Tangential bending and stretching of thin magnesium alloy sheets in warm conditions

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ABSTRACT

The present work aims at studying the tangential bending process (wiping) and the combined effect of a bending and stretching stress on thin (0.7 mm) magnesium alloy (AZ31) sheets when working in warm conditions. The test equipment was designed in order to heat the sheet only in the bending region and to stretch the sheet after the wiping process; it was used for investigating the parameters affecting the stretch-bending state of stress in the sheet, quite common in the stamping process. A preliminary screening analysis over a large set of process parameter was performed using a full factorial design. As a result, only the effect of the temperature, the speed and the bend radius were further investigated according to a central composite design and using the springback factor and the maximum stretching load as response variables. The present work can give useful guidelines in the warm forming of AZ31 Mg alloy sheets in terms of key process parameters, fillet radii of the equipment, material stretch-bending strength (according to temperature, bending radius and speed) and precision of the final part (springback amount).

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1. Introduction

One of the most important goals of many industrial fields (e.g. aerospace, automotive, electronics, and sport) is nowadays the production of lightweight parts. Since magnesium (Mg) alloys are characterised by very low density, they are receiving in the last years increasing attention, because of their potentialities in the applications [1]; especially in the automotive field the adoption of materials having a favourable strength/weight ratio (like magnesium) can increase the fuel efficiency of automotive transportation [2].

But it is often quite expensive and not simple to replace steel in the structure or body of vehicles with the Mg alloy, principally because this alloy exhibits poor formability at room temperature, much lower than typical steel sheets. Heating the material, is thus necessary in order to improve the Mg alloy ductility and formability by means of deformation mechanisms not active at room temperature [3,4]. Beside classic tensile test data [5], many research activities, also by the authors, were aimed at investigating the improvement of the drawability and the formability of the Mg alloy [6–9] when working in warm condition: it can be thus deduced from the literature that the most popular Mg alloy used for sheet forming applications (AZ31) is characterised by normal anisotropy coefficients which strongly reduce according to temperature, but which do not differs considerably according to the direction (small planar anisotropy); in addition, as concerns the temperature and the strain rate, such process parameters strongly affect the limit drawing ratio and the forming limit diagram.

Tests determining stress and strain states in the material near to critical working conditions can support the correct design of real applications, since they give additional information about the material behaviour [10]. A stress condition quite common in the stamping process is the combined effect of a tangential bending (wiping) and stretching stress (for example in the fillet radius regions). Analytical and numerical models were proposed for predicting the stretch-bending strength of the material (aluminium) at room temperature [11] or in warm conditions [12] and for evaluating the thickness reduction of the side-wall region of the part in the unsupported region between the draw die and the punch [13].

The research activity detailed in this work is purely based on experimental data and is focused on the stretch-bending state of stress induced in thin Mg alloy sheets when working in warm conditions. Stretch-bending tests were performed using a specific equipment (described in the next paragraph) able to heat the sheet only in the bending region and to consequently stretch the sheet.

The experimental activity was approached using the design of experiment (DOE) technique [14]. Main aims were both the evaluation and the investigation of the most important process parameters affecting the stretch-bending state of stress in the material. Preliminary tests for the screening of the parameters were scheduled adopting a full factorial design (FFD). Deeper analysis was consequently performed varying the most important process parameters according to a central composite design scheme in

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order to set up response surfaces for mapping the springback amount and the maximum stretching load according to the investigated levels of factors.

2. Experimental equipment

The experimental activity consisted in tests applying a stretching load by a punch to rectangular shaped thin sheets (40 × 150 × 0.7 mm) in AZ31 (Mg–Al 3%–Zn 1%) previously bent by the same punch. Tests were carried out in warm conditions. The scheme of the equipment is shown in Fig. 1; it is composed by a punch, two blank holders and a die.

The die is equipped with an electric cartridge able to heat the specimen in the bending region; the electric heater was placed in the proximity of the bending radius in order to reduce the heating time and focusing the material heating just in the bending area. In addition the die has four different fillet radii, thus allowing to perform tests using different bending radii simply changing its position by rotation. The blank holders are used for fixing the blank during the bending phase (blank holder 1) and for fixing the blank to the punch and allowing the stretching action after bending (blank holder 2). In fact each test consisted of two steps: the bending of the strip by means of the vertical stroke of the punch and the stretching until rupture by means of the further punch stroke after fixing the stripe to the punch itself. No lubricant was used in the tests.

Thermocouples were adopted for monitoring and controlling the temperature on the specimen during both the heating and the forming phases. As highlighted in Fig. 2, thermocouples were positioned in three different locations: in the bending area, at 10 mm and at 40 mm from the bending die.

As concerning the response variables, the attention was focused on both the springback factor (K) and the maximum stretching load (STRETCH). The response K is defined as the ratio between the final bending angle (αF) and the imposed bending angle (αL). As shown in Fig. 3, it was evaluated thorough the comparison between images of the bent strip at the end of the punch stroke and at the load removal.

Response K was collected in order to have a measure of the plastic strain accumulated in the bending region. In addition it could give important information concerning the spring back phenomenon affection the precision of a bent Mg alloy part.

In the stretching step the response variable STRETCH was measured through the continuous load data acquisition during the process by a load cell. As a result the load evolution as a function of the punch stroke was obtained for each test.

3. Screening of the process parameters

Preliminary tests using a full factorial design (FFD) were aimed at evaluating the most effective process parameters. A large number of process parameters were thus investigated. In fact factorial designs allow for the simultaneous study of the effects that several factors may have on a process. Varying the levels of the factors simultaneously rather than one at a time is efficient in terms of time and cost; in addition in such a way also interactions between the factors can be analysed. In a full factorial experiment, responses are measured at all combinations of the experimental factor levels. Each combination of factor levels represents the conditions at which a response measure will be taken.

In this preliminary experimental investigation four factors were considered: the die temperature (TEMP), the bending radius (BEND-RAD), equivalent to the die radius; the punch speed (SPEED) and the rolling direction (ROLL-DIR). Two levels for each factor were tested: 80–240 °C for TEMP; 2–8 mm for BEND-RAD, 6–60 mm/min for SPEED and 0–90° for ROLL-DIR. The responses (spring back factor, K and maximum stretching load, STRETCH) were collected at all combinations of the experimental factor levels.

3.1. Analysis of the stretch-bending load curves

Preliminary analyses have been performed measuring the stretch-bending load values. Figs. 4 and 5 report the load acquired during the stretching step of each test.
Fig. 2. Temperature acquisition during the heating phase using thermocouples.

Fig. 3. Evaluation of the springback angle when removing the bending load.

Fig. 4. Stretching load values measured when adopting a bending radius equal to 2 mm.
The effect of the temperature is evident for this material: moving from 240 °C to 80 °C, the load requested for stretching up to failure the sheet is more than double when using the 8 mm bending die. It may be noted that increasing the bending radius up to 8 mm, the load needed for stretching up to failure the sheets increases. In addition, it may be highlighted that the forming speed appears to be important only at high temperature, when adopting the smallest bending radius (2 mm); in fact the increase of the punch speed from 6 up to 180 mm/min determines, when working at 240 °C and using a 2 mm bending radius, a large increase of the final stretching load.

As concerning the effect of the rolling direction, it may be noted that, when using stripes cut in the direction orthogonal to the rolling direction (ROLL-DIR equal to 90°), it is needed a load which does not differ greatly form the load need for stretching the sheets cut along the rolling direction (ROLL-DIR equal to 0°). Such a result is in agreement with tensile test data from the literature [5], and will be confirmed by the ANOVA analysis detailed in the following.

### 3.2. ANOVA and ANOM analysis

The analysis of the two-level FFD was performed also considering the ANOVA and ANOM techniques. Since this is a full factorial rather than a fractional factorial design, all of the terms are free from aliasing. Table 1 lists the probability values concerning the main effects and the considered interactions of both the regression models, in order to understand is any of them may be not considered statistically significant.

The probability value (p-value) concerning a factor is the probability of making a mistake, if considering the calculated mean value variation determined by the factor not effectively due to the factor. The analysis suggests that both interactions and main effects are significant, since the p-value is smaller than the adopted confidence level (α-level equal to 0.1, in order to reduce the possibility of excluding important factors in the screening phase).

The sum of squares listed in Table 1 can be used for computing the mean square error (R²), as the ratio of the regression sum of squares (SSR) and the total sum of squares (SST) [14]. The large value of R² (98.9%) confirms the efficiency of the estimated regression models, (the models are able to explain about the 99% of the amount of variation in the observed response values).

In order to evaluate the factors and the interactions really affecting the response values, in Tables 2 and 3 all coefficients and correspondent effects of terms of the regression models have been listed. The absolute value of the effect determines its relative strength. The higher the value, the greater the effect on the response. It is quite immediately to note that the mean spring back value and the mean stretch value are largely affected by the temperature

### Table 1

<table>
<thead>
<tr>
<th>Source</th>
<th>d.f.</th>
<th>Sum of squares</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main effects</td>
<td>4</td>
<td>57.5928</td>
<td>100.02</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Two-way interactions</td>
<td>6</td>
<td>7.3096</td>
<td>8.46</td>
<td>0.017</td>
</tr>
<tr>
<td>Residual error</td>
<td>5</td>
<td>0.7198</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>65.6222</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In particular the temperature effect has a negative sign, thus indicating that the low temperature setting results in both a higher springback and stretch value. Tables 2 and 3 also put in evidence that the term ROLL-DIR is characterised by a p-value larger than the considered α-level, thus suggesting the possibility of not considering such a factor in the analysis of the stretch-bending process.

Additional considerations about the effect of terms can be supported by the analysis of Fig. 6, which plots the normalized (absolute) weight of each term included in both the models (for fitting response K and response STRETCH). It has to be put in evidence the different role that both the SPEED and the BEND-RAD seem to have: within the confidence interval of 90%, each of them (and the correspondent interaction with the temperature), seems to really affect the spring back phenomenon and the stretch load. In particular the speed seems to be more influent on the response K, while the bend radius is more effective in the stretching phase.

### 4. Analysis of the process parameters using a central composite design

The ANOVA and ANOM analyses on data coming from FFD revealed the rolling direction not to be statistically important. Further tests were thus performed focusing the attention on the die temperature (TEMP), the bending radius (BEND-RAD) and the punch speed (SPEED). In particular stretch forming tests were scheduled according to a central composite design (CCD), in order to set up response surfaces for mapping both the K and the STRETCH response variable over the explored region of investigated factors. CCD is composed by data from the two-factor FFD and seven additional axial or “star” points (with two replications in the central point). Table 4 reports the complete list of tests and the measured values of both the response variable.

Only linear and first-order interactions were considered for interpreting the experimental data.
In Figs. 7 and 8 weights of terms on the mean value of the response variables \( K \) and STRETCH have been plotted. It is possible to note that, beside the effect of the temperature, the effect of the interaction between the bending radius and the temperature itself plays the most important role.

In particular the SPEED and correlated interactions revealed to be less effective on both the steps of the process (wiping and stretching).

The analysis of the stretch-bending state of stress resulting in the Mg alloy sheet was performed considering both the acquired responses: the spring back factor and the maximum stretching load.

**4.1. Analysis of the spring back factor**

Effects of the process parameters on the springback phenomenon have been resumed in Figs. 9 and 10 using response surfaces; each of them was drawn fixing the third parameter at the lowest and at the highest value.

If comparing response surface in Fig. 9, it may be noted that, even if the shape of the surface does not change (meaning no effective interaction between the temperature and both the bending radius and the speed) the position of the surface strongly moves upwards when increasing the temperature from 80 °C up to 240 °C (the temperature strongly reduces the spring back of the stripe).
The analysis of Fig. 10 suggests that the bending radius effect on the $K$ values is different according to the temperature adopted; in particular this factor seems to be more effective, when working at low temperature, producing a springback reduction when adopting a small bending radius. When forming this material in warm conditions the reduction of the bending radius cannot determine further reduction of the springback phenomenon in addition to the temperature effect.
Fig. 10 also puts in evidence that the factor SPEED cannot be considered a parameter really affecting the springback phenomenon, since both the shape and the position of the response surface are not affected by the different speed values.

4.2. Analysis of the stretching load

The effects of the process parameters on the stretching load have been resumed in Figs. 11 and 12 using also in this case response surfaces; each of them was drawn fixing the third parameter at the lowest and at the highest value.

The first consideration from the analysis of response surfaces in Figs. 11 and 12 is that the temperature is the most important parameter affecting the stretch-bending state of stress. However, the effect is the opposite, if compared to the effect of the K variable, since the maximum stretching load the material experiences decreases, when adopting high temperature (240 °C). The response variables K and STRETCH are thus strictly related: such a result, also confirmed by numerical simulations [10], can be explained referring to the plastic strain the material accumulated in the wiping step, since the more critical the tangential bending (higher K values), the lower the maximum stretching load experienced by the material.

From the comparison of response surfaces in Fig. 11 the same conclusion about the speed effect can be deduced. In particular, the two tested speed values did not produce any considerable variation on the maximum stretch load response surface.

However, it may be also noted that the combined effect of the temperature and the bending radius determines a different effect of the bending radius on the shape of the response surface. In particular the response surface in Fig. 12 is modified along the BEND-RAD axis only when working at the lowest temperature. In fact the stretching strength increases when increasing the radius while working at 80 °C (if adopting the 8 mm die radius, the maximum load at 80 °C is higher than the one experienced by the material at the same temperature, but when using the 2 mm die radius), while it is almost unchanged, if increasing the radius when working at 240 °C. Such behaviour suggests that, when forming this material in warm conditions, sharp radii profiles can be obtained with the same difficulty of smooth ones, being the material stretch-bending response insensitive to the bending radius.

5. Conclusions

Key information about the behaviour of the Mg alloy sheet AZ31 under critical stress and strain conditions similar to the ones the material experiences in the stamping process in the fillet radius region were obtained from experimental results.

The initial screening activity, performed using a large confidence level (z-level equal to 0.1) in order to reduce the possibility of excluding important factors in the screening phase, allowed to exclude the effect of the rolling direction, thus restricting the number of the process parameters to three, the die temperature (TEMP), the bending radius (BEND-RAD) and the punch speed (SPEED).

The stretch-bending tests performed according to the CCD scheme allowed to determine useful guidelines in the warm forming of AZ31 Mg alloy sheets in terms of key process parameters, such as fillet radii of the equipment, material stretch-bending strength and precision of the final part. In particular the following conclusions can be drawn:

- The working temperature revealed to be the process parameter mostly affecting both the springback phenomenon and the stretch-bending strength of the investigated Mg alloy sheet.
- The bending radius showed to influence the springback amount most of all at low temperature, determining in such condition a reduction of the springback factor if a larger bending radius is adopted: when forming this material in warm conditions the reduction of the bending radius cannot determine further reduction of the springback phenomenon in addition to the temperature effect.
- The temperature also showed to remarkably affect the stretch-bending strength, reducing the value of such a response variable at 240 °C and making it insensitive to bending radius: when forming this material in warm conditions, sharp radii profiles can be obtained with the same difficulty of smooth ones.
- The response variable K was found to be strictly related to the stretching strength of the Mg alloy sheet, since the severity of the wiping operation (adopting a small bending radius and working at low temperature) determined an increase of the factor K (meaning a reduction of the springback amount) but a reduction of the final stretching load.

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