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A mechanism-driven plasticity model for deformation by glide and twinning and its application to magnesium alloys

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Abstract. The plastic deformation of two different rolled magnesium sheets (AZ31 and ZE10) under quasi-static tensile and compressive loading conditions at room temperature is studied. Beside glide by dislocation motion, deformation twinning leads to evolving flow stress asymmetry and evolving plastic anisotropy in these alloys. These mechanisms cause a significant change in the shape of the yield surface. A phenomenological plasticity model in which the primary deformation mechanisms, slip and (extension) twinning, are treated separately is developed here and incorporated in the finite element framework. Deformations caused by these mechanisms are modelled by a symmetric and an asymmetric plastic potential, respectively. The hardening functions are coupled to account for the latent hardening. The necessary input for model parameter calibration is provided by mechanical tests along different orientations of the rolled sheets. Tensile tests of flat notched samples and shear tests of sheets are furthermore incorporated in the parameter optimisation strategy, which is based on minimising the difference between experimental behaviour and FE result. The model accounts for the characteristic tension-compression asymmetry and the evolution of strain anisotropy. Both, the convex-up and the concave-down shaped stress-strain response are predicted. The method is further probed on the simulation of forming operations.

1. Introduction

Magnesium is the lightest metal in use for the production of structural components in the automotive and aircraft industry, hence it appears to be attractive for energy-saving products. Despite the high strength-to-weight ratio, the application of wrought magnesium to light-weight structures is still restricted. The limitation for its application is caused to a certain degree by its pronounced anisotropy, and the tension-compression asymmetry. The limited amount of slip systems able to accommodate plastic deformation lead to texture-dependent mechanical deformation characteristics [1, 2]. Furthermore, material failure is reported to be depending on the loading direction and the stress state [3, 4]. Both issues challenge practitioners in the production as well as model developers.

The application of wrought magnesium alloys requires reliable simulation tools for predicting the forming capabilities, the structural response to mechanical loads and the lifetime of the component. The respective constitutive models have to account for the mentioned peculiarities of the mechanical behaviour, demanding for non-state-of-the-art material laws. The choice of an appropriate yield



function capturing plastic yielding under multi-axial stress states is non-trivial. The prediction of strain localization, damage events and material failure is a topic of current research.

While several authors approach distortional hardening with one yield surface with coefficients in a linear transforming matrix depending on a measure of accumulated strain [5, 6], here two interacting yield functions mimicking the deformation mechanisms of glide and twinning, respectively, are used.

2. Materials and mechanical characterisation

The commercial magnesium alloys AZ31 (3%Al + 1%Zn) and ZE10 (1%Zn + 0.3% mischmetal) are considered in the following. Both sheets had a nominal thickness of 2 mm. The alloys were chosen due to their excellent availability and their potential for use in structural applications, notably load-carrying structures. AZ31 exhibits a strong basal texture with a preferential alignment of the basal planes parallel to the sheet plane, whereas ZE10 exhibits a significantly weaker texture. Mechanical tests (uniaxial tension, tension of U-notched specimens, in-plane uniaxial compression of cube specimens, and shear of butterfly-shaped specimens) were conducted in order to identify the load-elongation record [7, 8]. These tests were conducted along two orthogonal principal axes, namely the rolling direction and the transverse direction of the rolled sheets, in order to address the anisotropy of the materials and its evolution.

3. Constitutive model and failure criteria

For the analysis of plastic (irreversible) deformation, a constitutive framework is used which treats the deformation caused by dislocation glide and by mechanical twinning separately [8]. The total strain increment is commonly assumed to consist of the elastic and plastic parts. The plastic strain increment is additively decomposed into a portion by dislocation glide, $d\boldsymbol{\varepsilon}_g^p$, and one caused by twinning, $d\boldsymbol{\varepsilon}_t^p$. The deformation by dislocation glide is described using the non-quadratic, anisotropic yield criterion proposed by Barlat et al. [9] in conjunction with the combined isotropic-kinematic hardening law. The criterion relates yield function, f_g , and the hardening of the glide deformation mechanism, $\bar{\sigma}_g$:

$$\phi_g = f_g - \bar{\sigma}_g = 0 \quad (1)$$

The deformation by twinning is described using the non-quadratic, anisotropic and asymmetric yield criterion proposed by Cazacu et al. [10].

$$\phi_t = f_t - \bar{\sigma}_t = 0 \quad (2)$$

The plastic strain increments are obtained using the respective associated flow rule with the yield surfaces ϕ_g and ϕ_t . The interaction between two deformation mechanisms is realised through hardening of the two yield surfaces defined as follows

$$\bar{\sigma}_g(\bar{\varepsilon}_g, \bar{\varepsilon}_t) = R_g + H_g \bar{\varepsilon}_t + Q_{1g} [1 - \exp(-b_{1g} \bar{\varepsilon}_g)] + Q_{2g} [1 - \exp(-b_{2g} \bar{\varepsilon}_g)] \quad (3)$$

$$\bar{\sigma}_t(\bar{\varepsilon}_t) = R_t + H_t \bar{\varepsilon}_t + Q_{1t} [\exp(b_{1t} \bar{\varepsilon}_t) - 1] + Q_{2t} [1 - \exp(-b_{2t} \bar{\varepsilon}_t)] \quad (4)$$

Isotropic hardening of the glide yield surface is governed by the effective strain of glide, $\bar{\varepsilon}_g$, and the one by twinning, $\bar{\varepsilon}_t$. As implied in Eq. (4), the hardening of the twinning yield surface is not affected by the glide mechanism, whereas the hardening of glide is delayed by the twinning activity, see Eq. (3).

A common approach for predicting ductile fracture is to assume that fracture occurs when the accumulated effective strain weighted by a factor of $D(\sigma)$ reaches a critical value, D_{crit} that is, the critical damage indicator. The effective strain may be considered as the only measure of damage, or $D(\sigma)$ can be expressed as a function of the stress state. Alternatively, the dissipated plastic work can be used as the damage indicator (PW). A more sophisticated model for predicting ductile failure is the Mohr-Coulomb failure model (MMC), which recently was extended for the case of anisotropic failure (EMMC) [11]. All these criteria have to be calibrated by laboratory tests. Usually the tensile test along one direction is used to determine the ‘‘critical damage’’. In case of the MMC and the EMMC criteria,

respective parameters were optimized on the basis of several different mechanical tests covering different stress states [12].

The numerous model parameters of the constitutive model and the damage model are calibrated against uniaxial tensile tests, notch bar (tensile) tests, shear tests, through-thickness and in-plane compression tests.

4. Application and Predictions

4.1. Hydraulic bulge test

Finite Element simulations of a hydraulic bulge test are conducted for AZ31. Since the determination of the model parameters included a through-thickness compression test, the simulation of the hydraulic bulge test can be regarded as a prediction. The through-thickness compression (TTC) test is subjected to friction, and its resolution in term of strains is limited due to the small sheet thickness.

The respective FE simulations were conducted using Abaqus/Standard. The material behavior was connected via the Z-mat link of Z-Set (<http://zset-software.com>). The bulging sheet was meshed using shell elements, the die was modelled by a rigid solid. The orthotropy of the materials was exploited by introducing a two-fold symmetry to the model. Fig. 1 shows the stress components along the orthogonal axes as a function of the strain for both materials, AZ31 and ZE10. Apparently, each alloy has its own specific biaxial hardening behavior. In both cases, plastic deformation is accommodated by the glide mechanism exclusively. The symbols in Fig. 1 result from continuous through-thickness compression tests while the lines are taken at the dome position of the bulged sheet from the FE simulation. Since the materials are anisotropic, the two principal stress are not equal in the simulation. The simulations meet the experiments in a global sense. Due to seating and contact formation in the TTC experiments at low strains a better match with the bulge simulations cannot be expected.

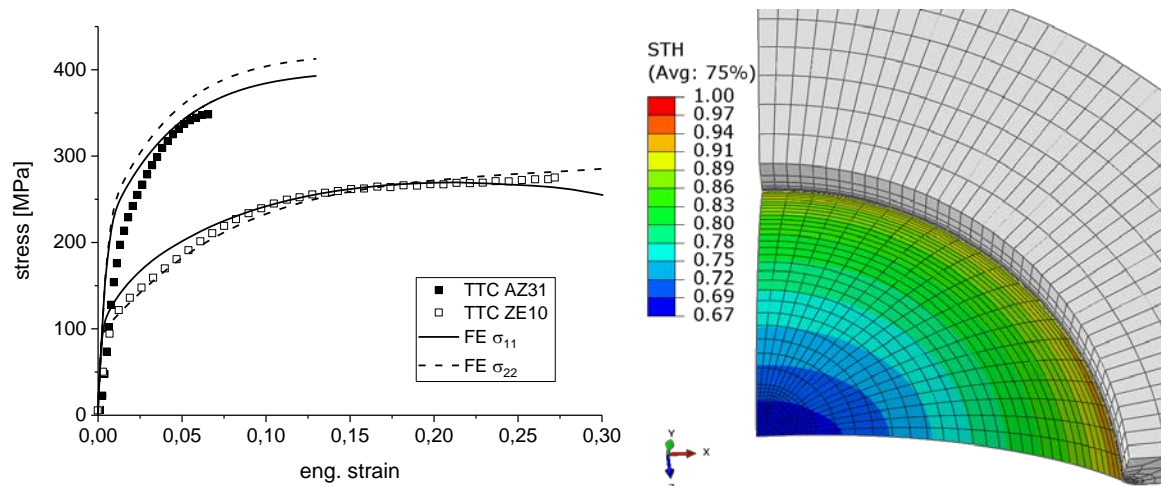


Figure 1. Simulation of the hydraulic bulge test based on the two-surface plasticity model.

4.2. Bendability of sheets

Bending is a typical deformation mode in many practical applications in transportation industries involving irreversible (plastic) deformation. It is indispensable in forming of magnesium alloys. During the bending process the outer region of the sheet is under tension whereas the inner region is under compression. As known from the Euler-Bernoulli beam theory, the absolute values of the maximum strains are equal on the top and bottom side in case of a rectangular cross section. This still holds true for a beam deforming plastically, provided that tensile and compressive behavior are

identical. However, this is not the case for textured magnesium alloys, which show a strength differential effect. Since the magnitude of the strength differential depends on the material, it is a priori not clear where the neutral axis is located during plastic deformation. Furthermore, as the ratio between yield in tension and compression develops with increasing strain, the position of the neutral axis will change. Consequently, the result of a (pure) bending experiment can be used to characterize the compressive hardening of an asymmetric material, provided that the tensile characteristic is known [13].

Here, a virtual bendability test is performed on AZ31 and ZE10 sheet strips. Using a three-point bending setup, a strip of sheet (1.2 mm thick) is bent by a punch with 2 mm radius. Cylindrical support ($r=5\text{mm}$) and punch are represented by analytical rigid bodies. The sheet is ad-hoc modelled by finite strain 3D elements. Due to the orthotropy of the sheet, symmetry conditions are exploited. The punch stroke – force records are shown in Fig. 2a. In the graphs, the limits of bendability as predicted by the damage models are included. These limits were established by assessing the damage indicators: Once the damage indicator reaches unity, cracks are initiated at the indicated stage. Under this assumption, the failure criteria predict early failure in case of AZ31, which is expected to be realistic. For ZE10, the predictions of the damage models vary significantly. This effect has already been observed in structural applications. While the strain (EF) and Modified Mohr-Coulomb (MMC) criteria predict failure close to the maximum load, the respective prediction of the Cockcroft-Latham criterion is rather poor in this particular case. The deformed configuration ($r=2\text{mm}$, AZ31) shown in Fig. 2b visualizes the Modified Mohr-Coulomb damage indicator.

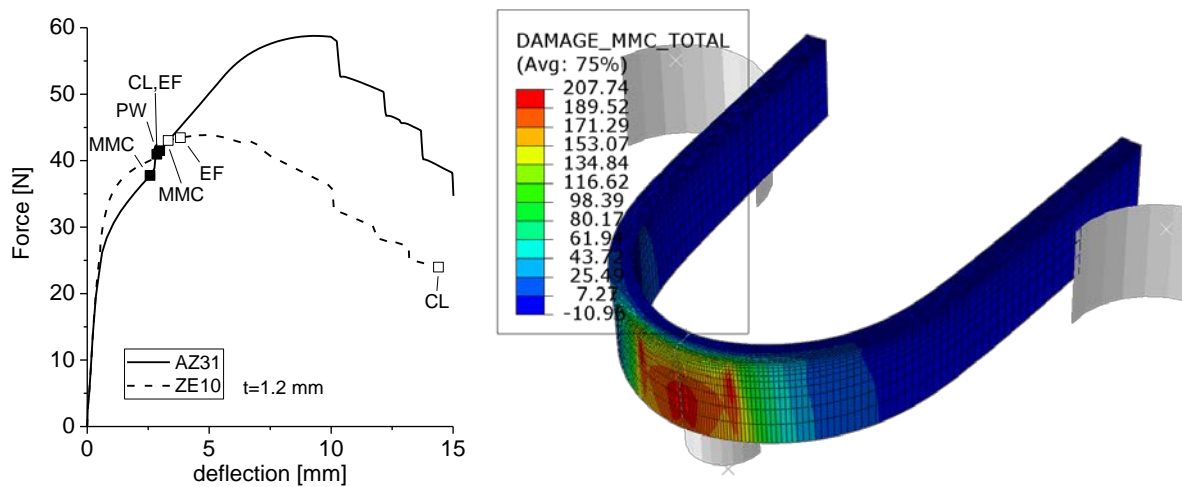


Figure 2. Simulation of a bendability test by three-point bending. (a) Macroscopic response, (b) damage indicator for AZ31

4.3. Forming of a square cup

The calibrated plasticity model together with the failure criteria can be used to predict sheet forming operations at room temperature. From this simulation one can obtain the exact shape of the formed part, the macroscopic response in terms of punch force, and the formability in terms of position and time when cracking occurs. In the following, the forming of a square cup from the two alloys under consideration with a thickness of 2 mm using shell elements is simulated. Two-fold symmetry of the

orthotropic sheet is exploited. The forming tools comprise punch, die and blankholder, each

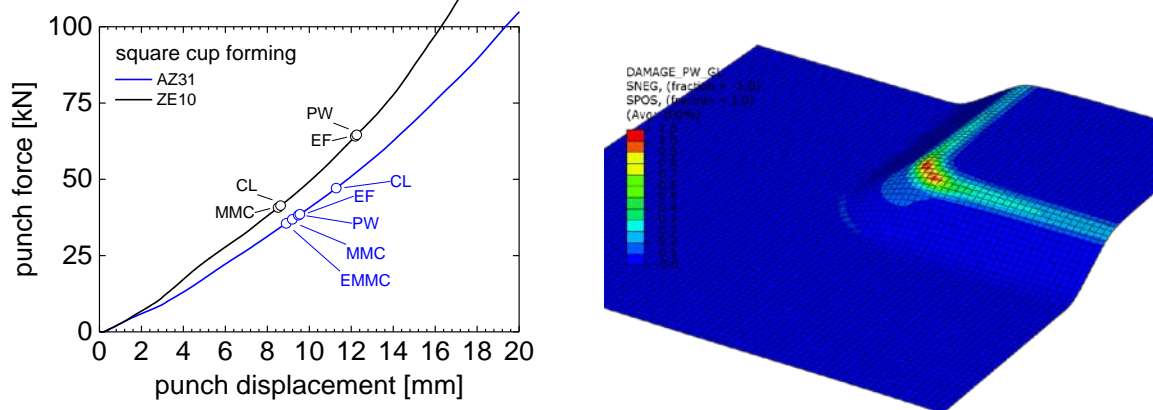


Figure 3. Forming of a square box: (a) predicted failure points for different criteria; (b) corner failure of AZ31 predicted by the plastic work criterion.

of them represented by rigid bodies. Figure 3a shows the simulated global behavior, including the predicted failure points (indicated by respective points). In case of AZ31, the order of failure with increasing load is similar to that of the validation experiment. For ZE10, however, all criteria yield to similar failure predictions. This can be understood by the biaxial (stretching) character of the stress state in the corner of the cup. At this point, the stress triaxiality is high, and similar to what has been achieved in the calibration experiment. Hence, all criteria retrieve failure realistically. Figure 3b indicates the onset of failure as simulated for the AZ31 sheet forming experiment for the plastic work criterion as a damage parameter as an example. Here, all criteria indicate failure on the convex side (outside) at the corner of the punch.

5. Conclusions

A phenomenological 3D plasticity model based on two coupled yield functions corresponding to dislocation glide and twinning, respectively, has been employed. This model captures the evolving tension-compression asymmetry of the two magnesium alloys AZ31 and ZE10 under monotonous loading. It has been shown that this model is a powerful tool to predict the flow stress under different loading orientations over a wide range of strains at ambient temperature. It is furthermore powerful to be used in structural applications, in which irreversible deformations occur. Combined with a damage criterion, which is evaluated in a post processing step and hence is decoupled from the deformation itself, predictions of the limits of the formability can be made. In its current form, contraction twinning and detwinning are not accounted for. Their implementation is generally possible by adding respective yield surfaces, but this rise in complexity would increase the simulation times significantly.

Different failure criteria were probed here. The Mohr-Coulomb type models are stress based and hence generally more suitable to describe brittle fracture rather than ductile fracture. A plastic strain at fracture for a given stress state can however be computed by inverting the hardening law after the failure criterion has been rewritten using the Haigh-Westergaard stress representation. The inverse of the fracture strain is then used so that the model becomes suitable to describe ductile fracture. This was demonstrated here by a bending and a forming experiment. Examples for structural application in the field of vehicle crash are provided by Lee et al. [12].

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