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Experimental Characterization and Material Modelling of an AZ31 Magnesium Sheet Alloy at Elevated Temperatures under Consideration of the Tension-Compression Asymmetry

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Abstract. Magnesium sheet alloys have a great potential as a construction material in the aerospace and automotive industry. However, the current state of research regarding temperature dependent material parameters for the description of the plastic behaviour of magnesium sheet alloys is scarce in literature and accurate statements concerning yield criteria and appropriate characterization tests to describe the plastic behaviour of a magnesium sheet alloy at elevated temperatures in deep drawing processes are to define. Hence, in this paper the plastic behaviour of the well-established magnesium sheet alloy AZ31 has been characterized by means of convenient mechanical tests (e. g. tension, compression and biaxial tests) at temperatures between 180 and 230 °C. In this manner, anisotropic and hardening behaviour as well as differences between the tension-compression asymmetry of the yield locus have been estimated. Furthermore, using the evaluated data from the above mentioned tests, two different yield criteria have been parametrized; the commonly used Hill'48 and an orthotropic yield criterion, CPB2006, which was developed especially for materials with hexagonal close packed lattice structure and is able to describe an asymmetrical yielding behaviour regarding tensile and compressive stress states. Numerical simulations have been finally carried out with both yield functions in order to assess the accuracy of the material models.

1. Introduction

In order to increase the vehicle fuel efficiency and to reduce CO_2 emissions, lightweight materials are becoming more important. Magnesium alloys have a high potential to be used as a construction material due to their excellent properties such as low density, high specific strength and recyclability [1, 2]. Since decades magnesium alloys are used in casting applications, although wrought alloys generally offer better mechanical properties, e. g. strength and ductility. In the near future, the application of wrought magnesium alloys in series production is probable due to cost-effective manufacturing processes, like strip casting, which additionally improves the grain structure of the wrought magnesium alloys [1].

A commercial use of wrought magnesium alloys also requires well designed forming processes. Nowadays numerical approaches are commonly used for an accurate prediction of the forming behaviour, especially in order to optimize component and process design as well as to shorten the development times. The numerical description of forming behaviour requires accurate material models; particularly an adequate modelling of the yielding behaviour is important. In sheet forming processes, the commonly used yield criterion for anisotropic materials has been developed by Hill et

al. (1948), abbreviatory called Hill'48 [3, 4]. This model well predicts the material behaviour of various anisotropic steels. Nevertheless, it could have been shown that the application of Hill'48 for the description of the yielding behaviour of AZ31 at room temperature is not sufficiently precise [5, 6, 7]. The reason is a wider variety of deformation textures and a strong anisotropy which hexagonal close packed (hcp) metals exhibit [8]. Particularly, AZ31 sheet alloys show a large asymmetry of yield and hardening for tensile and compressive loadings [8, 9, 10, 11].

In dependence of the loading situation different types of crystal twinning systems in the microstructure of the material are activated, called extension twins {10-12}<10-1-1> and contraction twins {10-11}<10-1-2> [10, 11, 13]. Cazacu et al. [13] have developed a model (CPB06), which is able to describe the yielding behaviour of hcp- metals like magnesium alloys under consideration of the asymmetric yielding between tension and compression. Chandola et al. [7] were able to show that Hill'48 is not sufficient for the numerical analysis of a torsional response in contrast to CPB2006 which have predicted the experimental trends in good accordance. Andar et al. [14] have performed a comparison of different yield criteria like Mises, Hill'48, Yld2000-2d and CPB06 for an AZ31 sheet alloy. The yield locus has been experimentally estimated for different stress states by using biaxial tests with a cruciform specimen in a range of $0.001 < \varepsilon_p < 0.008$. The experimental and by yield criteria estimated evolution of yield loci has been compared and it could be shown that CPB06 has shown the best accordance with the experimental data.

Studies evaluating the CPB06 criterion by experimental- numerical validation tests with relevant forming processes are very scarce in literature. Furthermore, mentioned-above comparative studies have been only performed at room temperature. However, magnesium alloys exhibit a poor formability at room temperature due to their hexagonal close packed (hcp) lattice structure. The formability increases significantly at temperatures above 200 °C due to thermal activation of non-basal slip systems [15]. Considering this dependency between formability and temperature, in sheet forming processes magnesium alloys are only useable at elevated temperature ranges.

Regarding the positive results in application of the CPB06 criterion and due to missing information on behaviour of CPB06 at elevated temperature, investigations of differences between the commonly used Hill'48 and the CPB06 yield criterion at elevated temperatures, where forming processes of AZ31 alloys are feasible, are of special interest. Main focus of this study is to carry out an adequate material characterization at elevated temperatures to describe the plastic behaviour as well as to evaluate both of the yield criteria with respect to the application in a deep drawing process at elevated temperatures.

2. Material characterization

2.1 Material

A commercial AZ31B alloy sheet has been used in this study, which was produced by POSCO due to the process of strip casting. The nominal thickness of the sheet is 2.0 mm. The chemical composition of the magnesium alloy is listed in Table 1. The main alloying elements are Aluminium and Zink with approx. 3 % and 1 % weight portion.

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

Al	Zn	Mn	Si	Fe	Ca	Cu	Ni	Mg
2.5-3.5	0.6-1.4	0.2-1.0	> 0.1	> 0.005	> 0.04	> 0.05	> 0.005	Balance

2.2 Tension and compression tests

In order to investigate the asymmetric plastic yielding behaviour, tension and compression tests have been performed. The tests have been carried out under quasi static strain rates (0,001 - 0,0025 1/s) at temperatures of 20 °C (RT), 180 °C and 230 °C. All specimens have been cutted out by water jet cutting. The tensile tests have been performed according to DIN 50125 with the geometry H 20 x 80 on an uniaxial tensile machine from Dynamess, type S100/ZD. Anisotropic properties have been

measured with the aid of extensometers, which are measuring the elongation in the width of the specimen.

The specimen geometry presented in Figure 1 has been used for the compression tests. This specimen has been designed by means of numerical and experimental tests to inhibit a premature buckling at compressive loadings. In this study specimens for compression tests have been investigated in RD. The compression tests have been performed at a dilatometer from TA Instruments (previously Bähr), 805A/D+T. By means of these tests, yield curves up to plastic strains of about 0.075 could be determined without buckling.
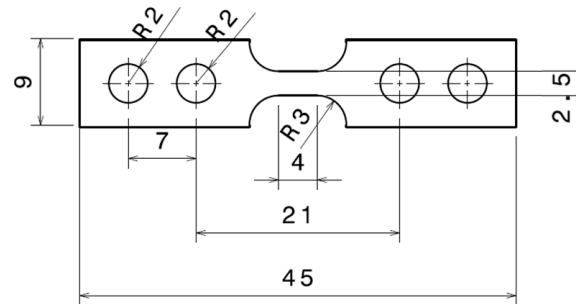

Figure 1. Compression specimen geometry

In figure 2, the yield curves are shown for the tested temperatures and three directions respective to the rolling direction (RD, TD, 45°). The yield stresses strongly decrease with increasing temperature. Figure 3 shows a comparison of hardening behavior with regard to the loading case in terms of tension and compression. At room temperature the material exhibits major differences between the tensile and compressive yield stress, which leads to strong asymmetry of the hardening behaviour as compared to elevated temperatures. At RT the alloy exhibits for compressive stress a different strain hardening curvature in contrast to elevated temperatures. The trend of the curve is in accordance with literature data, e.g. [16].
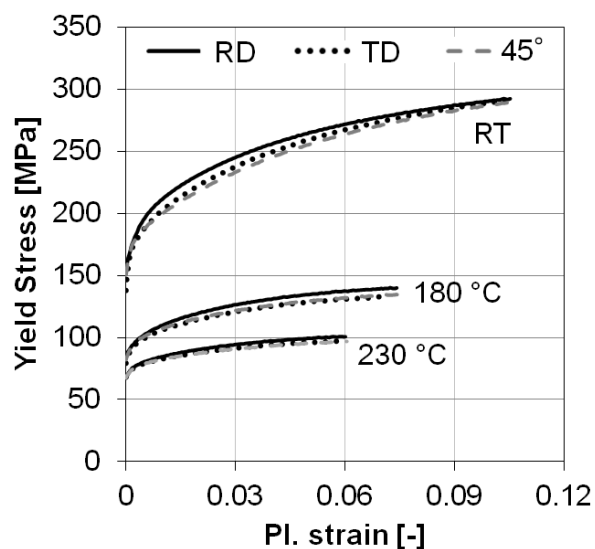
Figure 2. Yield curves for different temperatures and rolling directions
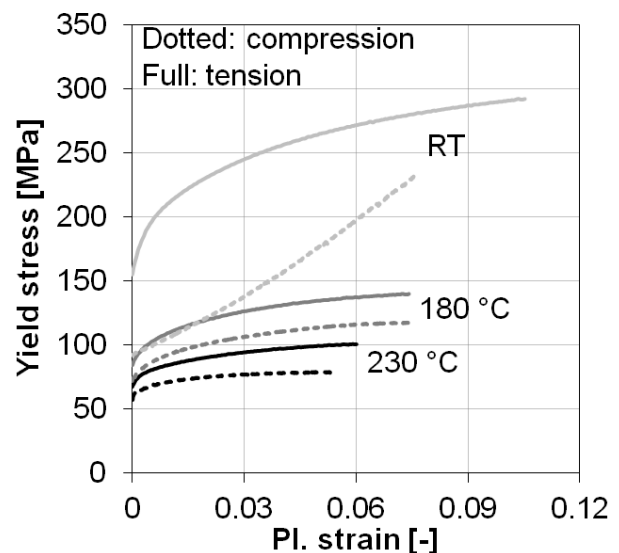
Figure 3. Comparison of yield curves of tension and compression tests (in RD)

2.3 Biaxial Tests

In order to parametrize the CPB06 yield criterion, besides tensile and compressive, also the estimation of the equi-biaxial yield stress is necessary [13]. Therefore, sheet layer compression tests have been performed with the aid of round sheet samples with a diameter of 15 mm. The sheet samples have been manufactured by wire cutting. To minimize the effects of friction, graphite spray is thoroughly applied on each sample before stacking up the samples. Eight sheet samples have been stacked up and put in the centre of a heat container. The core of the heat container is made up of ultra-high strength steel to minimize elastic tool deformation during compression process. In order to avoid tilting, the tools are vertically guided into the heat container. This design has been integrated in a servo hydraulic deformation simulator from Instron. The deformation simulator is equipped with a measuring system including an acceleration sensor and a piezoelectric force transducer.

Assuming a constant volume and a cylindrical geometry, the measured force F and the decrease in height Δh have been used to estimate the yield stress k_f and plastic strain φ. Therefore following equations have been used

$$k_f = \frac{F}{A} = \frac{4 \cdot F \cdot (h_0 - \Delta h)}{d_0^2 \cdot \pi \cdot h_0} \tag{1}$$

$$\varphi = |\varphi|_{max} = \left| ln \frac{h_0}{h} \right| \tag{2}$$

where A is the actual cross section, h_0 the initial height, d_0 the initial diameter and h the actual height.

3. Numerical analysis

CPB2006 and Hill48 yield criterion have been parametrized by means of the experimental tests and used to simulate the tension and compression tests. A parametrization of the Hill48 yield criterion requires the estimation of anisotropic parameters from the tensile tests, which have been carried out in three angles with respect to the rolling direction. CPB2006 has been parametrized by means of the estimated tensile and compressive as well as the biaxial yield stresses. Numerical simulations have been performed using commercial finite element code LS-Dyna, Version 971, and the implemented material models *MAT_233 (CPB06) and *MAT_122 (Hill48) (for more information, see LS-Dyna Manual). In Figure 4 the yield locus calculated by means of CPB06 and Hill48 yield criterion are exemplarily shown for the temperature of 230 °C. Differences between both yield criteria can be seen in all four quadrants.
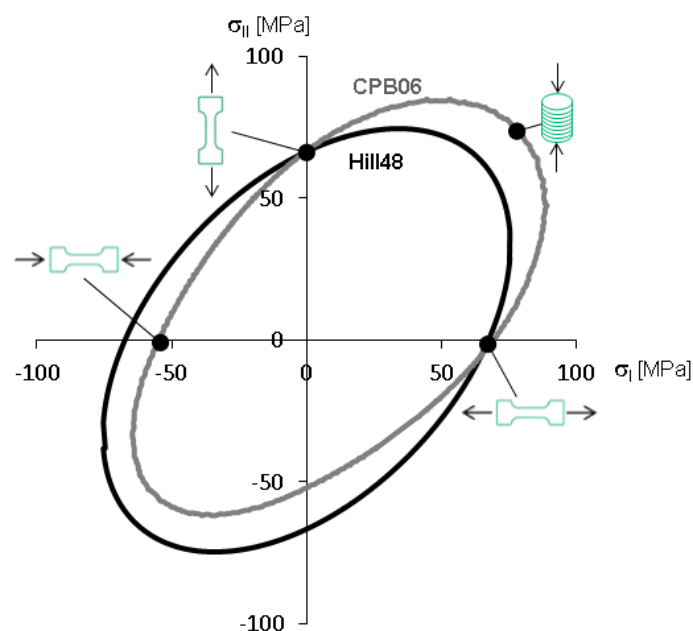
Figure 4. Yield locus of the Hill48 and CPB06 yield criterion for AZ31 (230 °C)

Besides the definition of a yield criterion, it is necessary to describe the hardening behaviour of the material. By means of tensile tests only the deformation up to the uniform elongation can be estimated, but in deep drawing processes also higher strains occur, which have to be considered. In order to describe the hardening behaviour at higher strains, extrapolation approaches like Voce, Swift or Hockett-Sherby are commonly used. Magnesium alloys can exhibit a softening behaviour at elevated temperatures due to dynamic recrystallization in dependence of the strain rate [17, 18, 19]. For a first consideration of the softening or a non-existent hardening rate, the hardening behaviour has been described using the yield curves measured by tensile tests and the Voce extrapolation approach; this means with a constant value of yield stress after the uniform elongation strain up to higher strains.

In Figure 5 results of the simulation for a tension (a) and compression test (b) in comparison with the experimental data for the temperature 230 °C are depicted. It can be clearly seen, that CPB06 is advantageous over the Hill48 yield criterion in the considered tests. Not only the compressive stress state, but also the necking process in the tensile test could be better described in terms of the force-displacement results.
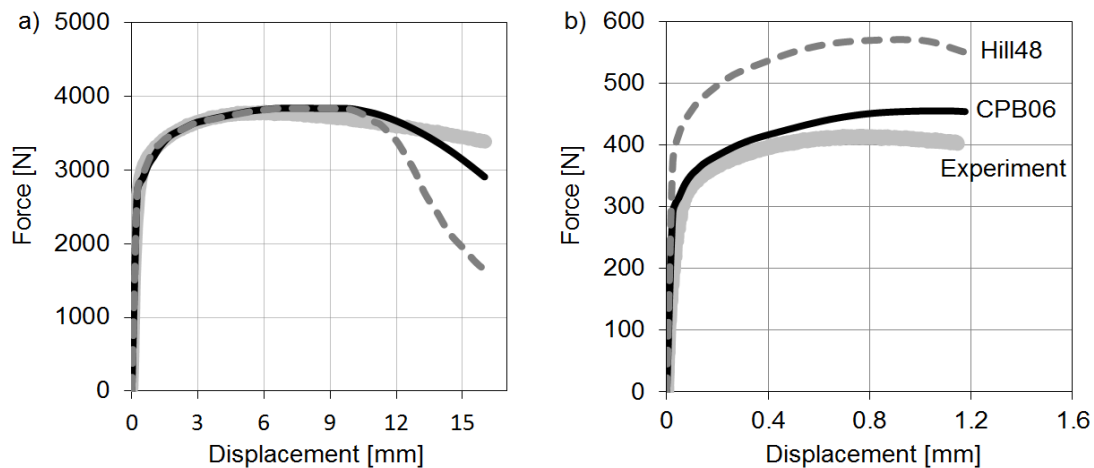

Figure 5. Simulation results for tension tests (a) and compression tests (b) (230 °C)

4. Conclusion

Material characterization tests in terms of tensile, compression and biaxial tests have been carried out at elevated temperatures to calibrate the yield criteria Hill48 and CPB06. The comparative experimental-numerical analysis revealed that the application of Hill48 in numerical simulations of sheet forming processes leads to inaccuracies for both, compressive and tensile stress loadings. CPB06 was able to describe the compressive and tensile stress ranges of the investigated tests with an adequate accuracy. Further validation tests are envisaged for a better assessment of both yield criteria in the application field of deep drawing processes at elevated temperatures.

5. Outlook

Looking forward, on the basis of the parametrized yield criterion, it is envisaged to perform a fracture characterization of the AZ31 alloy and to calibrate a stress-based damage model. The calibration of stress-based fracture models has not been standardized yet. A new butterfly specimen and test setup were recently developed at IFUM in order to estimate stress-based fracture data properly for various desired stress states by variation of the load application angle (see Figure 6). As far, the testing method showed prospering results with high strength steels [20].
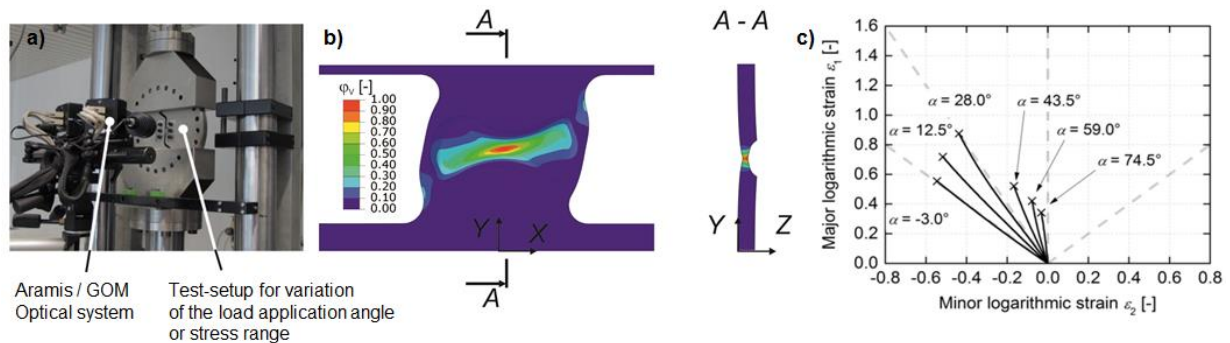
Figure 6. Test setup (a) for testing IFUM- butterfly specimen (b) in a wide range of stress states from tension to shear by variation of the load application angle (c)

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