Pulsed magnetic forming of the magnesium alloy AZ31 – Comparison to quasi-static forming*

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Abstract

Magnesium alloy AZ31 metal sheets were formed at room temperature with a pulsed magnetic field induced by a flat coil. For this a die with variable die radius and inside diameter was used. The forming results were evaluated regarding to deformation, die radius, inside diameter, micro hardness, texture examination of forming area and energy input. In addition high velocity forming process was compared to a quasi-static forming process at room temperature. Therefore an experimental setup with an adapted punch was constructed. Punch geometry was defined in dependence of the high velocity forming structure of a sample at well-defined energy input. By comparing texture and micro hardness at forming area a distinction of high-speed forming process and quasi-static process is determined.

Keywords

Magnesium, Impulse, Forming

1 Introduction

Application of lightweight components, e.g. magnesium alloys, aluminium alloys or CFRP composites are increasing constantly in many manufacturing areas. The constantly increasing technological development of electromobility offers potential for lightweight

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components in cars. In this case a significant reduction of car body weight is possible as mentioned in [1]. Production processes have to meet the requirements of these tendencies and must be suitable for mass production. Forming with the optimal utilization of material and high productivity offers potential for excellent accuracy. Forming of magnesium alloys is accomplished at high temperatures currently. A general challenge in forming of magnesium alloys will be in realizing forming process at lower temperature. Therefore the influence of further process variables, e. g. strain rates, should be investigated.

The comparison of high-speed forming and quasi-static forming of magnesium alloy AZ31 with an exact distinction between both processes led to the present study. For the description of the relation between energy input and deformation AZ31 metal sheets are formed in a die with different die radius. As a result a punch was designed in dependence of the forming geometry of the high-speed process. The comparison of both processes at defined deformation is the aim of the investigation. This paper presents investigations on the comparison of high-speed forming and quasi-static forming of magnesium alloy AZ31.

2 State of the Art

Magnesium and its alloys e. g. AZ31 have hexagonal crystal lattice. Due to the crystal lattice there are three linear independent sliding systems at room temperature. Von Mises criterion indicates that a homogenous deformation requires at least five linear independent sliding systems [2]. Therefore magnesium and its alloys accomplish low deformability at room temperature. Once temperature of 220 °C has been reached further glide planes in the pyramid plane are being activated. In this case deformability of magnesium and its alloys increase rapidly [3,4,5,6,7].

In addition to forming temperature, strain rates play a decisive role in forming processes. In contrast to low strain rates, high strain rates improve forming conditions of several metals e. g. magnesium alloys. Short process time on the order of 50 µs to 200 µs causes quasi-adiabatic process characteristics which increase ductility of magnesium and its alloys [8] and leads to higher deformation in comparison to low strain rate deformation. During deformation the generated heat cannot dissipate quickly enough into the whole sample and leads to local increasing of ductility in deformation area. Through this additional slip planes in the hexagonal lattice can be activated. A homogeneous deformation of the workpiece without failure can be realized because there are at least five independent slip systems now [9].

The characteristics of magnesium alloy AZ80 in dependence of forming temperature and strain rate was determined by [10]. It was discoverd that stress resistance increases rapidly, both rolling and transversal direction, at high strain rates independently from forming temperature as shown in figure 1. At low strain rates which occurs in conventional forming processes deformation is dominated by forming temperature. With increasing strain rates deformation is dominated by hardening and the influence of warming is less. At strain rates of 1000 s^{-1} quasi-adiabatic characteristics dominates forming process and leads to a significant increase of stress resistance as shown in figure 1.

The studies conducted so far show a strain rate dependency of magnesium alloys. The influence of different strain rates at various forming processes for production of identical structures will be studied in this investigation.

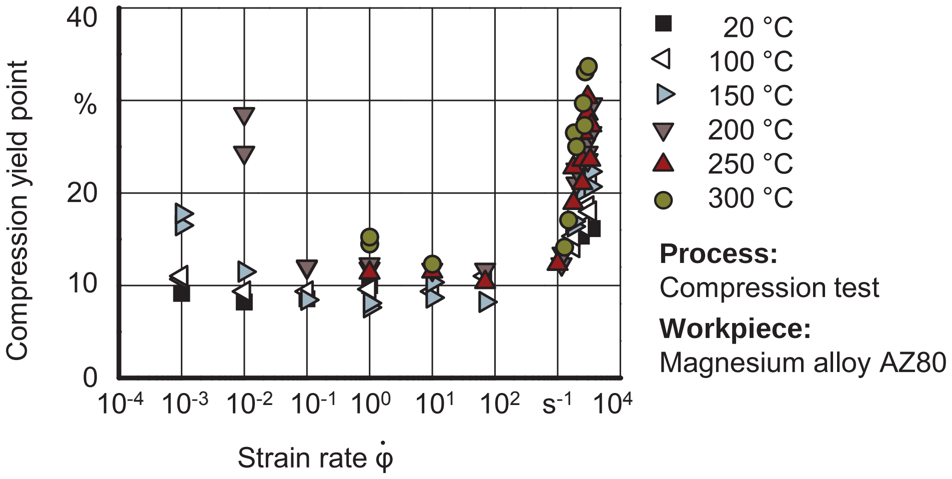


Figure 1: *Strain rate sensitivity of compression yield point at varying temperatures [8]*

3 Experimental Setup

A comparison of pulsed magnetic forming of magnesium alloy AZ31 to quasi-static forming is investigated. The high-speed forming characteristics depend strongly on energy input, coil geometry, inside diameter and die radius. Therefore the electromagnetic forming machine FA-60-1440-SW Magnepuls from the firm Elmag Inc., San Diego, USA, is used. To compare both high-speed forming and quasi-static forming, a defined punch geometry with defined inside diameter and is required. An experimental setup is constructed to compare both forming processes as shown in figure 2.

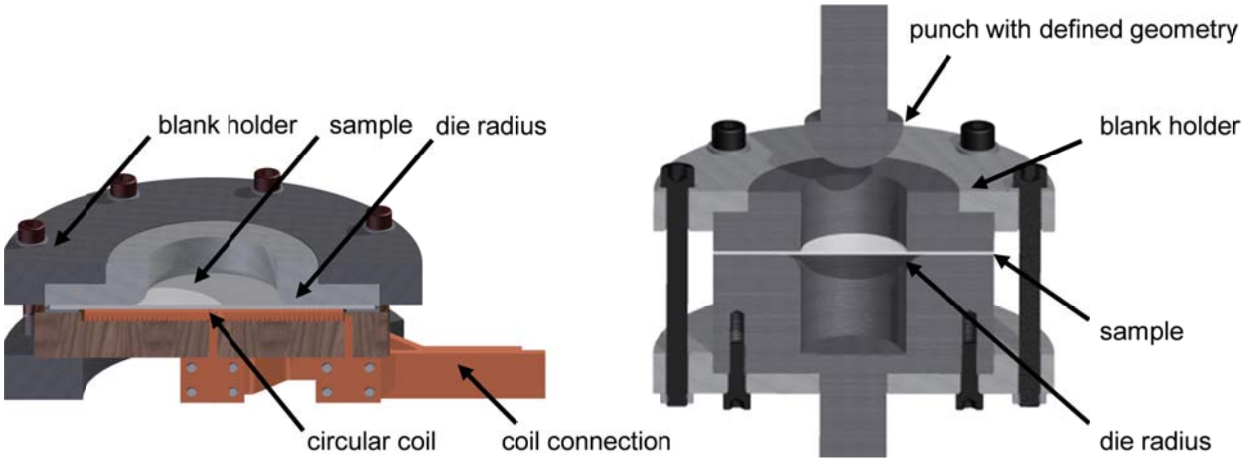


Figure 2: *Experimental setup for high-speed forming (a) and quasi-static forming (b)*

The discharge of a pulsed current is used to accelerate the workpiece into the die. The necessary energy is stored in capacitors and is unloaded as an alternating current. The magnetic field around the flat coil induces eddy currents in the workpiece opposite to the discharge current. By this the magnetic field of the flat coil is shielded. The Lorentz force appears at the surface of the workpiece and leads to deformation. In addition to high speed forming an experimental setup for quasi-static forming is developed as shown in figure 2 b). For this, boundary conditions like inside diameter, die radius, blank holder force and friction between workpiece and die in both experimental setups must be identical. The difference between both variants is determined in the forming zone. The high-speed deformation is realized without any mechanical punch and therefore without friction between punch and workpiece. The quasi-static forming is realized by a strain/compression testing machine ZA 150, from the firm Zwick GmbH & Co. KG, Ulm, Germany, with a mechanical punch. Establishing comparative conditions the punch is lubricated with grease to minimize friction.

Punch geometry is adapted to high-speed forming geometry of the workpiece at room temperature at energy input E = 2.5 kJ with inside diameter d_{inside} = 50 mm and die radius r_{die} = 10 mm as shown in Figure 3. For experiments a circular coil was used.

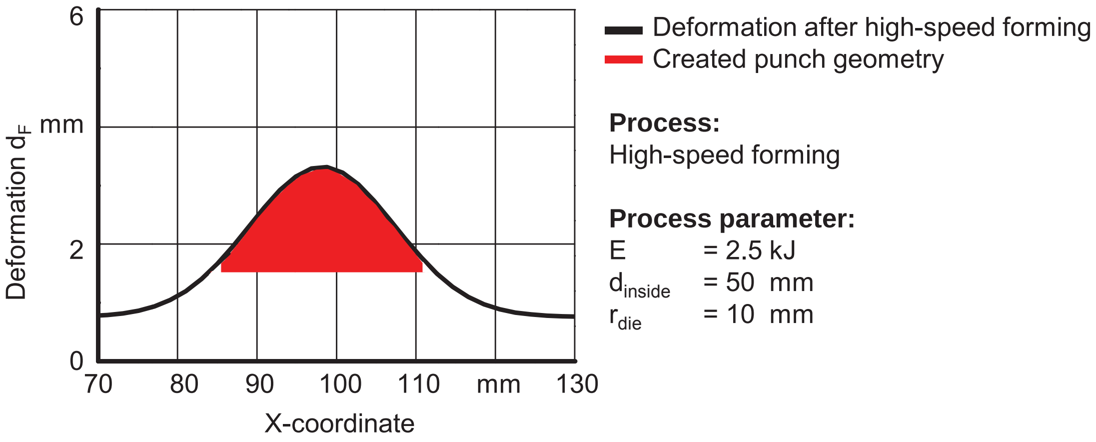


Figure 3: *Creation of punch geometry in dependence of high-speed forming deformation*

The workpiece is positioned in experimental setups as shown in Figure 2 a) and 2 b). The aimed deformation with identical forming geometry is distinguished from different force maximums in both processes. The quasi-static deformation exhibits the force maximum at the top of the mechanical punch. In contrast to this the force maximum of high-speed deformation occurs outside the centre of the coil as shown in figure 4. The configuration of the circular coil leads to force minimum in the coil centre.

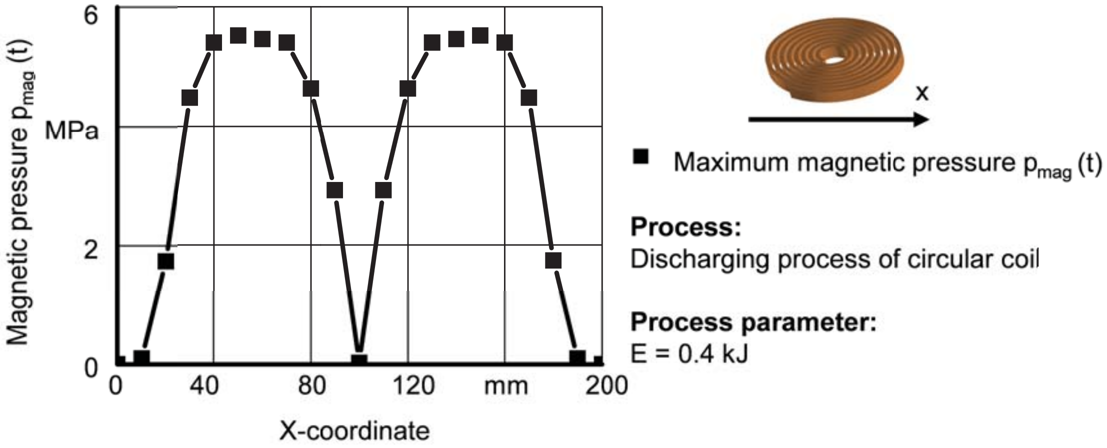


Figure 4: *Illustration of maximum magnetic pressure p_{mag} (t) at the surface of the workpiece during discharging process of the capacitors at process time t = 60 µs*

The determination of the forming process is done after deformation with an ARGUS measuring system from the firm GOM GmbH, Braunschweig, Germany. Therefore a grid with a defined dot pitch of 1 mm is applied on the surface of each workpiece. For the exact determination of process time of the high-speed forming process the high-speed camera Photron FASTCAM SA5 was used. This is required to determine the strain rates of the high-speed process.

For the determination of micro hardness and texture examination the area of maximum deformation is investigated as shown in figure 5. The hardness was determined at the Leitz MiniLoad 2.

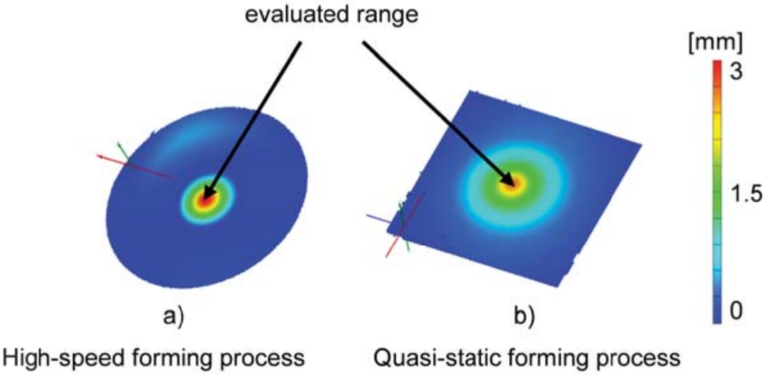
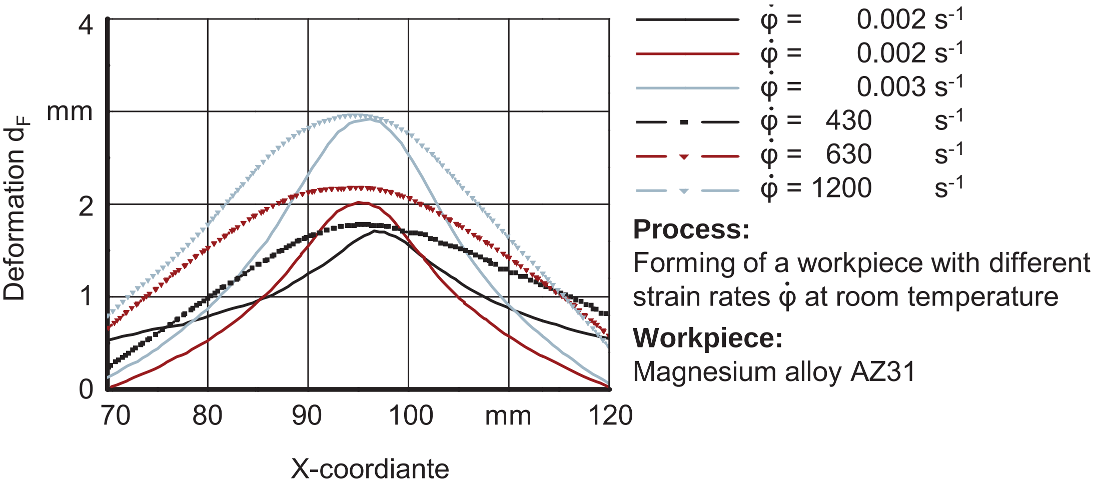


Figure 5: *Illustration of evaluated range for micro hardness and texture examination*

4 Experimental Results

To investigate the comparison of high-speed forming and quasi-static forming the maximum deformation d_F, plastic strain ε_{pl} and Vickers hardness HV at different energies respectively forces were measured. In addition to this texture examination of forming areas were compared. All investigated samples show no cracks in the deformation are. The comparison criterion was the geometry of the deformation. Therefore two dies with an identical inside diameter d_{inside} = 50 mm and die radius d_{die} = 10 mm were constructed as shown in figure 2. Figure 6 shows the results of deformation d_F with different strain rates $\dot{\varphi}$.



Process:
Forming of a workpiece with different strain rates $\dot{\varphi}$ at room temperature
Workpiece:
Magnesium alloy AZ31

Figure 6: *Forming area with deformations d_F at different strain rates $\dot{\varphi}$*

There were several deformations d_F performed. Due to the force maximum of both forming processes there is a difference in the course of deformation along the X-coordinate as shown in figure 6. The quasi-static deformation shows the force maximum at the top of the punch which leads to the highest deformation d_F in the area from $x = 95$ mm to $x = 97$ mm. Outside this area the course falls off steeply because the material is drawn while deformation. In contrast to this the high-speed deformation leads to a course which falls off slightly while the maximum deformations d_F also were measured in the area of $x = 93$ mm to $x = 95$ mm. This course is based on the fact that the deformation of outer areas takes place at first. The inner area follows the outer area due to the mass inertial and leads to a plastic deformation with a superposition of an elastic oscillation of this area. The duration of this entire process, plastic and elastic vibrations, takes up to $t_P = 140$ µs while the duration of the quasi-static deformation takes up to $t_p = 30$ s.

The following table 1 shows the maximum plastic strain ε_{pl} (von Mises) in the evaluated area. The measured maximum plastic strain ε_{pl} for quasi-static forming is significantly larger at each deformation d_F than for high-speed forming. The differences in maximum plastic strain ε_{pl} result from the acting forces in the forming area. With the increase of the deformation d_F larger forces were applied with the result that the friction between punch and workpiece increased. In contrast to this the maximum plastic strain ε_{pl} which occurs in high-speed forming processes is less because the maximum acting forces appear in the outer area. Thus, the same deformations d_F are obtained at different plastic strains ε_{pl}.

Quasi-static forming

Deformation d_F	Maximum plastic strain ε_{pl}
1.7 mm	8.0 %
2.0 mm	11.5 %
2.9 mm	not measurable

High-speed forming

Deformation d_F	Maximum plastic strain ε_{pl}
1.8 mm	3.8 %
2.2 mm	4.8 %
3.0 mm	6.0 %

Table 1: *Measured maximum plastic strain ε_{pl} in the area of maximum deformation d_F (as shown in figure 5) for both processes*

Due to the time-dependent process and the associated process behaviour there are differences in the investigated material properties at the same deformation d_F. Figure 7 shows the influence of strain rates $\dot{\varphi}$ on the Vickers hardness HV.

At low strain rates $\dot{\varphi}$ the calculated Vickers hardness is 74 HV up to 77 HV while at high strain rates $\dot{\varphi}$ the Vickers hardness increases to 83 - 88 HV. Therefore an average difference of Vickers hardness of 11 HV is resulting. With respect to the initial hardness of 63 HV thus follows an increase in hardness of about 19% at a quasi-static deformation. At the high-speed deformation there is an increase in the hardness of about 37%.

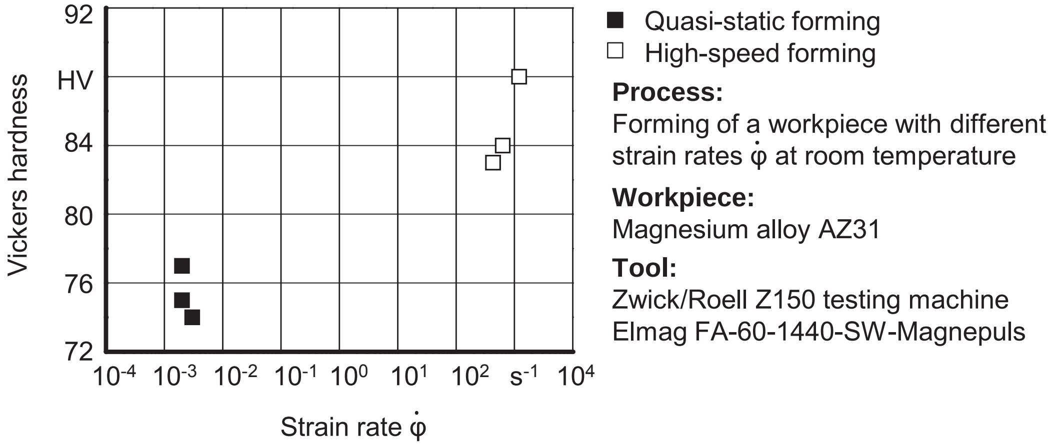
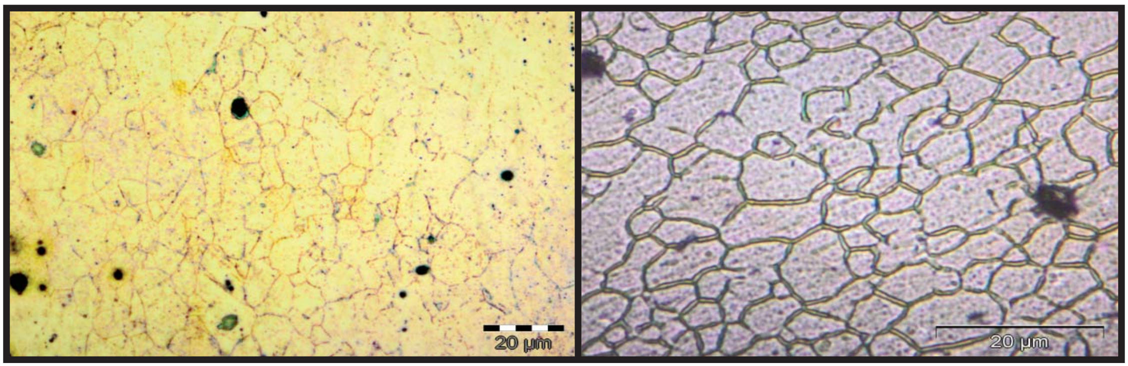


Figure 7: *Measured Vickers hardness of AZ31 in dependence of strain rate $\dot{\varphi}$ after forming process*

In correlation with a higher Vickers hardness HV the pulsed magnetic deformed workpieces show a fine microstructure. In contract, the quasi-static deformed workpieces show a coarser microstructure which correlates with lower Vickers hardness HV. Figure 8 a) shows the texture examination of deformation $d_F = 2.0$ mm at strain rate $\dot{\varphi} = 0.002\ s^{-1}$. In figure 8 b) the texture examination of deformation $d_F = 2.2$ mm at strain rate $\dot{\varphi} = 630\ s^{-1}$ is shown.



a) b)

Figure 8: *Texture examination of deformed areas: a) quasi-static deformation b) high-speed deformation*

5 Conclusion

The comparison of pulsed magnetic forming and quasi-static forming of the magnesium alloy AZ31 at room temperature shows significant differences between both processes. Two experimental setups were realized to produce comparable forming geometries. Both experimental setups have the same physical boundary conditions such as blank holder force and friction conditions between workpiece and die.

The identical deformations d_F in dependence of different strain rates $\dot{\varphi}$ were realized at different forming depths. The courses of the deformations d_F differ due to the process-dependent force maximum in the forming zone. Different plastic strains ε_{pl} occur in the investigated area at different deformations d_F in dependence of the process. In further studies with a modified flat coil which offers the force maximum in the area of maximum deformation d_F more accurate results will be achieved. In addition further studies with higher strain rates $\dot{\varphi}$ will be carried out. Furthermore, for comparison a simulative investigation of the entire process will be done.

The resulting Vickers hardness HV shows a significant dependency of strain rates $\dot{\varphi}$ at different deformations d_F. The Vickers hardness HV of pulsed magnetic formed samples is 15% higher in comparison to quasi-static formed samples. The evaluation of texture examination of both deformation areas indicates that at high-speed deformation in contrast to quasi-static deformation a fine-grained microstructure is formed. Fine-grained structures exhibit general a higher hardness which was confirmed with these studies. The influence of higher strain rates $\dot{\varphi}$ on the microstructure will be considered in further studies.

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