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Fracture modelling of magnesium sheet alloy AZ31 for deep drawing processes at elevated temperatures

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Abstract

Today, the reduction of CO2 emissions is essential to meet global climate requirements. In this context, a reduction in vehicle weight is the most efficient way to reduce the fuel consumption of a passenger car. Magnesium combines relatively high strength with low weight and is therefore an interesting construction material for lightweight solutions. In numerical process design, it is essential to be aware of the forming capacity of a material. The common method to describe the failure behaviour is the use of forming limit curve (FLC). Stress-based models offer the advantage of a strain path consideration and an extension in the area of shearing and compression. In this paper a stress-based damage model, Modified Mohr-Coulomb (MMC), was parameterized by IFUM Butterfly-Tests for an AZ31 magnesium sheet alloy under consideration of elevated process temperatures. For this purpose, the tests were carried out at different stress states and temperatures using a specially designed testing device. In addition, forming limit curves were determined by Nakajima tests. Finally, both methods, MMC and FLC, were compared to an experimental deep-drawing test. This comparison showed that the MMC Model achieved significantly better results regarding the fracture prediction in this application case.

Keywords: Magnesium Sheet AZ31B, Fracture Characterisation, Stress-based Fracture Modelling, IFUM Butterfly-Tests

1. Introduction

Magnesium is the lightest metallic construction material and offers excellent properties such as low density, high specific strength and recyclability. Currently, magnesium alloys are mainly used in casting applications. Due to cost-effective manufacturing processes like twin-roll strip casting, a more widespread use of magnesium in sheet metal forming processes is also likely. Nowadays, numerical approaches are commonly used for an accurate prediction of the forming behaviour, especially in order to optimise component and process design as well as to shorten development times. However, numerical simulations require realistic material data and thus investigations of the yielding and fracture behaviour of magnesium alloys have to be performed in an adequate way under consideration of process conditions.

The formability of sheet metal materials is usually described by a forming limit curve (FLC). FLC for the magnesium alloy AZ31 in dependence of the temperature have been determined in different studies yet [1, 2, 3]. Nevertheless, FLC are only valid for linear strain paths due to the determination procedure. Furthermore, this procedure does not imply material testing under shear dominated stress states and thus is not appropriate to predict shear dominated fracture. An alternative is the use of stress state dependent fracture models. By means of these models, the fracture is described in dependence on stress triaxiality η and normalised Lode angle $\bar{\theta}$ [4]. The calibration of stress-based fracture models is currently not standardised resulting in a variety of tests for their parameterisation [4, 5, 6]. Studies investigating the fracture behaviour of magnesium sheet alloys at relevant elevated forming temperatures in order to parameterise stress-based fracture models like the MMC

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model are missing until now. In this study, the authors present a methodology to parameterize stress-based fracture models in dependence of temperature using so-called IFUM Butterfly-Tests. Furthermore, conventional FLC were determined and finally both methods were compared by means of deep drawing tests.

2. Material

The material under investigation in the current study is a commercial AZ31B alloy sheet of 2.0 mm nominal thickness. It was supplied by the manufacturer Posco and was produced by strip casting. As shown in detail in Table 1, the material is mainly composed of the alloying elements aluminium and zink with about 3 % and 1 % weight portion.

Table 1. Chemical composition of magnesium alloy AZ31B (Posco) in %.

Al	Zn	Mn	Si	Fe	Ca	Cu	Ni	Mg
≈ 3	≈ 1	≈ 0.6	>0.1	>0.005	>0.04	>0.05	>0.005	Balance

Magnesium alloys exhibit an orthotropic yielding behaviour in dependence of the loading case caused by the activation of different crystal twinning systems in the microstructure of the material, called extension twins {10-12}<10-1-1> and contraction twins {10-11}<10-1-2> [7]. The yield criterion CPB06 is suitable for representing this material behaviour by an adequate description of the yield locus [8]. In order to parameterise the criterion for this particular AZ31 magnesium alloy, an approach by performing tensile, compressive and biaxial tests has been already presented by the authors in [9]. On the basis of the yield locus, in Figure 1 the flow criterion CPB06 is compared with the conventional one according to Hill 1948. Differences between the two models are evident for all stress combinations except the two parametrisation points for uniaxial stress.

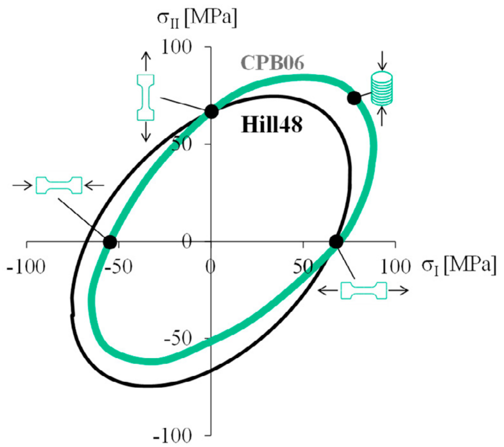

Fig. 1. Comparison of yield criteria Hill48 and CPB06 for AZ31 (230°C) [9].

The parameters of CPB06 were implemented in the material model MAT_233 of LS-Dyna. Furthermore, magnesium alloys exhibit a hardening deterioration (softening) at higher strains associated with dynamic recovery and dynamic re-crystallization. This softening behaviour beyond the uniform deformation limit of the uniaxial tensile tests has been characterised using an experimental extrapolation of flow curves by means of sheet layer compression tests presented by the authors in [9, 10]. The simulation of tension and compression tests revealed a clear advantage when using the CPB06 criterion compared to Hill48, since the experimental force-displacement courses could be reproduced more accurately [9].

3. Fracture Characterisation

3.1. Forming Limit Curve

Nakajima Tests at elevated temperatures of 180°C and 230°C were conducted in order to assess the formability by an FLC. The tests were performed according to the standard DIN EN ISO 12004, which is however only defined for room temperature. For the experimental procedure, a deep-drawing press with a temperature-controlled testing device consisting of a die, blankholder and punch with a diameter of 100 mm was used. In this device, all tool parts that are in contact with the sample are heated to a defined testing temperature by means of integrated heating elements. The sample itself is heated by heat transfer from the tools. Before starting a test, the temperature of the samples was checked by tactile measurements. Six different sample widths between 30 mm (uniaxial) and 200 mm (equi-biaxial) were used. The samples were manufactured perpendicular to the rolling direction via water jet cutting, because this is the preferred failure direction of the material, what could be identified by preliminary tests with a biaxial full sample. The clamped samples were deformed until fracture at a punch speed of 3 mm/s. The FLC determined in this way are shown in Figure 2. The influence of temperature on the formability of the material is clearly visible. For example, in the plain strain and biaxial range there is a strong impact in form of a doubling of the forming capacity. However, in the directions of the uniaxial range the influence is not as pronounced.

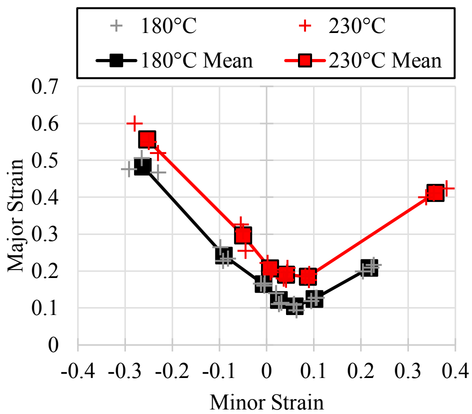

Fig. 2. FLC for AZ31 at 180°C and 230°C.

3.2. IFUM Butterfly-Tests

To investigate the damage behaviour under various stress states between shear and uniaxial tension, the experimental testing set-up and butterfly sample, shown in Figure 3 and 4a were developed at the IFUM [11]. The investigation area *S* of the sample has a specially optimised geometry with a thickness reduction of 25% on both sides of the original sheet thickness. Due to this geometry, failure initiation starts in the middle of the specimen at the specified stress state and a formation of edge cracks is prevented. With the help of the testing device, the load application angle can be varied by an adjustment of the specimen holders in the range of shear and uniaxial loading.

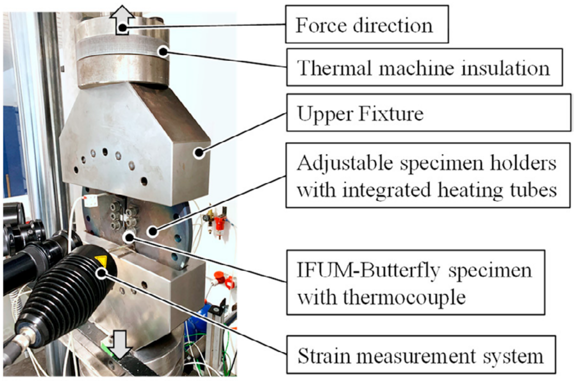

Fig. 3. Testing device for IFUM Butterfly-Tests at elevated temperatures.

To heat up the sample, heating pipes were integrated in the specimen holders. The temperature of the sample was monitored during the experiment with thermocouples welded on within the investigation area of the specimen. The tests were carried out at a forming speed of 0.02 mm/s to ensure a quasi-static strain rate. The investigation area was continuously measured with the optical measuring system GOM Aramis. The relative displacement of the specimen holders was also optically determined by reference points on the fastening plates. Tests were carried out with the presented specimen setup at three load introduction angles α of - 3°, 28° and 59°. The definition of the angle is shown in Figure 4b. Furthermore, the Butterfly-Tests were numerically simulated to determine the stress parameters, e. g. stress triaxiality and Lode parameter, required for the parameterisation of the damage model. The FE model and applied boundary conditions used for this purpose are shown in Figure 4b.

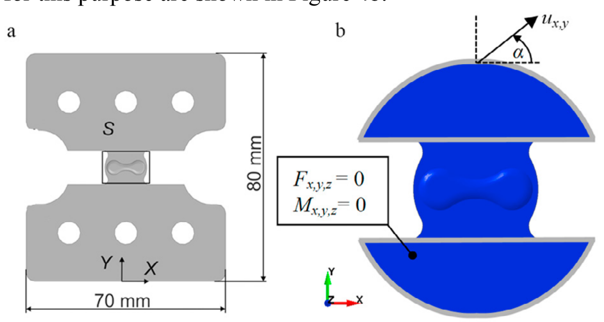

Fig. 4. Geometry of IFUM Butterfly-Specimen and FE-model of the investigation area.

3.3. MMC Damage Model

In the tests, the failure consistently initiated in the middle of the investigation area, as exemplarily shown in Figure 5. The crack initiation was determined optically using the strain measurement system. Due to the occurrence of high strains and the temperature influence on the paint, the facets in the investigation area could not be evaluated by the optical strain measurement until the appearance of a crack. Therefore, required information about the predominant stress and strain states at the time of crack initiation were numerically identified. The simulations were verified by comparison of experimental and numerical force-displacement curves. The optically determined displacement of the specimen holders was used as boundary condition within the numerical simulation.

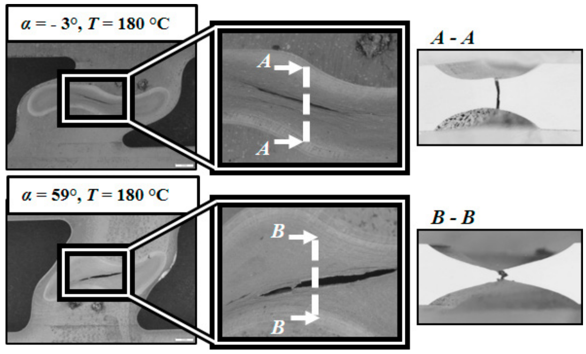

Fig. 5. Characteristic crack formation of IFUM Butterfly specimen for AZ31 (180°C) [10].

Elements exhibiting the highest strain (in the center of the investigation area) were evaluated from the simulations at the experimentally determined fracture displacements. By this means, the triaxiality and Lode angle developments were evaluated for each load application angle α. On the basis of a weighted mean, a specific triaxiality value was determined for each test. Subsequently, following equation was used to parameterise the MMC damage model [4]:

$$\bar{\varepsilon}_f(\eta,\bar{\theta}) = \left\{\frac{A}{C_2}\left[C_3+\frac{\sqrt{3}}{2-\sqrt{3}}(1-C_3)\left(sec\left(\frac{\bar{\theta}\pi}{6}\right)\right)-1)\right]\times \left[\sqrt{\frac{1+C_1{}^2}{3}}\cdot cos\left(\frac{\bar{\theta}\pi}{6}\right)+C_1\left(\eta+\frac{1}{3}sin\left(\frac{\bar{\theta}\pi}{6}\right)\right)\right]\right\}^{-1/n} \tag{1}$$

The stress triaxiality η results from the ratio of the hydrostatic pressure and the equivalent stress according to von Mises. The Lode angle $\bar{\theta}$ describes the deviatoric stress component based on a functionality of the three principal stresses. A detailed description is given in [4]. With equation 1, the fracture strain $\bar{\varepsilon}_f$ can be described by five parameters including three specific material parameters C_1, C_2, C_3. In addition, A and n are parameters of the Swift hardening law.

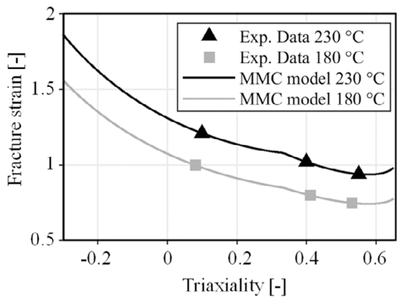

Fig. 6. MMC damage model for AZ31 at 180°C and 230°C.

The parameterised fracture curves of the MMC model for the investigated temperatures are depicted in Figure 6 for a plane stress condition. The parameters of the MMC model can be found in Table 2.

Table 2. Determined parameter of the MMC damage model.

Temp.	C_1	C_2	C_3	A	n
180 °C	0.081	0.197	1.022	191.1	0.121
230 °C	0.035	0.140	1.025	134.6	0.103

4. Validation

Deep drawing tests with a rectangular geometry were carried out to compare the quality of the MMC damage model and the FLC with experimental data. For the evaluation of the specific approaches, the tests were also numerically reproduced. As exemplary depicted in Figure 7a for a test at 230°C, the experimental and numerical punch force and stroke developments are in close agreement, which indicates a good quality of the material model applied. Stochastic marks were applied to the sheet metal blanks in order to be able to perform strain measurement of the components afterwards. Figure 6b shows the strain state determined on the surface of the deep-drawn part. The critical strain state at the position of the crack initiation is highlighted. For this position, the strain path was evaluated numerically, which exhibits a quite linear ratio of minor and major strain of about -1, which indicates that this critical area is affected by shear loading.

For the numerical calculation of a damage accumulation, the definition of a damage variable D is used. The equivalent strain $d\bar{\varepsilon}$ is incrementally contributed to the damage accumulation in dependence of $\bar{\varepsilon}_f(\eta,\bar{\theta})$ by following equation [4]:

$$D = \int_0^{\bar{\varepsilon}} \frac{d\bar{\varepsilon}}{\bar{\varepsilon}_f(\eta,\bar{\theta})} \quad (2)$$

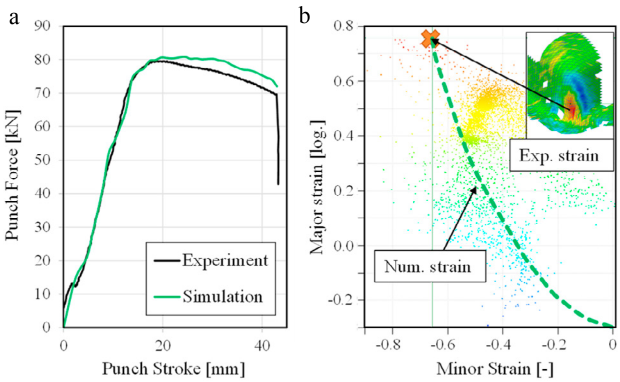

Fig. 7. Experimental and numerical punch force and stroke for a deep drawing test at 230 °C (a); Strain distribution of cracked deep drawn part and strain path comparison (b).

It is assumed that fracture initiates when D = 1. Based on this assumption for damage evolution, non-linear strain-paths (or non-radial loading paths) are considered as well. The damage component of the FLC is calculated via the ratio of the predominant to the endurable principal strain for a predominant minor strain. Conventionally, only the current state and not the history of the strain path is considered in this case.

The deep-drawn parts at 230 °C exhibit a crack initiation in the round area of the flange, which is exemplary depicted in Figure 8a. As described above, this area of the component is affected by shear loading. As a matter of fact, a conventional FLC is not able to consider such conditions that are depicted in Figure 7b. Therefore, the FLC did not provide good results in prediction of this type of failure as shown in Figure 8c. In contrast, the MMC model as shown in Figure 8b represents the local crack appearance very well. These results confirm the advantages of the MMC model over the use of a conventional FLC in such an application case.

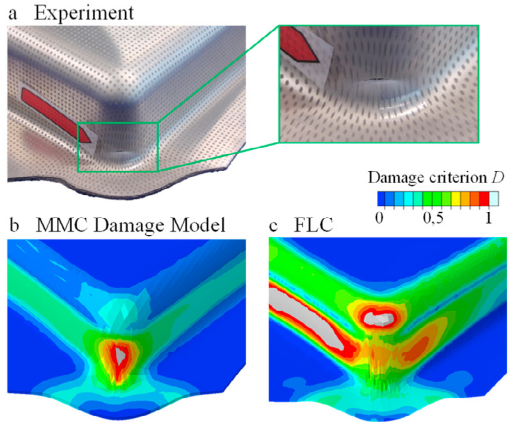

Fig. 8. Experimental and numerical results for a deep drawing test at 230 °C.

5. Conclusion

In this study, the authors present a methodology to parameterise stress-based damage models in dependence of temperature using so-called IFUM Butterfly-Tests. The tests were performed with a magnesium alloy AZ31 for different temperatures and stress states by varying the load-application angle with the presented setup. In addition, the tests were numerically simulated to determine stress characteristics that are required as an input for the used stress-based fracture model. In the numerical simulations of the Butterfly-Tests, the flow behaviour was reproduced with an orthotropic material model CPB06 suitable for magnesium materials, which had previously been parameterised by an extensive series of experiments. By means of the used experimental-numerical approach, the MMC damage model was parameterised for forming temperatures of 180 °C and 230 °C. The study proved applicability of the new setup for tests with IFUM-Butterfly Specimen in order to characterise the fracture behaviour of AZ31 magnesium sheet at elevated temperatures in dependence of the stress state. Due to a validation by means of a deep-drawing test, the good reproduction quality of the parameterised MMC damage model was confirmed.

Acknowledgements

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