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Modelling and Simulation of Extrusion of Magnesium Alloys

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ABSTRACT: Extrusion, as one of the bulk-metal forming processes, is of significant importance for the production of semi-finished components. For magnesium and its alloys, the technology for processing 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. Due to its hexagonal crystallographic structure, deformation mechanisms observed in magnesium alloys are rather different from those in fcc metals such as aluminium alloys. As a result, mechanical anisotropy and tension-compression asymmetry, i.e. unequal compressive and tensile yield stresses are observed. The resulting complexity in the yielding behaviour of such materials cannot be captured by conventional models based on J_2 plasticity. A phenomenological model derived by Cazacu and Barlat accounts for the respective phenomena by introducing the third invariant of the stress tensor. However, processes such as extrusion involve complex thermomechanical and multiaxial loading conditions which include large strain, high strain rates and moderate increase in temperature due to deformation. The capability of Cazacu and Barlat model is limited in this regard since strain rate and temperature dependency on flow behaviour were not considered in their original work. The respective modifications to capture these phenomena were performed and implemented successfully as user defined subroutine, VUMAT, into commercial Finite Element software, ABAQUS/Explicit. In order to capture the rate dependency on plastic deformation, Cowper-Symonds overstress model was chosen. Adiabatic conditions were assumed considering the rise of temperature due to plastic deformation.

Key words: Extrusion, Magnesium alloys, Rate-dependent-J_3 plasticity, Adiabatic analysis, VUMAT.

1 INTRODUCTION

Many advanced processes in engineering such as extrusion involve complex thermomechanical and multiaxial loading conditions. They include large strains, high strain rates and an increase in temperature due to deformation. Classical yield criteria define a surface in stress space, a formulation of all possible combinations of stress states that will lead to plastic yielding without any consideration of rate effects. In order to include effects of the loading rate into the modelling, Cowper-Symonds power law [1] was chosen due to being available in the commercial finite element (FE) software, ABAQUS [2], in combination with von Mises yield criterion [3], which applies for isotropic materials. Unfortunately, this yield criterion does not give satisfaction especially in the case of hexagonal closed packed (hcp) metals showing anisotropy in its mechanical behaviour as well as an asymmetry in tensile/compression behaviour.

The phenomenological yield criterion for anisotropic materials derived by Cazacu and Barlat [4] can also capture the latter phenomenon by introducing the third invariant of the stress tensor. To address temperature dependency, temperature will be included as internal state variable and adiabatic conditions are assumed considering the increase in temperature due to plastic deformation.
The modified version of Cazacu and Barlat model with respect to rate and temperature dependency on plastic deformation has been implemented successfully as user defined material, namely VUMAT [5], in ABAQUS/Explicit.

2 MATERIAL MODELS

2.1 Cowper-Symonds overstress power law

A widely used rate-dependent formulation, Cowper-Symonds power law,

$$\frac{R'}{R_o} = \left(\frac{\dot{\varepsilon}^{pl}}{D} \right)^{1/n} + 1, \tag{1}$$

is considered, where R' is the “dynamic” yield stress at a plastic strain rate $\dot{\bar{\varepsilon}}^{pl}$ and R_o is the yield stress under quasi-static conditions; D and n are model constants, reference strain rate and exponent, respectively.

2.2 Cazacu and Barlat yield criterion

The phenomenological model proposed by Cazacu and Barlat captures asymmetry in yielding in pressure-insensitive metals. Cazacu and Barlat considered generalisations of the second and third deviator invariants, J_2 and J_3. The proposed anisotropic and asymmetric yield criterion is given by

$$f = (\sqrt{J_2^\circ})^3 - J_3^\circ - \tau_y^3, \tag{2}$$

where τ_y is the yield strength in shear.

The generalization of J_2 to orthotropy, denoted by J_2° is expressed in the reference frame associated to the material symmetry as

$$\begin{aligned} J_2^\circ &= \frac{a_1}{6}(\sigma_{xx}-\sigma_{yy})^2 + \frac{a_2}{6}(\sigma_{yy}-\sigma_{zz})^2 \\ &+ \frac{a_3}{6}(\sigma_{zz}-\sigma_{xx})^2 + a_4\sigma_{xy}^2 + a_5\sigma_{xz}^2 + a_6\sigma_{yz}^2 \end{aligned}, \tag{3}$$

The generalisation with respect to orthotropy of J_3, denoted by J_3°, is expressed as

$$\begin{aligned} J_3^\circ &= \frac{1}{27}(b_1+b_2)\sigma_{xx}^3 + \frac{1}{27}(b_3+b_4)\sigma_{yy}^3 \\ &+ \frac{1}{27}\left[2(b_1+b_4)-b_2-b_3\right]\sigma_{zz}^3 \\ &+ 2b_{11}\sigma_{xy}\sigma_{xz}\sigma_{yz} + \frac{2}{9}(b_1+b_2)\sigma_{xx}\sigma_{yy}\sigma_{zz} \\ &- \frac{1}{9}(b_1\sigma_{yy}+b_2\sigma_{zz})\sigma_{xx}^2 - \frac{1}{9}(b_3\sigma_{zz}+b_2\sigma_{xx})\sigma_{yy}^2 \\ &- \frac{1}{9}\left[(b_1-b_2+b_4)\sigma_{xx}+(b_1+b_3+b_4)\sigma_{yy}\right]\sigma_{zz}^2 \\ &- \frac{\sigma_{yz}^2}{3}\left[(b_6+b_7)\sigma_{xx}-b_6\sigma_{yy}-b_7\sigma_{zz}\right] \\ &- \frac{\sigma_{xz}^2}{3}\left[2b_9\sigma_{yy}-b_8\sigma_{zz}-(2b_9-b_8)\sigma_{xx}\right] \\ &- \frac{\sigma_{xy}^2}{3}\left[2b_{10}\sigma_{zz}-b_5\sigma_{yy}-(2b_{10}-b_5)\sigma_{xx}\right] \end{aligned}, \tag{4}$$

The coefficients, a_k and b_j, which determine the shape of the yield surface, can be defined as functions of the equivalent plastic strain, $\bar{\varepsilon}^{pl}$, with the help of optimisation algorithms [6, 7]. To this end, a second-order polynomial function was selected in order to define the evolution of coefficients as seen below:

$$\begin{aligned} a_k(k=1,..,6) &= A_k(\bar{\varepsilon}^{pl})^2 + B_k\bar{\varepsilon}^{pl} + C_k, \\ b_j(j=1,..,11) &= A_j(\bar{\varepsilon}^{pl})^2 + B_j\bar{\varepsilon}^{pl} + C_j. \end{aligned} \tag{5}$$

Since the Cazacu and Barlat yield criterion is an extension of von Mises' yield criterion, one can mimic conventional von Mises plasticity by choosing the model parameters as

$$\begin{aligned} a_k(k=1,..,6) &= 1, \\ b_j(j=1,..,11) &= 0. \end{aligned} \tag{6}$$

2.3 Modified Cazacu and Barlat yield criterion

As mentioned before, neither strain rate nor temperature dependency is considered in the original work of Cazacu and Barlat. In order to capture these phenomena, the proposed modified version of the yield function can be written as a function of three internal state variables, namely equivalent plastic strain, plastic strain rate and temperature,

$$f = \left(J_2^\circ(\bar{\varepsilon}^{pl})\right)^{3/2} - J_3^\circ(\bar{\varepsilon}^{pl}) - \tau_y^3(\bar{\varepsilon}^{pl}, \dot{\bar{\varepsilon}}^{pl}, \theta). \tag{7}$$

The yield strength in shear, τ_y, can be expressed by the yield strength, σ_y, as measured from the uniaxial tensile test by

$$\tau_y = \left(\left(\frac{1}{6}(a_1+a_3)\right)^{3/2} - \frac{1}{27}(b_1+b_2)\right)^{1/3}\sigma_y. \tag{8}$$

Strain-rate hardening is modelled by the overstress law, Equation (1), and temperature softening as follows:

$$\sigma_y = \left[1-\beta(\theta-\theta_o)\right]\left[\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{D}\right)^{1/n}+1\right]\left[\sigma_o + H\bar{\varepsilon}^{pl}\right], \tag{9}$$

where σ_o is the initial yield strength, H is a hardening modulus, D and n are reference strain rate and exponent, β is a temperature softening parameter and θ_o is a reference temperature.

The calculation of temperature, θ, is based on the assumption of adiabatic processes, where plastic deformation introduces a heat flux per unit volume,

$$q^{pl} = \eta\sigma : \dot{\varepsilon}^{pl}, \tag{10}$$

where q^{pl} is the heat flux added into the energy

balance, η is the inelastic heat fraction to be specified by the user.
The heat equation solved at each integration point is

$$q^{pl} = \rho c \dot{\theta}, \tag{11}$$

where ρ is the material density and c is the specific heat.
Rise of temperature due to inelastic dissipation, $\dot{\theta}$, is hence calculated by combining Equations (10) and (11):

$$\dot{\theta} = \frac{\eta \sigma : \dot{\varepsilon}^{pl}}{\rho c}. \tag{12}$$

3 SIMULATIONS

3.1 Simulations of compression tests

The uniaxial compression or upset test [8] of a cylindrical specimen compressed with the help of a flat punch parallel to the supporting plane is a common test for measuring the flow stress for metal working applications [9,10]. Due to the symmetry seen in Fig. 1, a quarter of the specimen was meshed with axisymmetric continuum elements having 4 nodes with reduced integration, CAX4R.

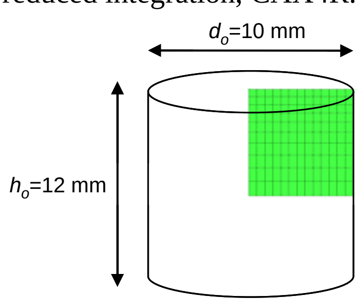

Fig. 1. Specimen geometry and used mesh with CAX4R

The punch was defined as a rigid surface having a reference node which was assigned to have ramped displacement to provide compression. The contact between the rigid punch and the top layer elements of the mesh was established. The standard Coulomb friction model provided by ABAQUS was used at the contact. The frictional stress, τ_{fric}, is proportional to the contact pressure, p, as

$$\tau_{fric} = \mu p, \tag{13}$$

where μ, the friction coefficient, is set to 0.05 for simulations.
The material under consideration was based on the experimental work of Kelley and Hosford [11]. The set of parameters labelled as CaBaCon (see Table 1) was generated with the help of an optimisation algorithm. Since hardening is assumed as isotropic, i.e. the shape of the yield function defined by the parameters remains unchanged, this set of parameters does not depend on plastic deformation.

Table 1 Parameters labelled as CaBaCon used for simulations

CaBaCon	A	B	C
$\mathbf{a_1}$	0.0	0.0	-0,041
$\mathbf{a_2}$	0.0	0.0	0,9
$\mathbf{a_3}$	0.0	0.0	0,77
$\mathbf{b_1}$	0.0	0.0	-0,2926
$\mathbf{b_2}$	0.0	0.0	0,9053
$\mathbf{b_3}$	0.0	0.0	1,5426
$\mathbf{b_4}$	0.0	0.0	-0,1609

Fig. 2 shows the effect of temperature softening with $\eta = 0.9$ and $\beta = 0.001$ not only for von Mises plasticity but also for the parameter set labelled as CaBaCon.

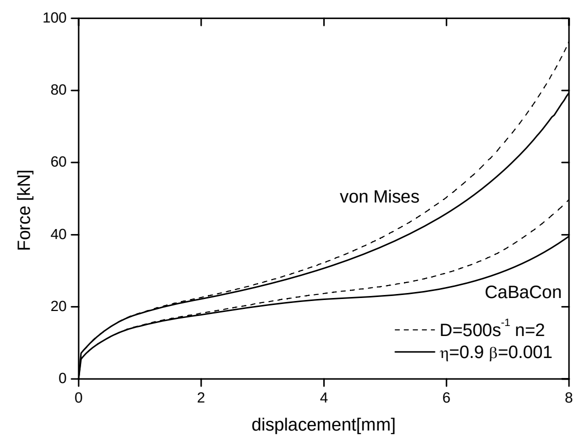

Fig. 2. Softening due to adiabatic heating

3.2 Simulations of extrusion trials

Adaptive meshing with Arbitrary Lagrangian-Eulerian (ALE) option [2] is recommended to be used in metal forming simulation where large strains evolve. ALE adaptive meshing provides control of mesh distortion without altering the topology, i.e. elements and connectivity. ALE adaptive meshing uses a single mesh definition that is gradually smoothed within the analysis steps. Fig. 3 shows the simulations of extrusion trials without ALE adaptive meshing leading to the penetration of billet material into the die considered as rigid body and highly distortion of elements, as well.

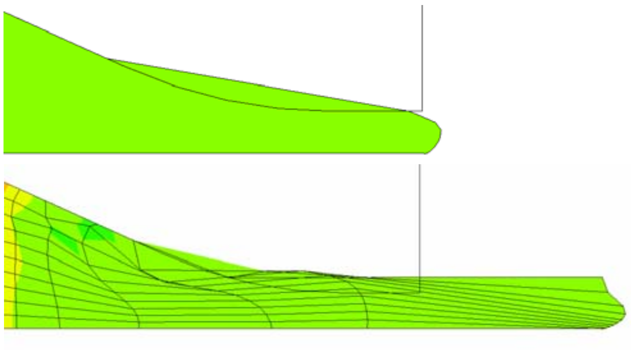

Fig. 3. Simulation results of extrusion trials without ALE

The simulations of extrusion trials were performed by VUMAT with a ram speed of 70 mm/s at 300°C. The billet material with an initial diameter of 90 mm was extruded via forward extrusion with an extrusion ratio of 28 to obtain a final diameter of 17 mm. Due to the symmetry, the billet was meshed with axisymmetric continuum elements, CAX4R. The material used as a billet was assigned as the same material used in the previous section except of the fact that rate-dependent model constants were chosen arbitrarily, i.e. D=1000s^{-1} and n=3. Simulation results with these input provide the strain rate and temperature distributions as seen in Fig. 4.

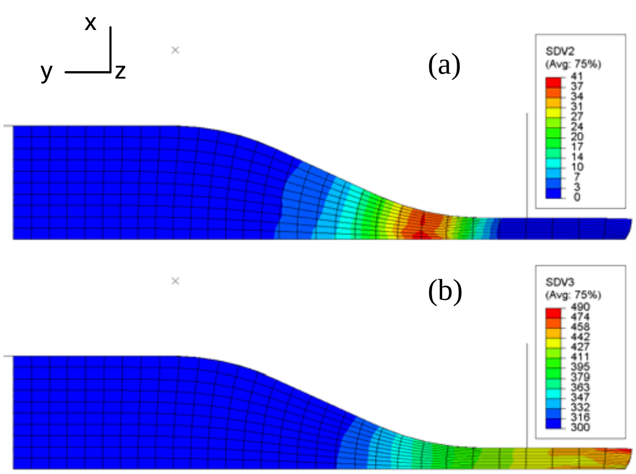

Fig. 4. Simulation results of extrusion trials: strain rate (a) and temperature (b) distributions

4 CONCLUSIONS

The developed user defined routine (VUMAT) of the modified Cazacu & Barlat model with respect to strain rate and temperature dependency on deformation for the general purpose finite element code ABAQUS/Explicit has been verified and validated for single element simulations.

Simulations of upsetting tests will be performed to fit the model parameters by comparing with the corresponding experimental results and then used as input data for simulations of indirect extrusion processes. A better understanding of experimental extrusion trials of magnesium alloys with different billet temperature and extrusion speed is aimed at.

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