Extension of formability of the magnesium wrought alloy AZ31B-O at room temperature by pulse magnetic forming

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Abstract

For having the lowest density of all metal construction materials of 1.75 kg/dm^3, magnesium wrought alloys are outstanding lightweight materials. The low formability at room temperature limits the industrial use of magnesium AZ31B-O. In this paper the influence of high strain rates was investigated with the aim to improve the formability of the alloy AZ31B-O at room temperature.

The negative strain rate sensitivity of quasi-static strain rates causes an early loss of material stability due to formation of local deformation zones on the work piece surface. This leads to a low formability in the forming state of plane strain, in which the forming limit (FLC) of magnesium alloy AZ31B-O has a critical minimum. For process illustration of multi-axial stress states - which appear in conventional forming processes - the pulse magnetic forming process is used. To create plane strain formability a flat coil is used. The applied die is used to control the free formability. Hereby, a change of the maximum loads on the power transfer zone to areas of plane strain formability occurs.

The results that have been achieved show that high strain rates at room temperature increase the permitted loads of the material with plane strain formability significantly. High speed forming is linked to a rising strain rate sensitivity which increases the flow resistance in critical forming areas, in favor of a rising material stability. This fact is represented by equally reduction of the sheet thickness on the power transfer area. The homogeneous work piece stress clearly increases the formability of AZ31B-O at room temperature compared to quasi-static forming process.

Keywords

Pulse magnetic forming, magnesium AZ31, plane strain formability

1 Introduction

National and international guidelines, e.g. reduction of CO_2 emission in automotives as well as the E-mobility sector due to previously limited energy density of batteries [1], require new lightweight components to reduce the whole weight of a vehicle and associated with these new production technologies. In comparison to steel components, lightweight components like magnesium alloys exhibit lower density and therefore lower mass.
The use of different materials – a so-called “multi-material design” – was investigated in the EU project “Super Light Car”. The mass of the front end structure of a vehicle was reduced up to 100 kilograms, thus the emission of CO_2 could be reduced to 8.4 gram per 100 kilometer. This value corresponds to a fuel economy from 0.3 to 0.5 liters [2]. Especially in the area of E-mobility the total weight of the vehicle structure exhibits a very important role. The average energy density of a lithium-ion battery is 0.10 kWh/kg. The average energy density of a gasoline engine, which was fuelled with premium gasoline, 12.0 kWh/kg. To achieve comparable distances with an electric motor in comparison to a combustion engine an accumulator with a huge energy density is required. The use of lightweight components at different areas in the car body is essential to reduce the weight. Therefore it is necessary to develop an efficient and environmentally sustainable process to form lightweight components like magnesium alloys.
Forming processes with optimal utilization of material and high productivity offer potential for excellent accuracy. Forming process of magnesium alloys is accomplished at high temperatures of 220°C currently. A general challenge in forming of magnesium alloys will be in the realization of forming processes at lower temperatures.
In the last years the pulse magnetic forming processes have gained an increasing attention from both manufacturing companies and research facilities [3, 4]. A considerable advance has been made in the field of process understanding. In this paper an approach for the extension of formability of the magnesium wrought alloy AZ31 by pulse magnetic forming at lower forming temperature is described.

2 State of the art

Formability of magnesium alloy AZ31

In the present work casting rolled and then hot-rolled sheets of the wrought magnesium alloy AZ31 in the condition O (O- temper AZ31B Mg sheet alloy) has been investigated. Magnesium crystallizes in the hexagonal densely packed unit cell (hcp) with an axial ratio c/a of 1.6236. As a consequence of its crystal structure, there are during the forming process at room temperature only two independent slip systems with ‹a›-Burgers vector on the ‹0001›-Basal plane [5]. The activation of the pyramidal slip system of second order which provides not only a deformation component with ‹c›-Burgers vector but also satisfies the ‘von Mises’ criterion of five independent slip systems takes place at temperatures above 225°C. Regardless the critical shear stress τ_{CRSS} possesses for dislocation motion on the ‹0001›-Basal plane the lowest values at all temperatures [6, 7]. Therefore, the ‹0001›‹10$\bar{2}$1›-sliding system is also at high temperatures the main sliding system of magnesium. Associated with this fact the expression of a sharp basal texture during sheet metal fabrication by rolling, in which the c-axis of the unit cell aligns parallel in the intensity maximum of sheet plane normal [8]. Due to the lack of dislocation activity in the sheet thickness direction at room temperature - parallel uni-axial tensile stress to Basal plane - the material is not able to oppose the geometric softening with dislocation hardening. In addition, the logarithmic degree of deformation ranges in the sheet thickness direction not to mechanical pressure twins for an additional strain contribution along the c axis to form in the sheet thickness direction. This is associated with an early loss of material stability and also a low elongation [9]. After CONSIDÈRE criterion, the material is not stable when the increment of the reduction in cross section exceeds the increment of the stress (1), [10].

$$\frac{dY_f}{d\varepsilon} = Y_f \qquad (1)$$

The connection between flow stress and deformation can be captured by using the „Ludwik“ equation in the power function by HOLLOMON (2), [11].

$$Y_f = C \cdot \varepsilon^n \qquad (2)$$

The low hardening capacity of AZ31B-O alloy by Basal texture is associated with a hardening exponent less than 0.2. This is associated with an early diffuse constriction in the uni-axial state of stress in the tensile test which ends without strain localization in shear failure [12]. Despite declining hardening exponent formability of AZ31B-O alloy increases with increasing temperature [13, 14]. Macroscopic background is a rising strain rate sensitivity of AZ31B-O alloy [15]. In the extended approach of the HOLLOMON equation the strain rate is taken into account with the exponent *m* of the strain rate sensitivity (3), [16].

$$Y_f = C \cdot \varepsilon^n \cdot \dot{\varepsilon}^m \qquad (3)$$

If a cross-section in the forming zone of the material occurs during the forming process an increase of the strain rate takes place. With a positive strain rate sensitivity in the forming zone the flow resistance increases in the relevant zone of the work piece and the forming zone differs in surrounding areas with low flow resistance. This is associated with an increase of the material stability in the form of uniform elongation [17]. At quasi-static strain rates at room temperature the AZ31B-O alloy has a low positive strain rate sensitivity of 0.05 which increases with increasing temperature at 0.7, [18]. Furthermore, the strain rate sensitivity can also assume negative values at pronounced tensile twinning. This reduces the achievable material stability significantly, [19].

The AZ31B-O alloy shows at high strain rates maximum CONSIDÈRE strain and maximum elongation at break at uni-axial stress state, see Figure 1. This circumstance is due to an increasing strain rate sensitivity m of AZ31B-O at high speed, [20].

In sheet metal forming, however, mainly multi-axial strain states are important. In particular, the plain strain constitutes for AZ31B-O alloy a critical state of deformation in deep-drawing processes and stretch forming processes. Due to the disabled minor strain the material flow mainly occurs from the sheet thickness. Therefore the forming limit curve (FLC) of AZ31 alloy has a critical minimum in the stress-strain state of deformation [21, 22, 23].

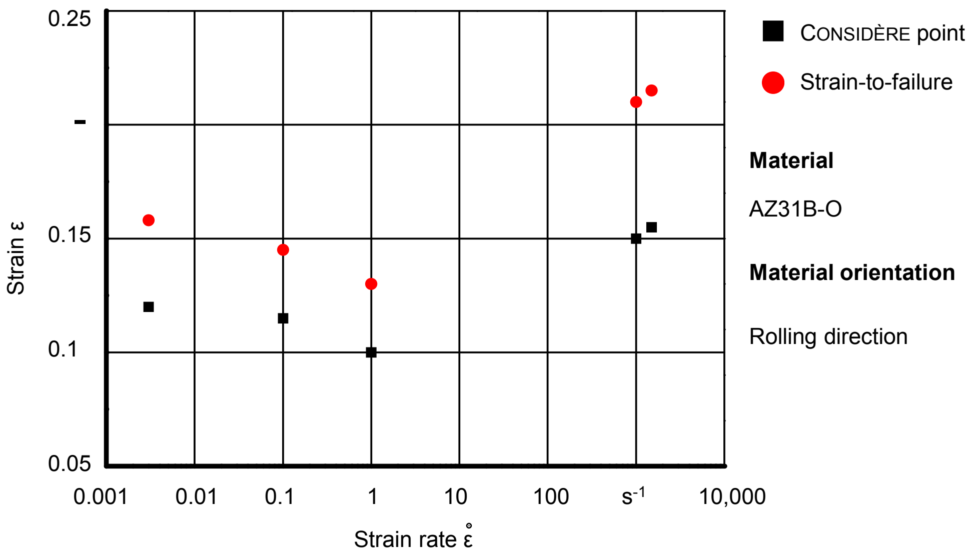

Figure 1: *Strain-to-failure strain and CONSIDÈRE strain of AZ31B-O at room temperature [20]*

ULACIA ET AL showed that an increase of strain rates up to $\dot{\varepsilon} = 1\ s^{-1}$ leads to a reduction of the deformability of the alloy AZ3 [24]. Increasing the strain rate $\dot{\varepsilon}$ comes along with an increase of the proportional elongation and breaking elongation [20]. Furthermore, it was shown that the magnesium alloy AZ31 shows a strong strain rate dependency. This results in an improved formability at high strain rates [25].

In the present study the behavior of the AZ31B-O is investigated in the state of plane strain. Pulse magnetic forming, which exhibit process-dependent high strain rates, is compared with a conventional quasi-static forming process at low strain rates.

3 Approach

Basically the forming behaviour of magnesium alloys at low forming temperatures is affected through process-dependent strain rates and the texture of the material [8]. By combining high strain rates which occur in processes like pulse magnetic forming as well as an optimized texture the formability of magnesium alloy AZ31B-O can be increased significantly.

Process principles

Pulse magnetic forming, which is an active-energy based process, is based on the physical effect of induction [26]. The required energy for the forming process is stored in capacitors by charging them to a high voltage *U*. By discharging the capacitors over a high-current switch, the arising large currents $I_{dis}(t)$ generate an intense magnetic field $H(t)$ outside the tool coil with the magnetic flux density $B = \mu H$ (see Figure 2). This magnetic field $H(t)$ induces eddy currents $I_{eddy}(t)$ in the workpiece which are running in the opposite direction compared to the primary currents $I_{dis}(t)$ in the tool coil (see Figure 2 A).

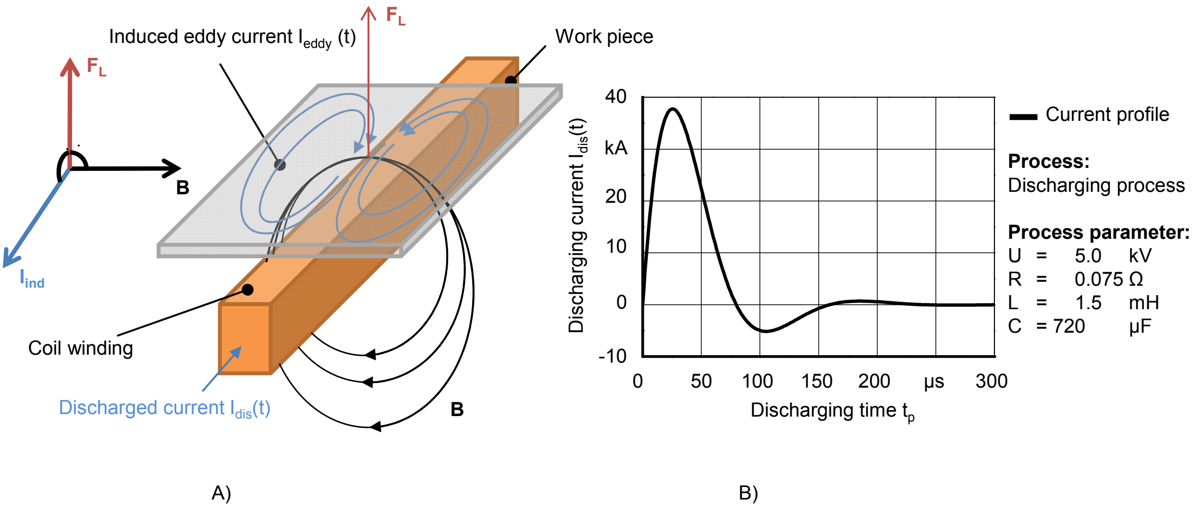

Figure 2: *Principle of discharging process and resulting Lorentz force F_L (A); characteristics of an damped sinusoidal discharged current $I_{dis}(t)$ (B)*

Due to the short process time t_p and high frequencies f of the discharging process (see Figure 2 B), the skin effect[1] causes that the induced eddy currents $I_{eddy}(t)$ are running near the surface of the sheet metal. Consequently the resulting Lorentz forces $F_L(t)$ which depend on the primary magnetic field $H(t)$ are acting for a short time of 50 µs to 100 µs on the work piece. The acting Lorentz $F_L(t)$ forces are converted as a magnetic pressure on the work piece surface. As now work piece and tool coil repel each other, the work piece will be deformed. Here, the yield stress Y_f is exceeded and as a consequence plastic deformation of the work piece takes place within milliseconds.
Pulse magnetic processes are assigned to high speed forming processes due to the high strain rates occurring during the process. The whole forming process is realized without any mechanical contact between work piece and tool coil.

4 Experimental setup

For the experimental study of pulse magnetic forming of magnesium alloy AZ31 at room temperature an experimental setup was designed, see Figure 3. The design of the die makes it possible to create plane strain in the forming area.

[1]Skin effect is the tendency of an alternating current to become distributed within an electrical conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor.

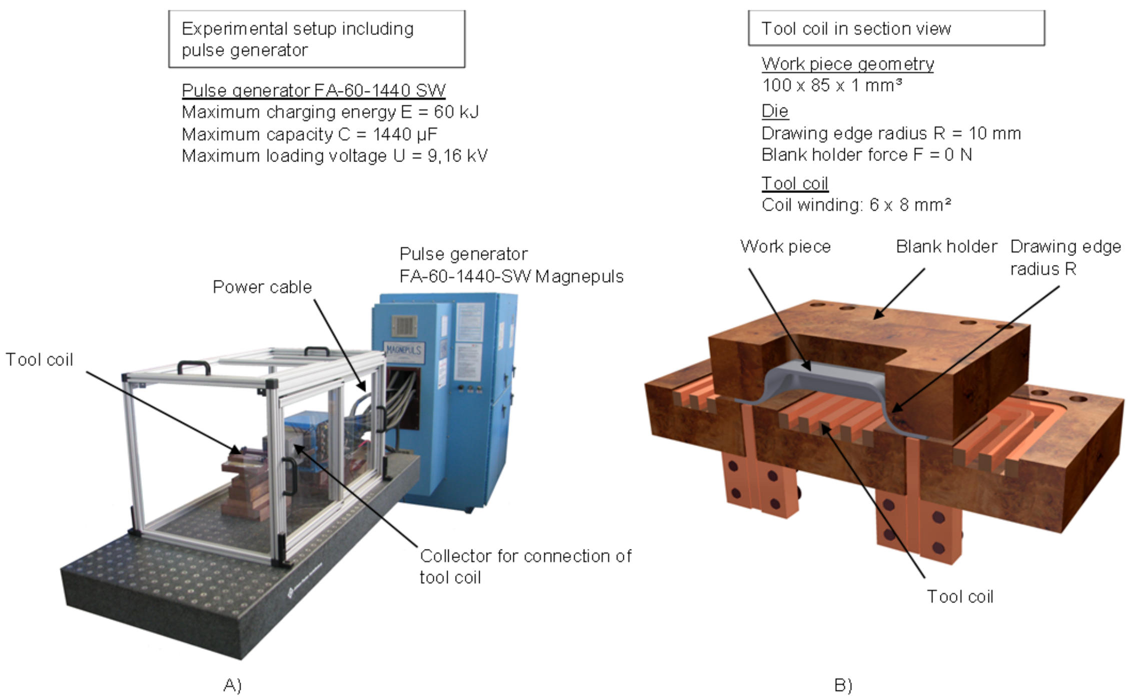

***Figure 3:** Experimental setup including pulse generator A), tool coil in section view B)*

5 Results

Figure 4 shows a comparison of plain strain forming limit distributions between a deformation at a high strain rate applied during pulse magnetic forming and during conventional forming at a quasi-static[2] strain rate, both conducted at room temperature. The major axis strains achieved at failure during conventional forming with a quasi-static strain rate are comparable to [27]. During forming at high strain rates, however, an increase in major axis strain of 61 % could be reached without any evidence of macro or micro cracks. One reason for the non-failure of the work piece at high strain rates can be found in the investigated loading charging energy of the pulse generator of $E = 25$ kJ, which was not high enough to reach the forming limit of AZ31B-O. Five samples were investigated. Its shift in position on the axis of major strain compared to the quasi-static results is, according to [28], a result of increasing strain rate sensitivity. As has been the case for tensile tests, the increasing strain rate sensitivity m leads to an increase in strain and material stability, [17]. Hence, an increase in strain rate sensitivity combined with a constant strain hardening coefficient leads to a rising flow stress of AZ31B-O [29] expressed by an increase in cold work hardening.

[2]The sample shape was generated by deep drawing. For this purpose a mechanical punch was used.

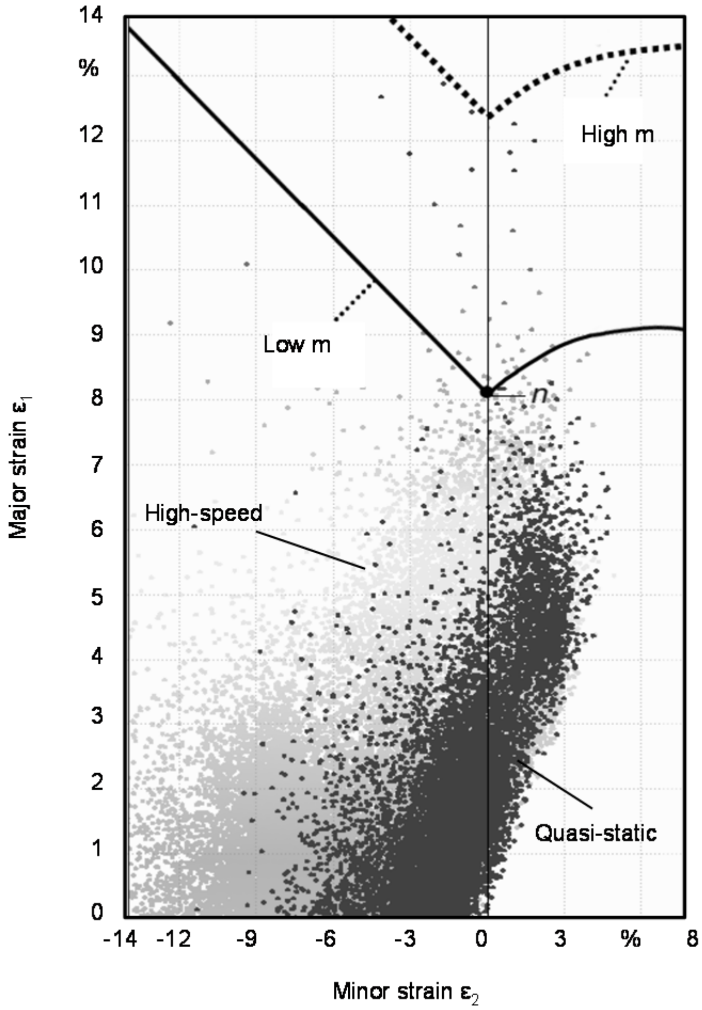

Figure 4: *Comparison of realized deformation in the field of plane strain of AZ31B-O with Basal texture; pulse magnetic forming (light gray) and quasi-static forming (dark grey) with the theoretical influence of strain rate sensitivity m on the location of the forming limit curve (FLC) [27]*

The quasi-static sample shows a significant gradient in terms of hardening which was obtained by determining the Vickers hardness *HV*. The hardness had been increased by 14.5 %, based on an initial hardness of 55 *HV* 4.9012/15, before cracks appeared on the upper surface. On the inner surface of the sheet, however, a hardly measurable increase in hardening of 3.6 % occurred. One possible reason for that behaviour can be found in the missing hardening mechanisms in sheet thickness direction due to the significant basal texture of AZ31B-O at room temperature. Consequently, the first cracks appeared on the outer surface of the sheet already after 8.1 % elongation.
The sample deformed by pulse magnetic forming also shows a significant gradient in hardening across the sheet thickness leading to a nonappearance of hardening on the inner side of the sheet just as it has been found for the quasi-static deformation. Despite this, the hardness of the upper surface increases by 27 % without the appearance of any

visible cracks, corresponding to a doubling in hardening compared to conventionally deformed samples. That increase is based on the strongly increasing flow stress of AZ31B-O during high speed deformation, [20]. Hence, the increasing ability for hardening during pulse magnetic deformation is tantamount to an increase in plain strain forming ability of AZ31B-O. According to the high material stability caused by an increase in strain rate sensitivity at high deformation speeds a consistent reduction in sheet thickness across the entire force transmission zone could be observed. On the other hand, during conventional deformation distinctive local deformation zones appear leading to a structural failure as a result of a strongly localized deformation. In conclusion, an increasing strain rate sensitivity at high speed deformations, reached e.g. in pulse magnetic forming processes, causes an increase in flow resistance at high strains which allows a better distribution of deformation on surrounding areas, leading to a consistent sheet thickness reduction. This results in an increasing forming ability of AZ31B-O at plain strain deformations.

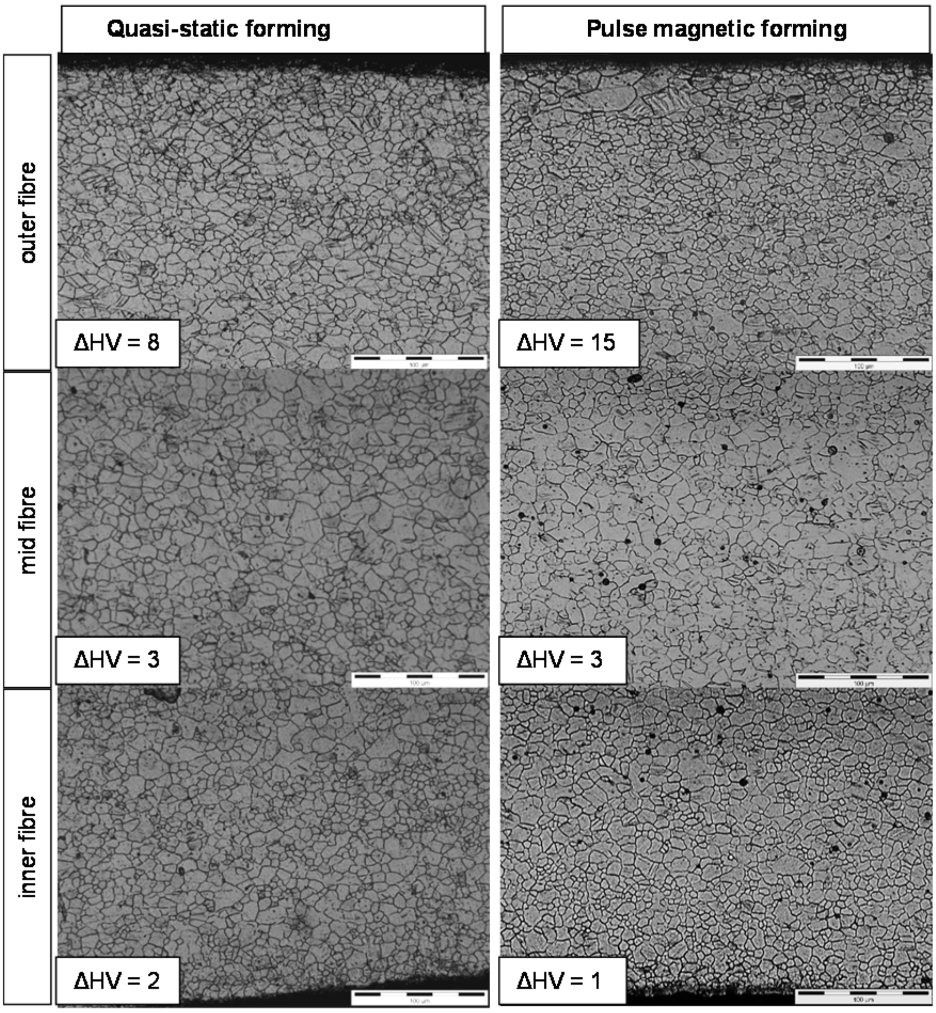

Figure 5: *Comparison of material hardening by measuring increase of hardness ΔHV of AZ31B-O (initial hardness: HV 4,902 55/15) at quasi-static rates and high strain rates (pulse magnetic forming)*

Conclusion

- The plain strain deformations achievable with pulse magnetic forming systems at least are higher than 61% compared to conventional deformation processes.
- During conventional deformation as well as during pulse magnetic deformation a significant gradient in hardness can be found across the sheet thickness at plain strain condition.
- High strain rates of pulse magnetic forming processes increase the hardening ability of AZ31B-O. This is caused by increased strain rate sensitivity at high speed deformations.
- The increasing strain rate sensitivity at high speed deformations enhances the material stability which is indicated by a consistent sheet thickness reduction across the entire load transmission zone.

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