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Modelling of thermo-mechanical Behaviour of Magnesium Alloys during Indirect Extrusion

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Abstract. A yield function for hexagonal closed packed (hcp) metals was modified with respect to strain rate and temperature and developed to capture the material behaviour during extrusion. Magnesium alloy ZEK100 was extruded indirectly at 300°C into a round bar. Compression tests were carried out at various strain rates, temperatures and sample orientation to characterise the material flow. These data were used as input data for fully thermo-mechanical coupled simulations of indirect extrusion. A successful prediction of the extrusion force and the temperature increase during extrusion is presented.

Introduction

Magnesium and its alloys have become promising materials saving structural weight and reducing fuel consumption especially for transportation industry, due to being the lightest metal for structural applications. One of the established production methods for semi-finished products is extrusion. For magnesium and its alloys, this technology is available today, but there is still a fundamental lack in understanding the factors that determine the development of microstructure and mechanical properties during the process. Such alloys show unusual mechanical characteristics such as deformation anisotropy and asymmetry in tension-compression, which originate from the hexagonal closed packed (hcp) crystallographic structure and the distinct textures that develop during massive deformation such as extrusion. A phenomenological model derived by Cazacu and Barlat [1] accounts for the complexity in the yielding behaviour of magnesium and its alloys such as anisotropy and asymmetry in tension-compression. However, the capabilities of this model for simulation of extrusion, where complex thermo-mechanical loading exists, are limited since strain rate and temperature dependency on flow behaviour are not considered. Modifications including these phenomena were derived [2] and implemented as user defined subroutine, VUMAT, into the commercial Finite Element (FE) software, ABAQUS/Explicit [3].

Material Model

In order to capture strain rate and temperature dependence on plastic yielding, the yield function, f, is written as a function of three internal state variables, namely equivalent plastic strain, $\bar{\varepsilon}^{pl}$, plastic strain rate, $\dot{\bar{\varepsilon}}^{pl}$, and temperature, θ,

$$f = \left(J_2^\circ(\bar{\varepsilon}^{pl})\right)^{3/2} - J_3^\circ(\bar{\varepsilon}^{pl}) - \tau_y^3(\bar{\varepsilon}^{pl}, \dot{\bar{\varepsilon}}^{pl}, \theta), \tag{1}$$

where J_2° and J_3° are generalisations of the second and third invariant of the stress deviator. In order to describe the strain hardening of the material, the invariants are assumed to be dependent on the equivalent plastic strain by a saturating exponential law.

Cowper-Symonds' overstress model [4] was chosen to capture the rate dependency of plastic deformation. The yield stress under quasi-static conditions is linked to "dynamic" yield stress via 2 model parameters: reference strain rate, *D*, and exponent, *n*, respectively as

$$\frac{\sigma_y'}{\sigma_y} = \left(\frac{\dot{\bar{\varepsilon}}^{pl}}{D(\theta)}\right)^{1/n(\theta)} + 1, \tag{2}$$

where *D* and *n* are defined as functions of temperature in order to take the variation of the rate dependence with temperature into account.

Compression Tests

Compression tests on cylindrical specimen with 10 mm of diameter and 15 mm of height machined from as-cast ZEK100 magnesium alloy were performed at different test temperatures (i.e. 300, 400, 500°C) and strain rates (i.e. 0.1, 1, 10 s^{-1}) and different directions in order to study the metal flow. FE simulations were executed to regenerate the experimental results. The pair of parameters, i.e. *D* and *n*, was identified for each test temperature, evidencing that the rate dependency depends on the test temperature. As a result, a single pair of the model parameters is not sufficient to capture whole rate dependency seen in Fig. 1.

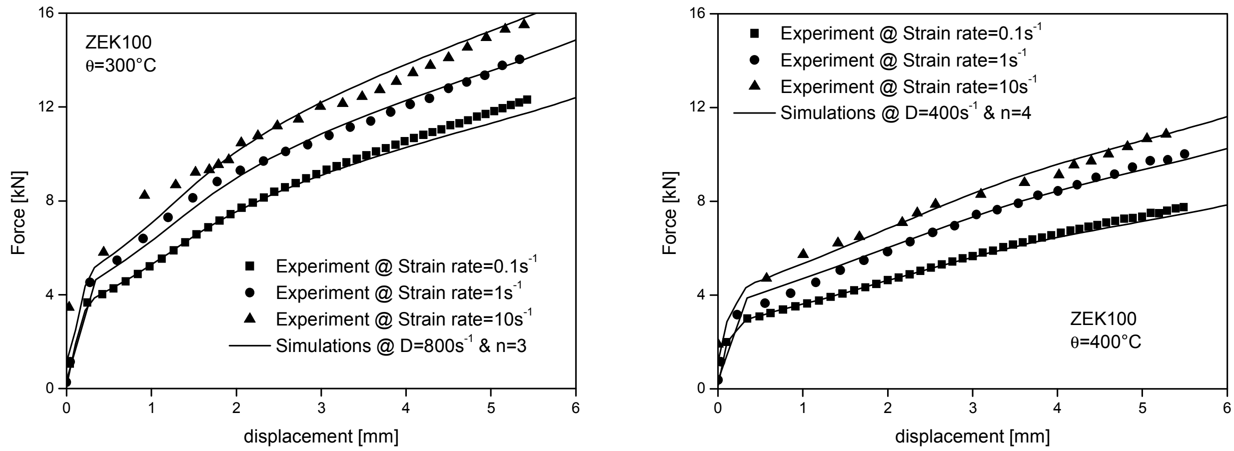

Fig. 1: The experimental and simulation results of compression tests at 300°C (left) and 400°C (right)

In order to capture deformation anisotropy in compression, the tests were performed on specimens prepared at different orientations, namely extrusion (L) and transverse directions (T).
Fig. 2 shows the yield loci drawn with set of parameters, *CaBaExpo2*, together with experiments. The parameters embedded in J_2° and J_3° were identified by minimizing the difference between model predictions and experimental results.

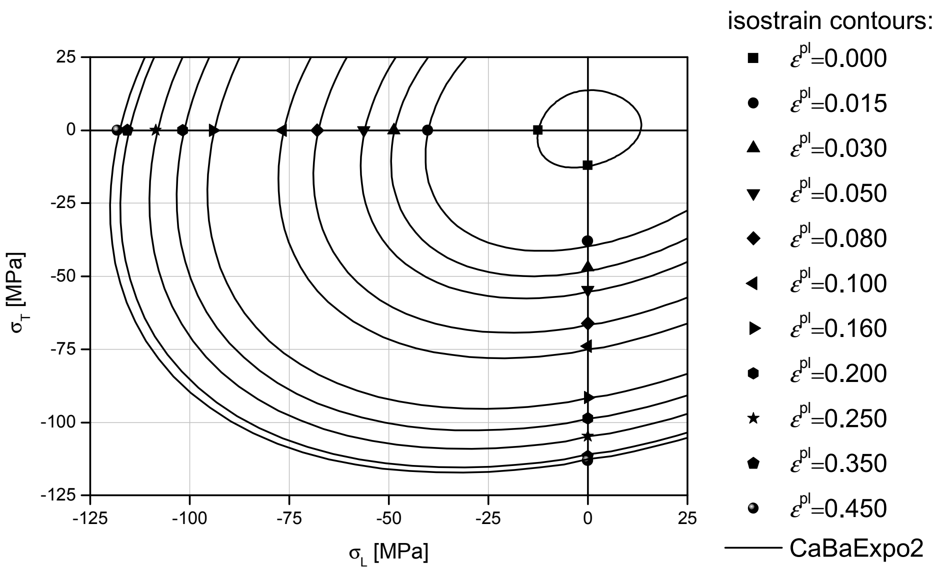

Fig. 2: Compression test results with the corresponding yield loci and hardening behaviour drawn by parameter set *CaBaExpo2*

Indirect Extrusion

Indirect extrusion was carried out at on the billet machined down to a diameter of 93 mm and a length of 300 mm at billet temperature of 300°C. The extrusion ratio is 1:30. During extrusion, a round bar with 17 mm diameter was produced with a profile speed of 10 m/min.

A fully coupled thermo-mechanical analysis, in which the temperature is assumed as an additional degree of freedom, was used in extrusion simulations for calculation of the temperature field by considering heat fluxes and heat generated due to plastic deformation. In the simulations, so-called Arbitrary Lagrangian-Eulerian (ALE) [5] formulation was used. In the Lagrangian (material) description, a material point is focussed, whereas a stationary spatial reference frame is observed during deformation in the Eulerian (spatial) formulation. The combination of both limits forms ALE. This eliminates the problems of mesh distortions that can occur in a pure Lagrangian approach. The metal flow was considered via Eulerian boundary condition. On the other hand, Lagrangian boundary conditions were applied to the die and the container. The problem is assumed to be axi-symmetric.

In order to keep reasonable computational cost, the container and the die were considered as analytical rigid surface, hence no deformation or temperature fields are able to be monitored on these surface. Since there is no relative displacement between the billet and the container, friction between the billet and the container does not exist in indirect extrusion. Therefore, the contact between the billet and the container was established without friction. The contact area with the die, on the other hand, was described by Coulomb friction. The friction coefficient is estimated in literature varying between 0.1 and 1 for different metallic materials [6, 7]. In this study, it was assumed as 0.5.

The die is equipped with a thermocouple at the inner surface. This enables the measurement of the profile temperature during the extrusion process. The temperature measurements seen in Fig. 3 were used to calibrate heat transfer properties between the billet and the die. Fig. 3 shows the agreement between the experiments and simulations in the case of both temperature and reaction force.

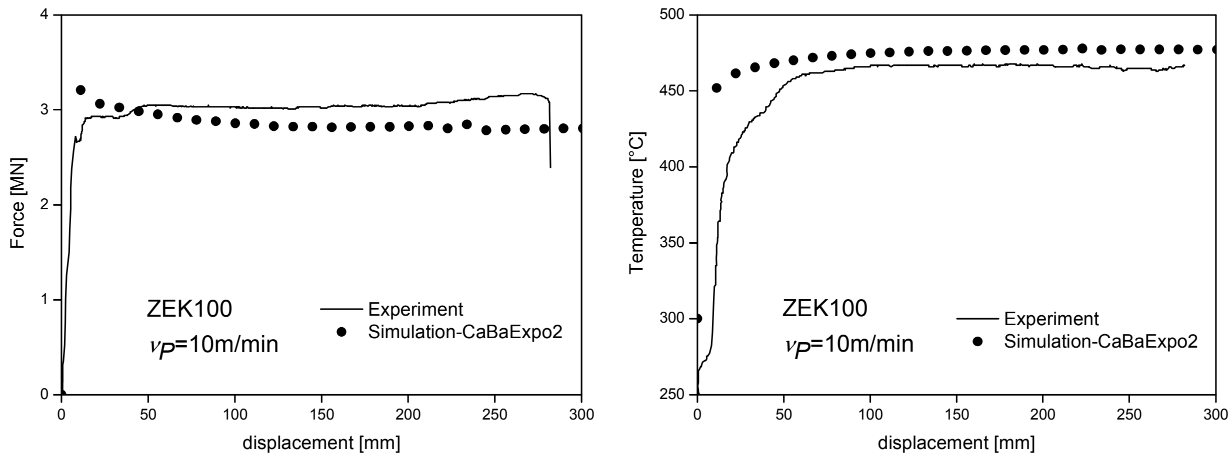

Fig. 3: Experimental and simulation results of indirect extrusion: force vs. displacement (left) and temperature vs. displacement (right)

Fig. 4 shows the von Mises stress and temperature distributions at ram displacement=300mm.

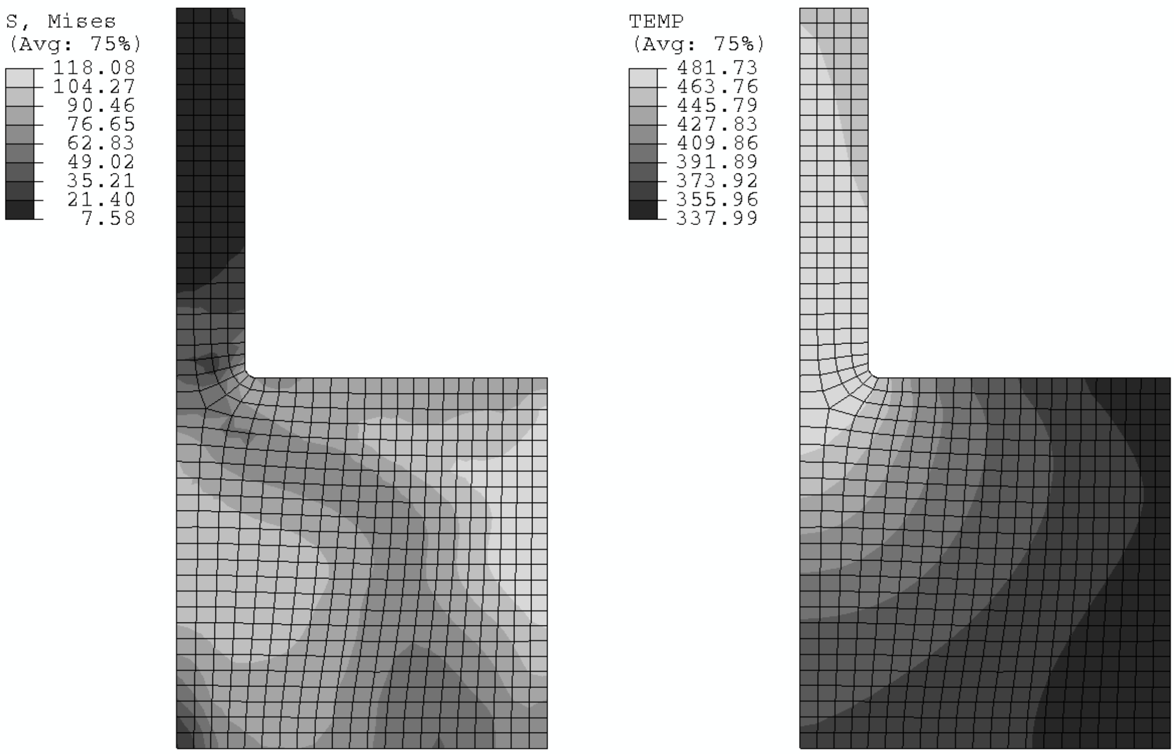

Fig. 4: von Mises stress (left) and temperature (right) distributions

It is predicted that the higher-stress-region is located where metal flow is in contact with the dead metal zone and container. The temperature at the die exit where large deformation takes place is predicted as the highest. The region close to the container heat transfer causes cooling down of the extrudate.

Summary

Compression tests were executed at different punch velocities and test temperatures in order to describe the rate dependency on deformation. Simulations of upsetting tests were performed to fit model parameters for rate dependency, temperature dependency and anisotropic yielding by comparing with the corresponding experimental results and then to use as input data for simulations of indirect extrusion. The simulations of indirect extrusion show good agreement between experimental results.

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