet, there is an increase of hardness with increasing height for all cups. At 150°C drawing temperature, the hardness increases from 50 to 78 HV5 from the bottom to the top. At the bottom, no significant change in hardness compared to the initial hardness of the material (54 HV5) is detected. For the cups being drawn with a drawing ratio of 1.6, there is a clear tendency of reduced hardness at the same position with increasing temperature.

The resulting specimen geometry in terms of wall thickness and profile height around the circumference of successfully drawn cups ($\beta_0$=2.9) at 200°C and 250°C is shown in Fig. 3. 0° represents the rolling direction of the sheet. It becomes obvious that there are four maxima of profile height, representing earing of the material. These maxima are coupled with minima in the wall thickness of the cup. The ears are distributed symmetrically at 45°, 135°, 225° and 315° relative to the rolling direction. Generally, the ears are higher for cups drawn at 250°C with the wall thickness being lower. The wall thickness over wall height as shown in Fig. 4 reveals that the wall thickness at the bottom of the cups drawn at 200°C and 250°C and a drawing ratio of 2.9 is approximately equal to the initial thickness of the sheet. A minimum in wall thickness is measured half way up the cup wall with this minimum being more pronounced for the cups drawn at 250°C. Towards the top of the cup, the thickness of the sheet increases during the forming process by thickening.

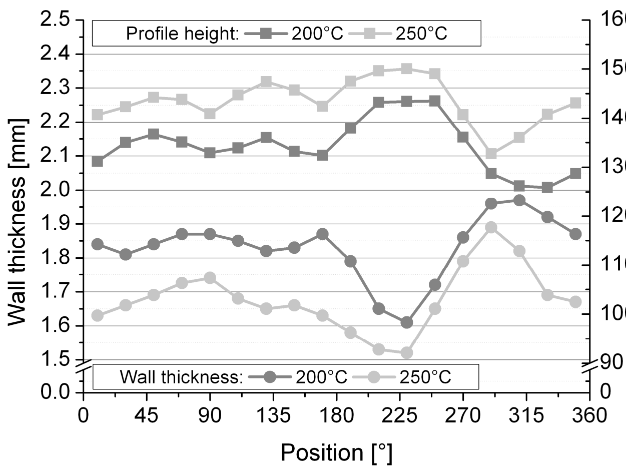


Figure 3: Profile height and wall thickness, β=2.9

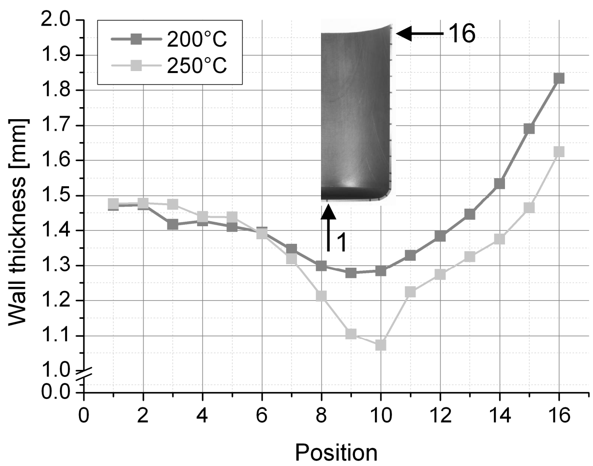


Figure 4: Wall thickness along the RD, β=2.9

Micrographs of the deformed cups at the centre of the wall are presented in Fig. 5 and 6. Figure 5 of a cup, drawn at 150°C with a drawing ratio of 1.6, reveals a high volume fraction of twins. The grain size is comparable to the initial grain size. Figure 6 shows a different morphology. At a drawing temperature of 200°C and drawing ratio of 2.9, small recrystallised grains accompanied by few grains of the initial size are found.

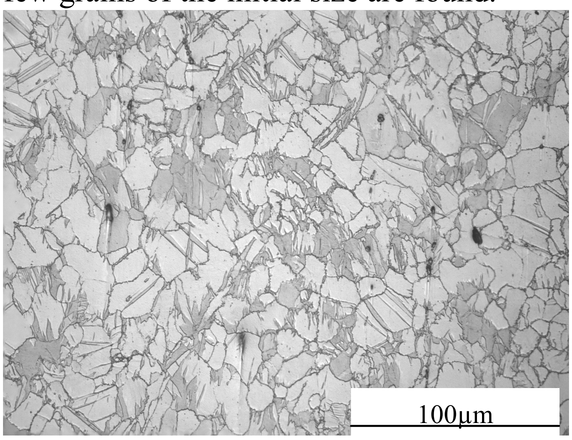


Figure 5: Microstructure of a cup, at the centre of the wall, drawn at 150°C, β=1.6

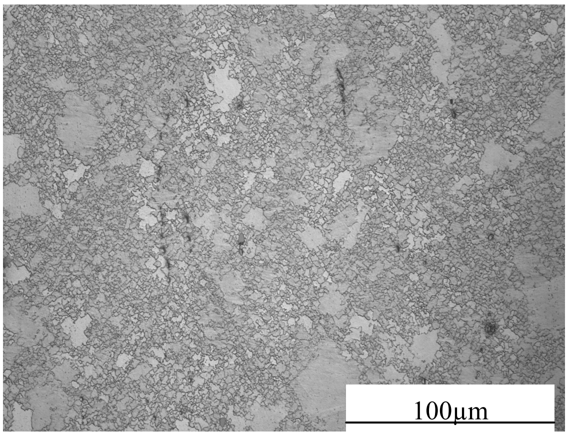


Figure 6: Microstructure of a cup, at the centre of the wall, drawn at 200°C, β=2.9

## Discussion and conclusion

The achieved drawing ratios clearly show the influence of temperature on the formability of magnesium alloy AZ31 sheet. While the drawing limit ratio is found to be rather poor at 150°C, impressive cups were drawn at higher temperatures. It is notable that raising the temperature from 200°C to 250°C does not yield an improvement of the limit drawing ratio. The findings of this study are in good agreement with forming limit tests [4] and deep drawing tests [5] of similar sheets which confirm no increase in formability under deep drawing conditions from 200°C to 250°C. An increase in temperature results in a reduced strength of the material and thus, in lower forces that can be transferred from the punch to the deformation zone. Furthermore, figure 4 clearly shows that the material's tendency for thinning is enhanced at 250°C compared to 200°C drawing temperature. The reduced cross section of the material cannot transfer a higher load that would be necessary for higher drawing ratios. This thinning is caused by the increased tendency to flow from the thickness direction of the material in the temperature range between 200°C and 250°C [4]. Increased activity of non basal slip systems such as <c+a> pyramidal slip is responsible for this change which is also responsible for the reduced wall thickness of the ears and increased earing height at 250°C drawing temperature.

The hardness profile of the deformed cups correlates with the increasing degree of deformation from the bottom up the wall of the cup. Work hardening of the material results in higher hardness, especially for 150°C drawing temperature. At higher drawing temperatures, dynamic recovery and dynamic recrystallisation take place, yielding lower hardness values. The active deformation mechanisms also show a dependency on temperature. While at low drawing temperature twinning contributes significantly to the overall deformation, at higher temperature the contribution of twins is neglectable. Strain in thickness direction of a strongly textured magnesium sheet can be accommodated either by twinning or, at elevated temperatures, by <c+a> pyramidal slip. Combined with the findings above, it can be stated that the optimum drawing temperature for the investigated AZ31 sheet is in the region of 200°C.

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