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MECHANICAL CHARACTERISATION OF MG ALLOYS AND MODEL PARAMETER IDENTIFICATION FOR SHEET FORMING SIMULATIONS

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ABSTRACT: The understanding of forming process of Mg alloys at elevated temperatures can be enhanced with help of numerical simulations. As such a constitutive model was implemented in a finite element frame work. For calibration of the constitutive response mechanical characterisation of Mg alloys were performed. The mechanical characterisation employed uni-axial tensile tests of two Mg alloys, namely AZ31 and ZE10 in heat treated condition, at room temperature (RT) and 200°C. The uni-axial tensile test at 200°C compared to those at RT revealed an increase in ductility but also a decrease in yield strength. Planar anisotropy was recorded in terms of differences in yield stresses as well as r-values between three different material orientations. It was also observed that the planar anisotropy is affected by the test temperatures. The r-values, especially at 200°C, found to be dependent on the accumulated strain. This observation is contrary to the usual practice of assuming a constant r-value. Using the test results the constitutive model parameters were identified.

KEYWORDS: Mg sheet forming, Anisotropy, Parameter identification

1 INTRODUCTION

An increasing demand for lighter structural components attracts materials such as Mg and its alloys. These structural components are often obtained through sheet metal forming process. So called phenomenological material models [1] can be effectively used for numerical modelling of forming process in the frame work of finite elements. This is because they can be applied to complicated processes with less computational effort compared to, for example, crystal plasticity approaches [2]. Due to strong anisotropy [3] and strength differential effects associated with Mg and its alloys capturing the material response with traditional material models is limited. In the past several material models which account for such effects have been proposed [1].

Among these models is one proposed by Cazacu and Barlat (CaBa2004) [4]. Later it was modified to account for model parameter evolution as a function of accumulated plastic strain. The model is also implemented as a user subroutine [5] in ABAQUS [6]; a finite element based software. To control the accuracy of results obtained from model prediction an appropriate mechanical characterisation is required. In the study presented here, a characterisation was carried out using standardised uni-axial tensile tests. Due to their poor formability at room temperature forming has to be conducted at high temperature. Thus the investigation presented here was extended to elevated temperature, i.e. an exemplary test temperature of 200°C.

2 EXPERIMENTS

Tensile tests were conducted at room temperature and 200°C at a strain rate of 0.02/s. The tests comprised two magnesium sheets. These were AZ31 in a heat treated condition (AZ31 O-temper) and its counterpart from new magnesium alloy, ZE10, both having a thickness of 1.3mm. The two alloys were chosen due to a significant difference in their mechanical behaviours as studies made by Bohlen et al showed [7]. This difference is understood to have come from different textures the alloys exhibit. Flat tensile test specimens were prepared for each alloy oriented in rolling direction (RD), 45° and 90° (TD) from RD. At least two specimens were used per orientation to check reproducibility of test results. The tests were conducted by using a ZWICK universal testing machine. Attached to it was a forced furnace for elevated temperature tests. For deformation measurement mechanical extensometer and an optical field deformation measuring system (ARAMIS system) [8] were used. Results obtained from the tensile tests were presented as direction dependent flow curves and r-values. r-value is a measure of strain ratio as defined as:

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln(1+\Delta b / b_o)}{\ln(1+\Delta t / t_o)} \tag{1}$$

ε_w, ε_t, ε_l are logarithmic strains in the width, thickness and longitudinal direction, respectively. The strain in thickness direction is obtained by assuming a constant volume such that $\varepsilon_t = -\varepsilon_l - \varepsilon_w$. The stress quantities used in flow curves as plotted in all figures are true stress while the ones in tables are engineering stress.

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Tests at room temperature reveal a yield strength variation of less than 5MPa between different specimens of the same orientation and same material type. This confirms the reproducibility of the test results. Stress vs. strain curves of material type ZE10 show higher yield stress in RD than in TD and 45^o, which appears to be close to each other, see Figure 1. An observable difference between strain at uniform elongation and failure strain indicates that deformation localisation is significant; refer to Table 1. Similar tests from AZ31 reveal results with higher yield stress in TD than in 45^o which in turn is greater than yield stress in RD, see Figure 2. These observed differences in the yield stresses confirm a yield anisotropy in the materials.

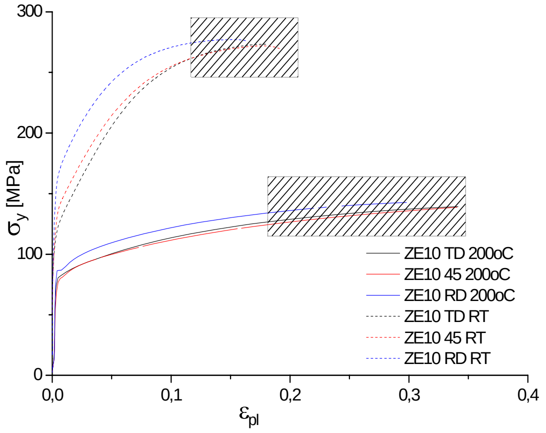

***Figure 1**: True stress-strain curve for ZE10 at RT and 200^{o}C, localised deformation region is shaded*

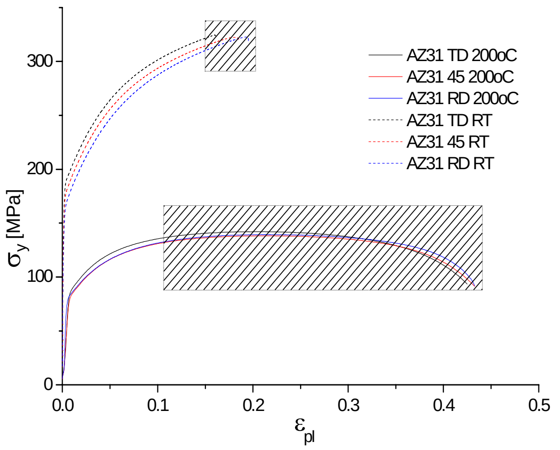

***Figure 2**: True stress-strain curve for AZ31 at RT and 200^{o}C, localised deformation region is shaded*

A comparison of r-values, evaluated based on the strain measurements obtained from ARAMIS system, is also carried out for the different materials. The r-values for ZE10 at RT are found to be small in magnitude. As shown in Figure 3, the different orientations indicate a slight difference in r-values implying a small planar anisotropy. Also the r-value vs. strain curves reveal a converging tendency with increasing strain. Similarly the different r-values obtained from AZ31 for the different orientations confirm the planar anisotropy in the material. For strain range between 5% and 12%, r-values are found to be slightly strain dependent. Such behaviour contradicts the conventional approach of adopting a constant r-value, taken at strain value of 5% or 8% or 10%.

***Table 1**: Yield stress and strain as engineering quantities for ZE10 and AZ31 at RT*

	Ori.	Rp 0,2 MPa	Rm MPa	Ag %	A %
ZE10	TD	111	220	15.7	19.0
	45^o	121	221	15.2	22.6
	RD	144	229	11.3	16.3
AZ31	TD	187	275	17.0	17.4
	45^o	175	269	16.7	20.3
	RD	163	266	18.3	21.5

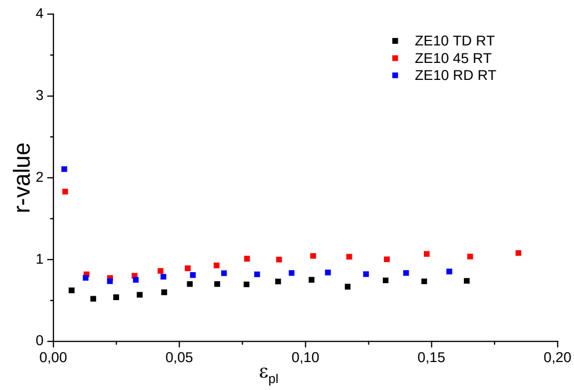

***Figure 3**: r-value vs. strain curve for ZE10 at RT*

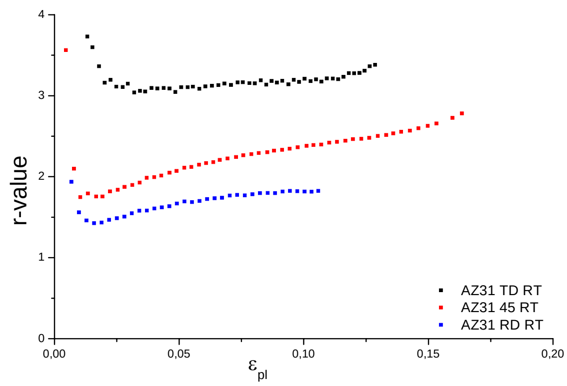

***Figure 4**: r-value vs. strain curve for AZ31 at RT*

Test results of ZE10 at 200^{o}C show a significant increase of fracture strain confirming the improved formability, see Table 2. During the test, large portion of the deformation involved localisation, i.e. the difference between uniform strain and failure strain has shown a significant increase. However the yield stress decreases compared to that measured at RT see Figure 1. It is also observed that the yield anisotropy is relatively lower. A large increase in the fracture strain is also recorded for AZ31 compared to results at RT. However, the uniform deformation is smaller than that measured at RT. The yield stress diminishes by more than 50% of the stress at RT. A relative decrease in yield anisotropy is also observed. The yield stress in TD is again found to be greater than that measured in 45^o and RD.

***Table 2**: Yield stress and strain as engineering quantities for ZE10 and AZ31 at 200^{o}C*

	Ori.	Rp 0,2 MPa	Rm MPa	Ag %	A %
ZE10	TD	80	105	19.3	64.4
	45^o	78	104	19.5	73.7
	RD	86	112	17.1	50.7
AZ31	TD	86	122	10.3	52.5
	45^o	82	118	10.9	53.7
	RD	80	119	12.1	53.8

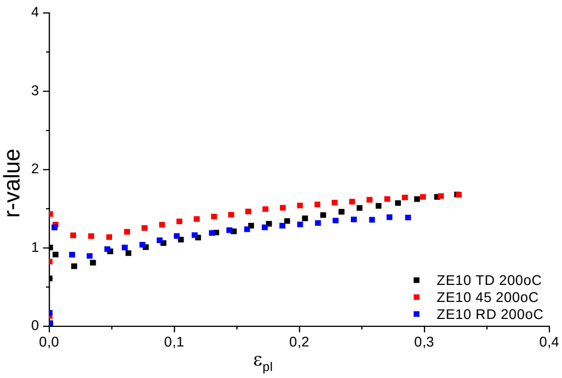

***Figure 5**: r-value vs. strain curve for ZE10 at 200^{o}C*

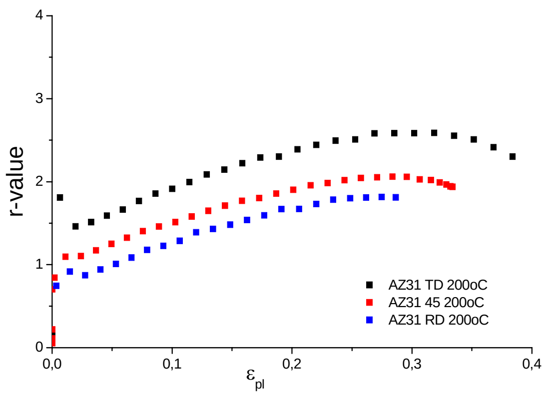

***Figure 6**: r-value vs. strain curve for AZ31 at 200^{o}C*

Following strain measurements from ARAMIS system the calculated r-value for ZE10 at 200^{o}C reveal an interesting feature. As already discussed r-values for ZE10 at RT were shown to be below or around one where as at 200^{o}C r-values are greater than one. On the other hand AZ31 shows lower r-values for the corresponding strain ranges when compared to results obtained at RT, see Figure 6. Another observation made on the r-value shows no convergence with in the uniform deformation range. This suggests that r-value has stronger dependence on strain at 200^{o}C than at RT.

3 PARAMETER IDENTIFICATION

For the investigation of forming process of Mg alloys a constitutive model with the CaBa2004 yield criterion was implemented in a user subroutine in ABAQUS. The yield criterion comprises generalised forms of the second and third deviatoric invariants; J_2° , J_3°; as follows:

$$f = \left(\sqrt{J_2^o}\right)^3 - J_3^o - \tau_y^3 \qquad (2)$$

The inclusion of third deviatoric invariant is to capture the strength differential effect. In the 3D formulation the model involves seventeen parameters. As it is the case with uni-axial tensile tests and sheet forming process the assumption of plane stress condition reduces the number to ten. The corresponding J_2° , J_3° are expressed as:

$$J_2^o = \frac{(a_1+a_3)}{6}\sigma_{xx}^2 + \frac{(a_1+a_2)}{6}\sigma_{yy}^2 + a_4\sigma_{xy}^2 \text{ and} \qquad (3)$$

$$J_3^o = \frac{(b_1+b_2)}{27}\sigma_{xx}^3 + \frac{(b_3+b_4)}{6}\sigma_{yy}^3 - \frac{b_1}{9}\sigma_{yy}\sigma_{xx}^2 - \frac{b_2}{9}\sigma_{xx}\sigma_{yy}^2 + \frac{\sigma_{xy}^2}{3}\left[b_5\sigma_{yy} + (2b_{10}-b_5)\sigma_{xx}\right] . \qquad (4)$$

The yield strength in shear, τ_y, is expressed in terms of yield stresses measured from the uni-axial tensile test, σ_y ; see below:

$$\tau_y = \left(\left(\frac{(a_1+a_3)}{6}\right)^{3/2} - \frac{(b_1+b_2)}{27}\right)^{1/3}\sigma_y . \qquad (5)$$

Setting a_i to 1 and b_j to 0 gives the von Mises yield criterion. Due to the limited number of experimental data presented here some of the parameters have been adopted from von Mises case. To account for strain hardening, the parameters are assumed to be functions of the accumulated equivalent strain, $\bar{\varepsilon}^{pl}$. This was done by introducing an exponential function defined as:

$$a_i(i=1,\ldots,6) = A_i + B_i\left(1-e^{-C_i\bar{\varepsilon}^{pl}}\right), \quad b_i(j=1,\ldots,11) = A_j + B_j\left(1-e^{-C_j\bar{\varepsilon}^{pl}}\right) . \qquad (6)$$

For the parameter identification a genetic algorithm [9] was used with an objective function expressed as:

$$\gamma = \sum_k \sum_l \left[{}^{kl}\mu^{\sigma}\left({}^{kl}\sigma^{set} - {}^{kl}\sigma^{ref}\right) + {}^{kl}\mu^{r}\left({}^{kl}r^{set} - {}^{kl}r^{ref}\right) \right] . \qquad (7)$$

Where: k loading path, l iso strain curve,

$$ {}^{kl}r^{set} = -\frac{\partial \phi}{\partial_{kl}\sigma_L} / \left(\frac{\partial \phi}{\partial_{kl}\sigma_L} + \frac{\partial \phi}{\partial_{kl}\sigma_T} \right) \tag{8} $$

This function incorporates terms which account for yield stresses as well as r-values. ${}^{kl}\mu^{\bar{\sigma}}$ and ${}^{kl}\mu^{r}$ are weighting factors to control the effects coming from stress and r-value respectively. The term *ref* refers to the reference values obtained from experiment while *set* refers to the values obtained from a predicted parameter set. The term r^{set} is an equivalent r-value obtained from the derivatives of the yield function with respect to the stress components.

From experiments a more pronounced anisotropy with respect to r-value is observed in AZ31 than ZE10. Moreover, an improvement is seen at 200°C compared to RT. However, the anisotropy observed at 200°C is not negligible and hence need to be considered in modelling. To demonstrate accounting such effects in the parameter identification procedure the experimental results from AZ31 at 200°C were used. As it is shown in Figure 7 a good fit for the experimental results with respect to iso strain stress components was found. The predicted parameters also captured the increase in r-value with increasing plastic strain. The fit depicted in Figure 8 show a good agreement with the experimental results. It should be noted that for proper description of strength differential effect and bi-axial yield behaviour additional data are required. This can be achieved by conducting compression and bi-axial tests. The same identification procedure can be used to predict the parameters for ZE10.

4 CONCLUSIONS

The low formability behaviour and material anisotropy of magnesium alloys at RT were confirmed by the small strain values measured and anisotropy in terms of yield stress as well as r-values. The r-values at RT indicated a certain converging tendency with increasing strain values. At 200°C, an improvement in the formability and material anisotropy was observed. This was seen from the increase in the total strain measured. Also a relative decrease in the material anisotropy in terms of yield stress was recorded. Stronger strain dependency was observed on the r-value at 200°C than at RT. No convergence of the r-value was observed with in the uniform deformation range. This contradicts the common practice of adopting a constant r-value for a given material orientation. Finally anisotropy as described in terms of yield stress and r-values was utilised in predicting the constitutive model parameters. AZ31 for its pronounced anisotropy behaviour compared to ZE10 was selected for demonstration. A good fit was found with the predicted parameters for the experimental data. However, more data is required for complete calibration of the constitutive response such as strength differential effect and bi-axial yield behaviour.

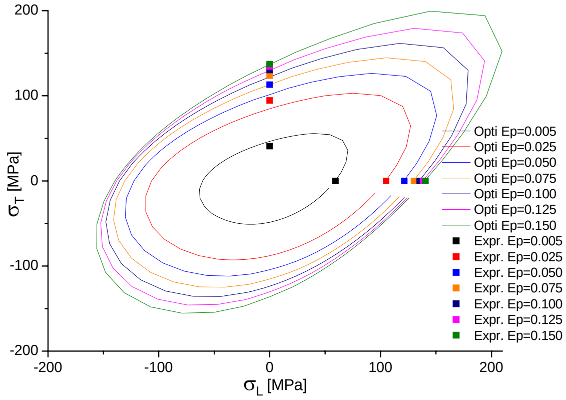

***Figure 7**: Iso strain curves for AZ31 at 200°C*

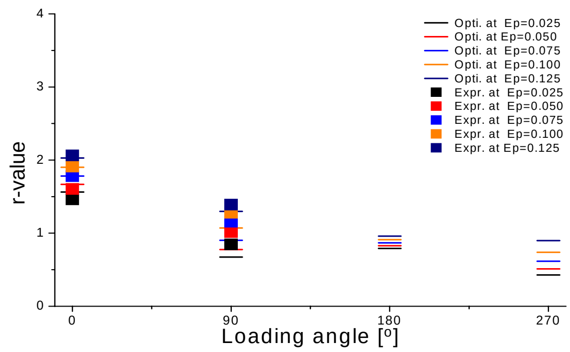

***Figure 8**: r-value vs. loading paths (angle) for AZ31 at 200°C*

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