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MATERIALS MODELS OF Mg ALLOYS FOR BIOMEDICAL APPLICATION

Magnesium alloys are more often used in aerospace, automotive, electronics etc. industries. These alloys are formed similarly to other metals, using processes of rolling, forging, extrusion, stamping and many other technological processes applicable at elevated temperatures [1–4]. Performed studies in [5–8] have shown that by certain improvement of the chemical composition (usually adding a small amount of Ca, Li), magnesium alloys achieve a high level of biocompatibility with the human body and dissolve in the body without significant medical problems. Several new magnesium alloys for biomedical applications (such as MgCa, LAE442, MgCa0.8) were developed at the University of Hanover [5, 9]. Production of surgical threads to integration of tissue can be an example of application of these types of alloys. These applications requires fine wires with diameters from 0,1 mm to 0,9 mm. Due to poor formability and limited ductility of magnesium alloys in room temperature, drawing process to dimension 0,1 mm is difficult.

In Bach et al.'s work [10] a new manufacturing technology of tubes made of Mg alloys is proposed. In this technology the metal is heated by a hot die and the process of warm deformation is performed. The theoretical description of the wire drawing process with a heated die is presented in [11, 12].

The model of material ductility is a very important element of the FE program for simulation of drawing. Availability of this model enables optimization of the process of wire drawing on the basis of the FE simulations. Fracture problems for magnesium alloys are precisely described in literature [12–14]. However, these works for only few parameters of drawing, such as the die angle and the reduction ratio. The ductility models of Mg-Ca alloys are scarse in the literature. The yield stress models of the latter alloy for warm deformation are not available in the literature, either.

The goal of this paper is the development yield stress model and ductility function for MgCa0.8, ZEK100 and Ax30 magnesium alloys, implementation of these models into the FE code and simulations of warm wire drawing processes.

Ductility model

The key parameter, which presents fracture, was named ductility function. This parameter is determined by the following formula:

$$\psi = \frac{\varepsilon_i}{\varepsilon_p(k,t,\xi_i)} < 1, \qquad (1)$$

where k – triaxility factor, $k = \sigma_0 / \sigma_s$; t – temperature; ξ_i – strain intensity.

Critical deformation function $\varepsilon_p(k,t,\xi_i)$ is obtained and is based on experimental studies. In the Drawing2d FEM code equation (1) was implemented as a following integral:

$$\psi = \int_0^{\tau} \frac{\xi_i}{\varepsilon_p(k,t,\xi_i)} d\tau \approx \sum_{m=1}^{m=m_\tau} \frac{\xi_i^{(m)}}{\varepsilon_p(k,t,\xi_i)} \Delta\tau^{(m)}, \qquad (2)$$

where τ – time of deformation; $\Delta\tau^{(m)}$ – current time increment, $\xi_i^{(m)}$ – values of the strain rate in the current time; m – index number of time step during numerical integration along the flow line.

Critical deformation function $\varepsilon_p(k, t, \xi_i)$ can be obtain on the basis of experimental results for the upsetting and tension tests at different values of k, t, ξ_i.

Yield stress model

Yield stress model σ_s for analyzed alloys was proposed as a modified Hansel-Spittel equation:

$$\sigma_s = A\exp(-m_1 t)\varepsilon_i^{m_2}\xi_i^{m_3\left(\frac{t-20}{280}\right)^{m_6}}\exp\left(\frac{m_4}{\varepsilon_i}\right)(1+\varepsilon_i)^{m_5 t}\exp(m_7\varepsilon_i)\xi_i^{m_8 t}t^{m_9}, \qquad (3)$$

where A, m_1-m_9 – empirical coefficients.

Experiment shows that σ_s is independent of the strain rate in low temperature (below 200 °C), consequently, the expression $\left(\frac{t-20}{280}\right)^{m_6}$ was added to equation (3).

Experimental studies

Magnesium alloys as MgCa0.8, ZEK110 and Ax30 were used as a testing materials. Upsetting tests were used to determine the flow stress model. Both upsetting and tensile tests were used to calculate coefficients of critical deformation function. The material tests were performed in a Zwick Z250 testing machine at the AGH University of Science and Technology in Krakow, Poland. Results and conditions of all the tests for MgCa0.8 and ZEK100 magnesium alloys are presented in work [15]. The range of temperature and strain rate changes in the experiments were selected in accordance with the conditions for the deformation of metal during wire drawing in the heated dies.

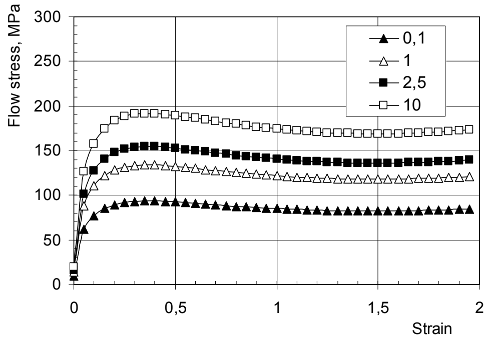
The coefficients in equation (3) were determined using the inverse approach [16] with the least squares method. The objective function was formulated as the root-mean-square difference between experimental and predicted loads. A relative error in the objective function for MgCa0.8 alloy was 0.055. The values of coefficients of equation (3) are presented in table 1. Results of inverse analysis (stress – strain curve) for MgCa0.8 magnesium alloy are shown in fig. 1.

Table 1

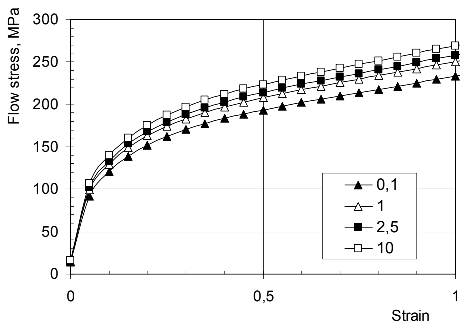
Coefficients of yield stress equation (3)

	A	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9
MgCa0.8	447,4	0,0007542	0,4485	0,2867	-0,0001899	-0,009392	2	0,8318	-0,0004359	0,007962
ZEK100	656,5	0,001210	0,4445	0,05207	-0,0006153	-0,009350	2	0,5107	0,0002455	0,01805
Ax30	177,7	0,0038137	0,4308	0,0600	-0,0048309	-0,0096126	6,6635	0,55048	0,00049796	0,3698

Stress strain curve for temperature 300 °C and 200 °C and strain rate 0,1, 1,0, 2,5 and 10 s^{-1} are presented in fig 1. In fig. 2 and 3 shows microstructure of the MgCa0.8 alloy before (fig. 2, a and fig. 3, a) and after (fig. 2, b and fig. 3, b) tensile test for tool velocity during test 60 mm/min and temperature 300 °C (fig. 2) and 200 °C (fig. 3). Decrease in flow stress fig. 1, a is caused by recrystallization of the material during test what is shown in fig. 2, b. It's mean that for multi pass drawing process which is needed to obtain small wire diameter as 0,1 mm annealing in not necessary because microstructure after each pass is backing to initial state.



a



b

Fig. 1. Stress strain curves of MgCa0.8 magnesium alloy for temperatures:
a – 300 °C; b – 200 °C, strain rate 0,1, 1,0, 2,5 and 10 s^{-1}

a b

Fig. 2. Microstructure of MgCa0.8 for temperature 300 °C and tool velocity 60 mm/min correspond to fig. 3, a:

a – before tensile test; b – after tensile test

a b

Fig. 3. Microstructure of MgCa0.8 for temperature 200 °C and tool velocity 60 mm/min correspond to fig. 3, b:

a – before tensile test; b – after tensile test

Critical deformation function

Data in work [15] shows that critical deformation is dependent on the temperature, strain rate and value of *k* coefficient (in upsetting tests critical deformation is higher, than in tensile tests). Due to this fact the following relationship is proposed as a function of strain limit:

$$\varepsilon_p = d_1 \exp\left(-d_2 k\right) \exp\left(d_3 t\right) \xi_i^{d_4} , \tag{4}$$

where $d_1 - d_4$ – empirical coefficients.

The following algorithm is proposed to calculate parameters of equation (4):

1. Using Forge software the numerical simulations of all experimental tests have been performed. Flow stress model was implemented in the form of equation (3) and the coefficients from table 1 were adopted.

2. Performed numerical modeling of all tests (upsetting and tensile) to determine changes in temperature, strain rate and *k* coefficient from the beginning of the test until the material cracking in the experiment.

3. Basing on the analysis of samples, the location of crack initiation was found. For upsetting tests it was observed that crack nucleation takes place in a corner of the sample, while the tensile cracking begins in the axis of the sample. Reading of the process data from FEM models of tests was done in these points, which correspond to the location of the formation of the material crack.

4. The sets of parameter *k*, strain rate and temperature of the tensile and compression tests were used to develop coefficients $d_1 - d_4$ of the function (4). Coefficients were calculated using the least squares method. Change of ψ was described by equation (1). The sum of squares of difference between ψ_m^{calc} and 1,0 for strain, which corresponds to the crack observed in the experiment, was used as a goal function for the current test:

$$\delta = \sum_{m}^{m_{test}} \left(\psi_m^{calc} - 1\right)^2 . \tag{5}$$

The following values of coefficients of equation (4) for MgCa0.8 and ZEK100 magnesium alloy were obtained:

MgCa0.8: $d_1 = 0{,}01531$; $d_2 = 0{,}1288$; $d_3 = 0{,}01576$; $d_4 = -0{,}2354$.

ZEK100: $d_1 = 0{,}05503$; $d_2 = 0{,}1388$; $d_3 = 0{,}01036$; $d_4 = -0{,}1216$.

A relative error in the objective function was 0,04 (MgCa0.8) and 0,025 (ZEK100).

Analysis of the drawing process

Developed models of the flow stress (3) and the ductility (1) were implemented into the Drawing 2d [17] software. For the analysis of damage of the material three variants of drawing process were analyzed. General data given for all 3 variants (common data) are: coefficient of heat exchange with the environment 4000 W/m^{2}C; die temperature t_c = 350 °C, the temperature of the wire at the entrance to the valley of strain t_0 = 100 °C; initial wire diameter d_0 = 0,5 mm, drawing angle α = 4 °; length of the calibration part of die L_2 = 0,1 mm; radius of the transition from the conical part of the calibration r = 0,05 mm, coefficient of friction f = 0.03; drawing angle α = 4 °.

The following numerical analyses were performed:

Variant 1. Final diameter d_1 = 0,38 mm; v = 0,05 m/s;

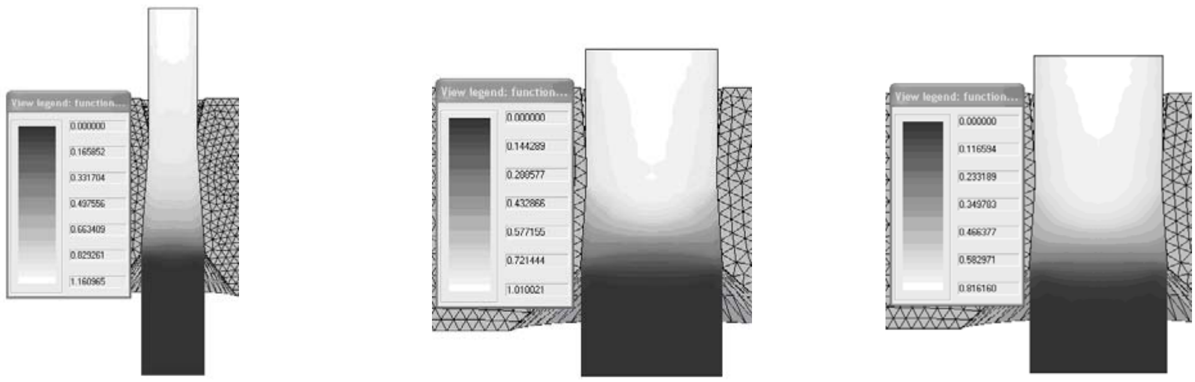
Variant 2. Final diameter d_1 = 0,46 mm; v = 0,05 m/s;

Variant 3. Final diameter d_1 = 0,46 mm; v = 0,02 m/s.

The simulation results are shown in fig. 4. Variant 1 corresponds to the elongation factor 1,73. The experimental knowledge based on drawing of Mg alloys shows that with such a large elongation factor, a break of the wire should be observed. The analysis of strain distribution makes it possible to assert that the deformation is localized in the place of the application of force of wire drawing. This indicates the break of wire at the output from the zone of deformation. Parameter ψ takes the maximum value (ψ_{max} = 1,16) in the same place, which means that the ductility function allows to predict not only the fracture in the deformation zone, but also outside of the die (fig. 4, a).

The second variant of the simulations was performed for a smaller elongation factor (1,18). In this case also fracture in drawn wire is predicted (ψ_{max} = 1,01), but the location of ψ_{max} is in the axis of drawn wire in the deformation zone.

In the third version of simulation the speed of wire drawing was lowered. This led to an increase in the temperature of metal and consequently, the amount of critical deformation. As a result ψ_{max} = 0,86 and the fracture of metal did not occur (fig. 4, c).



a b c

Fig. 4. Results of simulation distribution of ψ parameters for simulations variant: 1 – (a); variant 2 – (b); variant 3 – (c)

CONCLUSIONS

1. Ductility of MgCa0.8 and ZEK100 magnesium alloys is strongly dependent on temperature and strain rate.

2. Analysis of microstructure of MgCa0.8 shows that in temperature about 300 °C dynamic grain recrystallization is occurring during tensile stress.

3. Experimental – theoretical methodology to calculate the parameters of empirical yield stress for MgCa0.8, ZEK100 and Ax30 and ductility models of MgCa0.8 and ZEK100 were developed.

4. The FE simulations show examples of possible mechanisms of material fracture during drawing: break of the wire at the exit from the zone of deformation and exhaustion of the plasticity of the material deformation in the zone of deformation.

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