Improving the formability of magnesium by cushion-ram-pulsation

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Abstract. The application of forming processes using lightweight magnesium alloys is known to be difficult with regard to minor formability caused by a small number of active slip systems, especially at low temperatures. However, a new approach for deep drawing at elevated temperatures considers flexible motion profiles of a servo-screw press. The so-called cushion-ram-pulsation (CRP) is a newly developed method of position-controlled motion. As a result, the process limitations for deep drawing are significantly extended. This study investigates the deep drawing process of AZ31 cups by variable motion profiles of cushion and ram, focusing on enhanced drawability. Therefore the initial AZ31 sheet was fabricated by twin-roll casting. Furthermore, the adjustment of the forming temperature for an improved forming process and optimized component properties are described. In addition, the results were evaluated in comparison to conventional deep drawing, and the superior technological potential will be outlined.

Keywords: Deep drawing, Magnesium, Sheet metal

1 Introduction

Due to the continuing trend towards lightweight design, magnesium as a construction material is predicted to become increasingly widespread [1]. Despite major advances in manufacturing technology, alloy development and corrosion protection, a broad range of applications is still limited in terms of formability [1–4]. Thanks to its crystal structure, the hexagonal solidifying magnesium has only a small number of independent slip systems at low temperatures: two instead of the required five [5,6]. Additionally, the flow performance of AZ31 sheet metal depends very much on the strain rate. . Higher strain rates lead to a lower logarithmic strain at fracture [2,7]. Therefore, in the past magnesium has only been successfully deep-drawn at low forming speeds and high process temperatures as described in [3,8–10].

Accordingly, the objective of the present study is to extend the process window of this process, to increase productivity and open up new areas for magnesium application. For this purpose, the investigation deals with the effect of cushion-ram pulsation (CRP) on deep drawing of magnesium blanks. Cushion-ram pulsation is a new method to extend the process limitations, despite the fact that it takes more time to conduct the position-controlled process by using a servo-screw press [11].

2 Experimental procedure

2.1 Production of the blanks

The initial sheets of magnesium alloy AZ31 were produced by a twin-roll casting process (TRC) [16]. After the TRCs the material (t = 5.35 mm) were hot rolled in three passes with a heat treatment between the first two passes (430° C, 8 h) and after the last pass (330° C, 0.5 h).

A sheet with a thickness t of 1.5 mm and a blank diameter of 220 mm also of 240 mm were used. The chemical composition was obtained of 3.09 Al, 1.02 Zn and 0.456 Mn (all wt.%) and cut in the samples.

2.2 Cushion-ram-pulsation and utilized process parameters

A DUNKES servo-screw press with 800 kN maximum ram force and 300 kN maximum cushion force was used (Fig. 1) to investigate the formability of magnesium by cushion-ram-pulsation (CRP), The servo-screw is characterized by a special axial powertrain layout.

Fig. 1. Servo-screw press [12].

The servo-driven spindle press technology allows high variability in motion of the ram and the cushion. Using

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the press technology, special movements are possible such as CRP and conventional deep drawing. The motion and speed of cushion and ram are individually programmable, which enables the adjustment of variable flange gaps.

The process of CRP is a variable kinematic process and consists mainly of two steps. The first step starts with a ram dwell time. Therein, the flange gap increases as the cushion moves away from the ram. In the next stage, the ram moves to draw the part while the gap between the die and the blankholder is opened by a defined value. In the following second step, the ram is stopped during the holding time and the blankholder flattens the flange by closing the flange gap. The resulting wrinkles are formed back by the movement of the blankholder. For the investigation in the present study, a modified CRP technique was used (Fig. 2) to close the flange gap to initial sheet thickness. The process cycle was adapted from former investigation of press hardening using CRP technology [12]. The final holding time is not implemented in this present study of forming magnesium sheet.

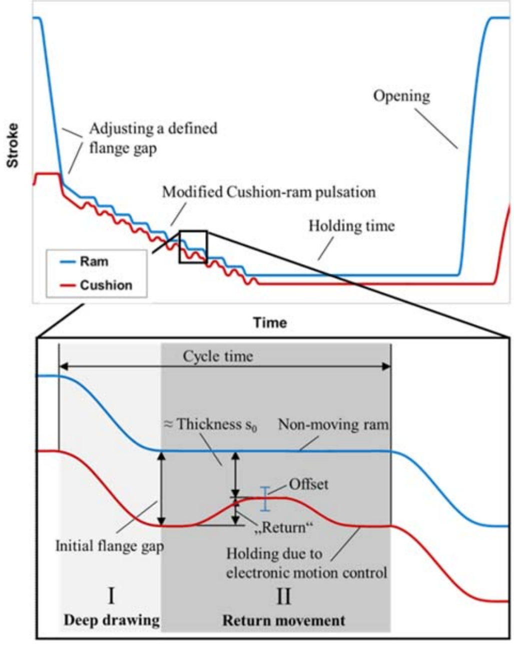

Fig. 2. Stroke-time-curve of the cushion ram pulsation [12].

A ram-speed of 85 mm/s and a flange gap (gap between die and blank holder) of 4 mm was defined for CRP as well as the conventional deep drawing process. The forming tool for the processes includes active elements such as die, blankholder and punch which are guided by pillars and bushings. Furthermore, die and the blank holder were heated up with integrated heating elements. The forming temperature was varied with a constant value of 150 °C or 250 °C, which are controlled by temperature regulation. The punch diameter is 100 mm and for the die 104 mm which results in a drawing gap of 2 mm. The radius at the punch and the die is 10 mm. The specimens were heated up for 5 minutes in a test furnace up to 350 °C for a forming temperature of 250 °C and 200 °C for 150 °C respectively. This is necessary due to the cooling during the transfer between furnace and forming tool. After the subsequent transfer to the tool the forming operation starts. The drawing experiments were realized with lubricant MoS2. (Fig. 3). After completion of the operations, the sheet thickness distribution was investigated using the GOM ATOS 3D scanning and inspection system.

The influence of forming profiles on the variation of the thickness can be stated clearly by optical coordinate measuring. After forming, the specimen were cut in half and clamped in a measuring frame.

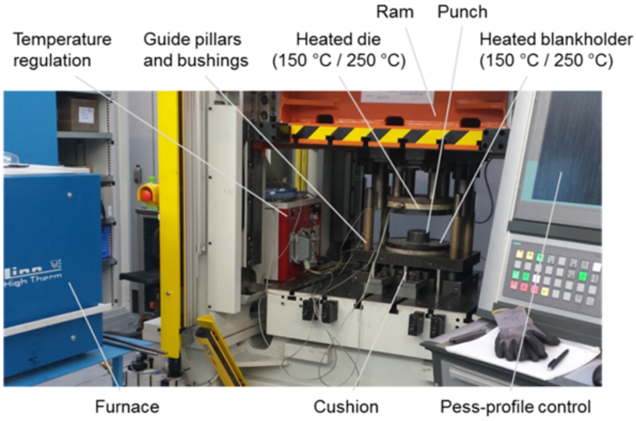

Fig. 3. Experimental setup of the deep drawing investigations.

The experimental process parameters are summarized in table 1. According to Dröder [2], the Limiting Drawing Ratio of the AZ31 at 225 C is 2.5. For this reason, a diameter of 220 and 240 mm was chosen for the investigations.

Table 1. Process parameters.

Process parameter	
material	AZ31
material thickness	1.5 mm
blank diameter	220 mm, 240 mm
lubricant	MoS_2
ram speed	85 mm/s
forming temperature	150 °C, 250 °C
tool temperature	150 °C, 250 °C
motion profile	conventional, CRP
flange gap	4 mm

2.3 Characterisation of the drawn cups

After the drawing experiments, the formed cups were analyzed in different positions (1 - 6) with regard to the local and microstructure and hardness (Fig.4). Since it turned out in preliminary trials that the material behaves symmetrically, only one side of the cups is discussed below. For analyzing the microstructure, the samples were grinded in several steps using SiC sandpaper, polished with OPS suspension, etched using picric acid and finally studied with an optical microscope. To measure the grain size the linear intercept method was used by analysing approx. 500 grains per sample in the centre of the sheet. For mechanical characterization, HV1 Vickers hardness measurements were carried out with the testing device Zwick ZHU 250.

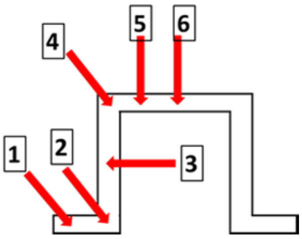

Fig. 4. Schematic illustration of the removal positions.

3 Results and discussion

3.1 Material characterization

The sheets of the initial material have a uniform microstructure with an average grain size in the middle of the sample of 8.2 ± 3.0 µm (Fig 5.).

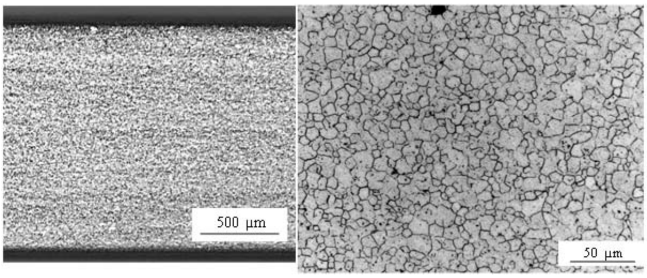

Fig. 5. Microstructure of the source material. Left: overview; right: detailed view.

3.2 Comparison between conventional process and CRP

Two different forming technologies are investigated. The first is a conventional deep drawing process with a ram speed of 85 mm/s and a constant flange gap of 4 mm (Fig. 6).

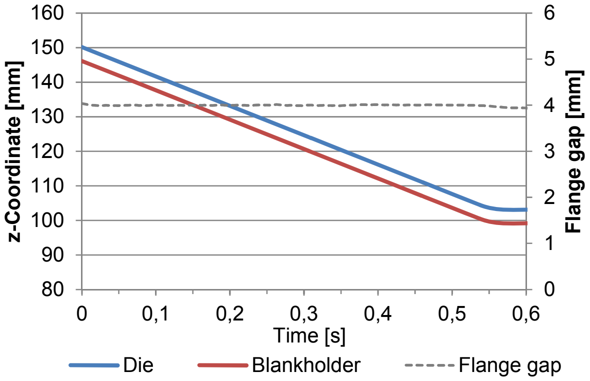

Fig. 6. Displacement - time dependent motion for Conventional deep drawing.

The second is a CRP-profile with a flange gap of 4 mm in the drawing process and a closing gap to 1.5 mm during the holding time of the ram. The CRP motion profiles are divided into forming steps of 5 mm depth and steps to form back the wrinkles which result in a cycle time of 0.4 s. The ram speed in the drawing step reaches 85 mm/s maximum. The process starts with an adjustment of a starting gap between the die and the blank holder. Afterwards the forming process begins (Fig. 7).

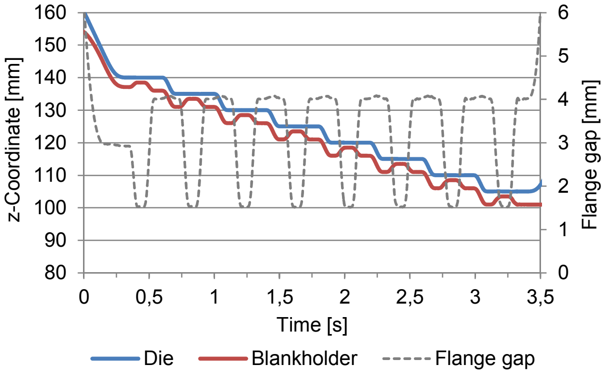

Fig. 7. Displacement - time dependent motion for Cushion Ram Pulsation (CRP).

Table 2 shows cups with the maximum reached drawing depths depending on the motion profile and the forming temperature. The different test parameters show a clear influence on formability. The maximum drawing depth achieved with the conventional process and CRP by a forming temperature of 250 °C was 45 mm. Because the limitations of the experimental set-up, this was the maximum possible depth. At the forming temperature of 150 °C, the maximum drawing depth achieved with the CRP and a blank diameter of 240 mm was 32 mm (Fig. 8). The samples have wrinkles. This is due to the opening of the die and blank holder between the drawing stages.

Fig. 8. Appearance of the deep draw cups for CRP (left) and conventional process (right) at 150 °C.

Whereas the influence of the blank diameter is of secondary importance, a clear impact of the process temperature is evident. CRP at both temperatures results in well-shaped cups in contrast to conventional deep drawing where cracking occur at 150° C tool temperature. However at 250 °C the maximum drawing depth is reached. It is assumed that pyramidal and prismatic sliding systems can be activated at this temperature [13], leading to an improved formability.

Table 2. Maximum drawing depth.

blank diameter [mm]	forming temp. [° C]	tool temp. [° C]	motion profil	drawing depth [mm]
220	250	250	conv.	maximum possible depth: 45
220	250	250	CRP	maximum possible depth: 45
240	250	250	conv.	maximum possible depth: 45
240	250	250	CRP	maximum possible depth: 45
220	150	150	conv.	crack at 25
220	150	150	CRP	27
240	150	150	conv.	crack at 30 (Fig. right)
240	150	150	CRP	32 (Fig. left)

3.3 Sheet thickness profiles after deep drawing

According to the applied press motion profile, a significant influence on the thickness distribution can be stated. Forming of cups at a tool temperature of 250 °C by conventional forming leads to commencing necking at the cup wall, whereas the bottom keeps its initial thickness (see figure 9 a). The amount of thinning can be estimated with up to 0.2 mm. In contrast, a CRP motion profile at the same forming conditions exhibits a homogeneous thickness reduction of about 0.05 mm at the bottom and the wall of the cup (see figure 9 b). The deep drawing process at a lowered tool temperature of 150 °C causes fracturing of the specimen at conventional forming. Cracking starts in the corner of the most heavily loaded zone, where a material flow in thickness direction is required [8].

As a result of the limited forming depth of 30 mm, an increased thinning as observed at a forming depth of 45 mm cannot be stated (see figure 9 d). In contrast, deep forming with CRP at 150 °C tool temperature causes again homogeneous thinning at the bottom and the wall with about 0.05 mm thickness reduction. Due to the reduced forming depth of 32 mm, enhanced thickening at the flange is not observed. All specimens exhibit an increasing thickness at the flange where wrinkles occur.

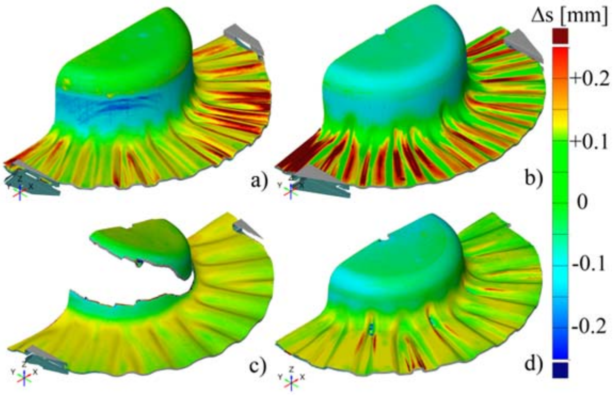

Fig. 9. Sheet thickness distribution of cups by varying press motion profiles. a) T = 250 °C, conv. b) T = 250 °C, CRP
c) T = 150 °C, conv. d) T = 150 °C, CRP

An explanation for that is the material flow in the feed section. The same phenomenon was observed for the deep drawing of steel [12].

3.4 Characterization of the formed parts

All examined states of the formed sheet showed the same microstructure characteristic: a fine structure in the middle of the sheet as well as large grains with diameters of approx. 50 micrometers in the edge areas. These coarse grains already originated from the initial material.

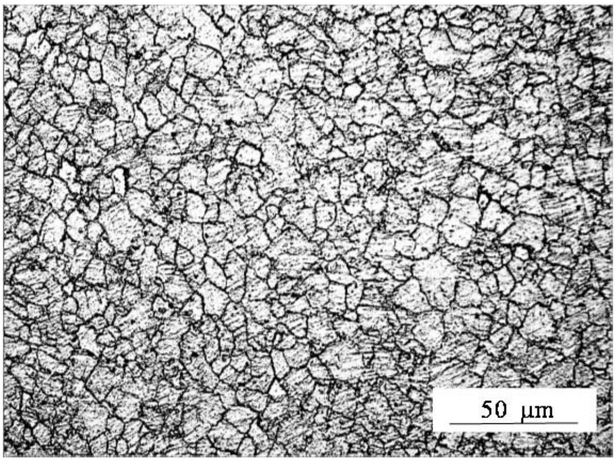

Fig. 10. Microstructure of the at 250 °C conventional-drawn cup at position 4.

The grain size of positions 2 - 6 does not show any significant differences with regard to the process parameters temperature and pulsation (Fig. 12). In figures 10 and 11 this fact is exemplarily demonstrated for position 4 at a forming temperature of 150 °C. The measured deviations were all within the scattering range.

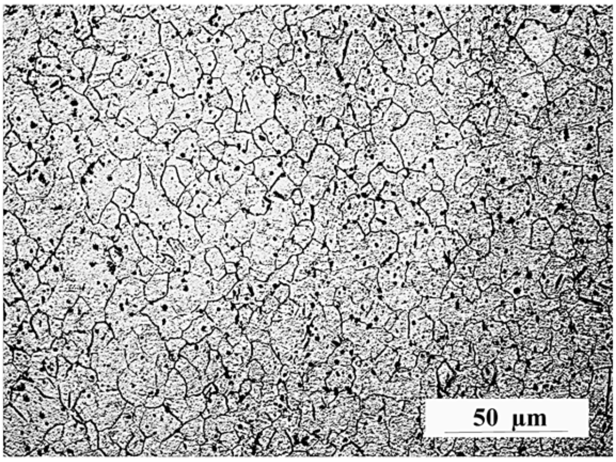

Fig. 11. Microstructure of the at 250 °C CRP-drawn cup at position 4.

However, there are major differences for position 1 (and to a lesser extent in position 2). The authors assume that this effect is not due to the process parameters but to the random local wrinkling at the point of sample extraction.

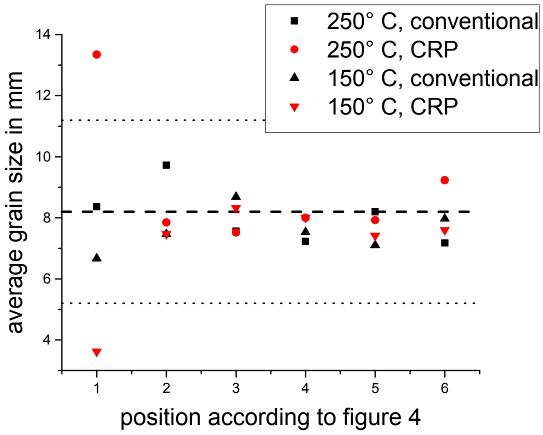

Fig. 12. Dependence of the average grain size from the position according to figure 4. The dashed lines symbolize the average grain size of the initial material and the associated scattering.

The cups drawn at 150 °C show a strong twinning formation over the entire sheet thickness (both conventional and CRP). These are either evenly distributed over the entire cross-section of the sheet or arranged into twin bands (see Fig.13).

At 250 °C deformation temperature, twins are observed only sporadically in the edge grains, especially on the exposed sheet metal side. The local temperature gradient could cause this to occur.

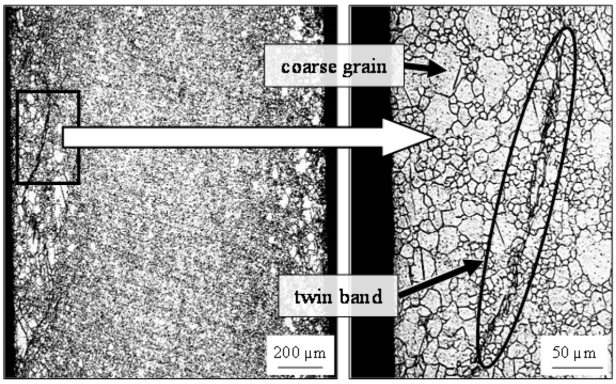

Fig. 13. Cross section through the conventional deep draw cups at 150° C with the occurrence of twin bands.

No indications for recrystallization are visible. Consequently, the increase in hardness (Fig. 14) occurring in the process could be caused by hardening effects. The strong scattering of the hardness values at position 1 are probably similarly, caused by random local wrinkling. The highest degree of deformation is at the cup walls (see Fig. 9) and therefore the biggest hardness increase is observed at position 3. This explanation is also supported by the fact that no pronounced temperature dependence was spotted. The process temperature of 250 °C lies above the recrystallization temperature, 150 °C below [7].

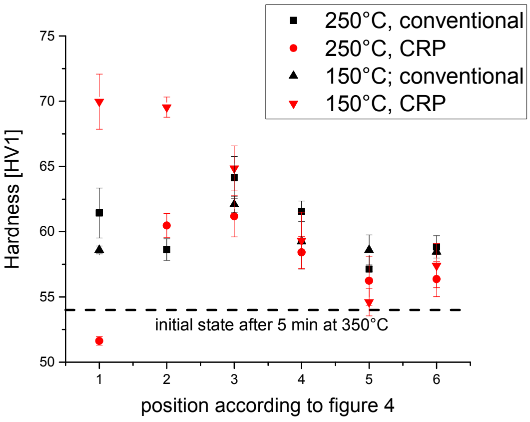

Fig. 14. Dependence of the hardness from the position according to figure 4.

4 Conclusion and outlook

The potential of pulsation superimposed deep drawing for magnesium is demonstrated. While it was possible to achieve a more uniform constriction of the cup walls compared to conventional deep-drawing, the potential of a process temperature reduction was also illustrated. As shown in [13], the critical shear stress of both the basal slip and the twin formation has only a very low temperature dependence for magnesium. As a result, a further reduction of the process temperature seems possible without significant losses in formability. In addition, the transfer of the method to other forming operations such as forging seems conceivable.

However, the underlying mechanism for the substantially improved forming ability were not clarified with the investigation methods used. On the one hand, the changed friction conditions between sheet and punch certainly play a decisive role. On the other hand, there may also be softening effects between the impacts. This mechanism was introduced for CRP of 22MnB5 by Birnbaum et al. [14]. With help of the inclusion of additional investigation methods such as EBSD measurements, a better process understanding on the microscale could be achieved.

As a part of future research, further investigations on the depth drawabilty of this magnesium alloy should be carried out to identify the process window. In this context it is important to determine the Limiting Drawing Ratio (LDR) as a function of tool and forming temperature as well as tribological system (tool material, lubricant e.g.).

References

[1] J.F. King, Magnesium, Materials Science and Technology, **23** (2013)

[2] Doege, E., K. Dröder, Journal of Materials Processing Technology, **115** (2001).

[3] K.F. Zhang, D.L. Yin, D.Z. Wu, International Journal of Machine Tools and Manufacture, **46** (2006)

[4] S. You, Y. Huang, K.U. Kainer, N. Hort, Journal of Magnesium and Alloys, **5** (2017)

[5] R. v. Mieses, Zeitschrift für angewandte Mathematik und Mechanik, **8** (1928)

[6] G. Gottstein, *Physical foundations of materials science* (Springer, Berlin, 2004)

[7] F. Berge, L. Krüger, H. Ouaziz, C. Ullrich, Transactions of Nonferrous Metals Society of China, **25** (2015)

[8] S. Yi, J. Bohlen, F. Heinemann, D. Letzig, Acta Materialia, **58** (2010)

[9] J.S. Lee, H.T. Son, Y.K. Kim, I.H. Oh, C.S. Kang, J.C. Bae, Material Science Forum (2007)

[10] S.H. Zhang, K. Zhang, Y.C. Xu, Z.T. Wang, Y. Xu, Z.G. Wang, Journal of Materials Processing Technology, **185** (2007)

[11] K. Osakada, K. Mori, T. Altan, P. Groche, CIRP Annals, **60** (2011)

[12] D. Landgrebe, A. Rautenstrauch, A. Kunke, S. Polster, S. Kriechenbauer, R. Mauermann, *Proceedings of the 19th International ESAFORM Conference on Material Forming*, 2016

[13] M.R. Barnett, Metallurgical and Materials Transactions A, **34** (2003)

[14] P. Birnbaum, M. Baumann, A. Kunke, V. Kraeusel, D. Landgrebe, MRS Advances, 2 (2017)

[15] H. Kirchner, P. Birnbaum, J. Quellmalz, H. Schlegel, V. Kräusel. Proceedings of the 10th ICIT&APT, 2017

[16] Ullmann, M., R. Kawalla, and H. P. Vogt, Metallurgia Italiana ,**106** (2014)