Experimental analysis of AZ31B magnesium alloy sheet failure using punch stretching

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Abstract. The formability of magnesium alloy sheets at room temperature presents anisotropy in mechanical properties and difficulties in terms of occuring cracks easily, especially in regions with bend radius. In addition, the elastic spring-back is significant, leading to massive deviations from the desired shape. Recent studies conducted in this field lead to stretch forming magnesium alloys sheets using thermo-mechanical treatments at temperatures up to 400°C. The present study was conducted on 1 [mm] thick magnesium alloy AZ31B sheet to investigate its formability when stretching at room temperature by several dies with different radius. The stretching process was conducted on a hydraulic press, using 3D printed PLA dies with the following values: R180, R320, R540, R720, R900 and R1080. The samples were stretched until fracture to highlight the fracture force, distance to fracture, deviation from the die radius and bend angle.

1. Introduction
In the last decade, the interest has increased significantly on magnesium-based alloys, especially in the field of automotive industry. The high interest is due to the fact that magnesium alloy have a very good strength to weight ratio, high vibration damping and effective electromagnetic screening [1]. Contrariwise the downside of this alloys is that, at room temperature, they present low mechanical strength, poor microstructure control during processing and anisotropy of fatigue [2], [3]. There is an undesired failure mode, usually called the shear fracture, which mainly results from the low ductility of advanced metal sheets. Metal sheets with little amount of necking exhibit the fracture surface slanted along the maximum shear stress direction through its thickness [4]. In traditional thermo-mechanical processing of magnesium alloy sheets (such as extrusion) there are always obtained strong basal textures, with the c-axis of most grains being nearly parallel to the normal direction (ND) of sheet. These Mg alloy sheets usually exhibit low plasticity and formability at room temperature, which lead recent researches to focus on improving texture by tailoring. It has been accepted that the press formability of sheets at room temperature is strongly affected by the Lankford value (r-value) [5]. Researchers proposed to reduce the springback in bending of ultra-high strength steel sheets by bottoming and additional bending. Also, lubricants, coatings on the tool surface and tool material are effective to improve the tool wear. However, the reduction in shearing force by control of deforming behavior of the sheet in punching and shearing is an alternative approach [6]. When sheet metal forming magnesium alloys the deformation is defined by the flow curves. Regardless of the type of forming at room temperature classic processes do not offer the required results, leading to prematurely breaking [7].
2. Experimental set-up

This experimental work is part of a comprehensive case study. The purpose is to determine how magnesium alloys sheets behave when using stretching and single point incremental forming (SPIF) with different types of dies and working temperatures. The present paper aims to study the behavior of magnesium alloy AZ31B sheets when stretch to the breaking limit. This study aims to analyze the force and distance required to fracture, and the spring-back effect for both radius and bend angle. The results are necessary to develop a system that allows to perform stretch forming and SPIF processes using the same clamping device. The experimental setup for this research paper is composed of two parts: the 3D printing process and the stretching process setup.

2.1. 3D printed die

Rapid improvement in 3D printing technologies has led to substantial improvement in the complexity of shape, size, and materials that can be obtained and used. From simple home-made parts to entire industries (aerospace, automotive, organ replication, civil constructions), it is expected that, in the next decade, this process to be the next key manufacturing technology [8]–[10]. Our approach is to use this technology for 3D printing forming punches, figure 1. This comes as a solution to the problem generated by the complex machining procedures that take place when manufacturing from metal.

A total number of 6 punches were printed, with various radii (180, 360, 540, 720, 900, 1080). They were manufactured on an Ultimaker Original Plus 3D printer, using 2.85 [mm] thick Innofill PLA wire. The printing parameters taken into account were: layer height (0.4 mm), wall thickness (1.6 mm), infill density (75 %), infill pattern (45° lines), printing temperature (210 C°), build plate temperature (60° C) and printing speed (60 mm/s). An auxiliary fastening system was manufactured in order to assure the connection between the dynamometer and the hydraulic press (figure 1).

3D printed parts deviate from the desired shape, as the plastic material cools. As a result the punches were measured for radius size and deviation from circularity on a 3 axes Tesa 3D Micro Hide CMM equipment. The designed shape and the measured values are presented in table 1. As can be noted, there are deviations from the ideal shape so these measurements were taken as reference.

| Designed radius [mm] | 180  | 360  | 540  | 720  | 900  | 1080 |
|-----------------------|------|------|------|------|------|------|
| Measured radius [mm]  | 182.383 | 365.146 | 553.904 | 738.847 | 942.176 | 1149.946 |
| Deviation from circularity [μm] | 0.005 | 0.123 | 0.006 | 0.06 | 0.061 | 0.083 |

Figure 1. a) 3D printed trajectories b) fastening system and c) assembly drawing

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2.2. Set-up description

The experimental study was conducted using 1 [mm] thick magnesium alloy AZ31B blanks, cut at 315 x 46 [mm]. The equipments used was a hydraulic press (Hydramold HPHL-075.300), on which can be controlled the travel distance and speed of the hydraulic driving system (1) in the vertical direction (figure 2). The base plate (2) has two roles: it fixes the hydraulic clamping system (4) and, because it has a central cut up, allows the punch free travel. The blank (5) is fixed in position using metallic jaws (3), on which the hydraulic clamping system operates at 20 [bar]. The punch (6) is fixed to the Kistler 9272 dynamometer (8), using the fastening system (7).

The experimental plan is based on three deformation speeds (0.2, 0.7, 1.2 [mm/s]), for each punch, meaning a total number of 18 trials. The study implies that the magnesium blanks are stretch until failure, at room temperature. The values for force and distance were obtained from the dynamometer’s software (DEWESoft X3), while the shape measurements were made using the GOM ATOS 3D imaging metrology system.

![Figure 2. Experimental setup of the stretch failure process](image)

1-hydraulic driving system, 2-base plate, 3-jaws, 4-hydraulic clamping system, 5-AZ31B blank, 6-3D printed punch, 7-fastening system, 8-dynamometer

Shown in figure 3 is the failure limits mechanism of the magnesium blanks. There can be observed three distinct steps (4, 5 and 6), which coincide with the initial position (4-the punch touches the blank), the intermediary position (5) that is right before breaking and the finish position, which represents the distance to fracture. After breaking (6) and unclamping the parts presented a major spring-back effect. Corresponding to the obtained parts the following parameters were studied: R₁ (the radius that corresponds to the punch radius) and θ₁ (spring-back angle).

![Figure 3. Schematic representation of the stretching process](image)

1-Punch, 2-AZ31B blank, 3-jaws, 4-initial position, 5-intermediary position, 6-finish position
3. Results and discussions

The input parameters were the deformation speed and the punch radius, while for the results were: fracture force, distance to fracture, bend angle and radius. As the blanks were stretch until fracture, the ideal shape was considered position 5, figure 3. Compared to the ideal shape, the magnesium AZ31B blanks present significant deformations (figure 4). The elastic spring-back, in this case, was analyzed for R1 and $\theta_1$, figure 3.

![Figure 4. Stretched parts and 3D scanned model](image)

3.1. The analysis of the fracture force and distance to fracture

Highlighted in figure 5 is the distribution of the force with reference to the deformation speed. A slight increase can be noted when using higher speeds. Although the maximum recorded force of 3163.6 [N] was identified when stretching with 0.2 [mm/s], the overall values are higher for 0.7 and 1.2 [mm/s]. The minimum amount of force required to break was 1680.21 [N]. It can be noted that failure has occurred under 2000 [N], only at slower speeds.

In the case of the punch radius effect, presented in figure 6, the maximum force increases as the punch radius has higher values. A lower fracture limit was recorded when R360 and R540 punches were used, while the R720 and R1080 ones record the highest value.

![Figure 5. Influence of the speed [mm/s] on the fracture force [N]](image)

![Figure 6. Influence of the punch radius [mm] on the fracture force [N]](image)

The influence of the speed and punch radius upon the distance to fracture can be noted in figure 7 and figure 8. The distance to fracture presents higher values when higher speeds are used. The values

![Figure 7. Influence of the speed [mm/s] on the distance to fracture [mm]](image)

![Figure 8. Influence of the punch radius [mm] on the distance to fracture [mm]](image)
are distributed between 8 and 12 [mm]. Below this threshold only the 0.2 [mm/s] speed has recorded values. A higher breaking limit is recorded when higher speed are used, 14.77 [mm] for 0.7 [mm/s], respectively 15.96 and 19.32 for 1.2 [mm/s]. The distance to fracture presents greater limits when smaller radius punches were used. Although the parts stretched with the R1080 punches withstand higher forces they have a lower distance to fracture. There can be noted that using R180 and R360 punches leads to a higher distance to fracture, over 14 [mm].

3.2. The analysis of the punch radius deviation, bend radius and angle
This analysis was conducted taking into consideration the spring-back coefficient (1), (2) for the obtained punch radius and bend angle. A factor close to 1 means that the spring-back effect is weak, while when is near to 0 heavy significant deformation occurs. For the angle spring-back the coefficient takes into consideration only the initial and final measurements whereas the one for the radius is defined regarding the neutral deformed fiber. The theoretical angle was determined analytically from position 5 (figure 3), witch corresponds to the position of a tangent line connecting the jaws and the punch radius against the initial blank position. When analysing the radius spring-back the assumption was that the required radius of the part is that of the corresponding punch.

\[ K_R = \frac{\theta}{\theta_1} \]  
\[ K_R = \frac{R + 0.5t}{R_1 + 0.5t} \]  

Represented in figure 9 is the effect of the theoretical and measured angle on the spring-back coefficient \( K_\theta \). The results have shown that the difference in initial and final angle is between 2.39 [°] and 28.96 [°]. A large distribution of the measured values is between 150 and 160 [°] while the theoretical ones are from 166 to 178 [°]. This difference in results leads to a spring-back coefficient value from 0.83 to 0.98.

![Figure 9. Effect of the theoretical and measured angle on the spring-back coefficient \( K_\theta \)](image)

![Figure 10. Effect of the punch radius and blank radius on the spring-back coefficient \( K_R \)](image)
The radius spring-back coefficient values are spread over a larger field, with values between 0.19÷0.98 (figure 10). Most of the obtained values are lower than 0.5, which are specific to severe deformation. These results are obtained when small radius punches are used. In almost 25% of the cases the spring-back effect ranges between 0.19÷0.30.

4. Conclusions
The present study aimed to highlight the fracture limits when stretching magnesium alloy AZ31B sheet over a 3D printed die by analysing the maximum force, distance to fracture, spring-back angle and radius.

It has been concluded that the fracture force depends on the punch radius, as the contact surface increases, therefore the contact pressure. With the increase in force the distance to fracture decreases. This decrease was also observed when using large radius punches.

The spring-back effect indicates significant deformations in the case of the radius, particularly when small radius punches are used. In the case of the spring-back angle the experimental study indicates that severe deformation take place.

AZ31B magnesium sheets present low resistance with high deformations when stretch. This phenomenon takes place as magnesium alloys have low ductility at room temperature. Stretch forming can be carried out when higher temperatures are used.

The 3D printed punches were not affected during the stretch process.

5. References
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