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MULTI SCALE MODELING AND INTERPRETATION OF TENSILE TEST OF MAGNESIUM ALLOYS IN MICROCHAMBER FOR THE SEM

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Abstract

In the presented paper magnesium alloys wire drawing process for medicine application is investigated. The magnesium alloys has a low plasticity at room temperature and cold drawing process is difficult. That way, predicting of wire fracture is very important from theoretical and technological point of view. Analyzing of tensile test of magnesium alloys in micro and macro scale using results from 10000N Tensile/Compression Stage for the SEM, allow understanding a numerical model of fracture phenomena.

The purpose of paper is to develop a mathematical models of flow stress and damage phenomena for magnesium alloys and implementation those models to FEM code.

Key words: drawing process, magnesium alloy, fracture, inverse method

1. INTRODUCTION

The magnesium alloys are often use in medicine because of high compatibility with human organism [1-2]. Corrosion research in environment for those types of specific magnesium alloys shows that there is possibility to use it for solubility implants. This kind of application calls for fine wires with diameter from 0,1 mm to 2 mm. The drawing process of magnesium alloys is difficult because of low formability and limited ductility of magnesium alloys at room temperature [3-5] ascribed to their hexagonal close-packet (HCP) crystal structure with limited number of sleep system. On the other hand, the experimental optimization of wire drawing process allowed to make opportunity of increase the technological plasticity of those alloys [6,7] during drawing on 20-30%. One of the most problems at development of cold deformation technology of magnesium alloy is a theoretical prognosis of fracture.

Prediction wire of fracture phenomena during drawing process allows to obtain at means of FEM simulation a draft plan to get required wire diameter and to optimize of drawing parameters.

Magnesium alloys for biomedical applications have different mechanism of fracture. That why, before development of fracture model, the fracture mechanism analysis is necessary. The investigation and modeling of mechanisms of fracture (by the grounds boundary or by grains) need to calculate a fracture model parameters in micro and macro scales. In this work the experimental investigation in 10000N Tensile/Compression Stage by "Kammrath & Weiss GmbH" for the SEM of AZ80 and CaMg08 magnesium alloys unixaxial deformation was done. The aims of this test are:

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1. Experimental analysis of fracture mechanism for specific magnesium alloys (AZ80 and CaMg08) for biomedical application.
2. Determinate of mechanical properties and parameters of fracture model in macro - scale by inverse analysis of tensile tests.
3. Numerical modeling of fracture phenomena during tests in macro and micro scale.
4. Implementation of macro models of flow stress and fracture phenomena into FEM code for drawing process simulation.

2. EXPERIMENTS

The objective of the experiment was supplying the data for inverse analysis of flow stress model in macro scale and fracture models in micro and macro scales. This experiment was made for two kind of specific magnesium alloys: AZ80 and CaMg08. The shape of sample is shown on figure 1a.

The analysis of fracture phenomena during cold tensile test was done in micro and macro scale using testing machine 10000N Tensile/Compression Stage for the SEM (show in figure 1a). Experiment in chamber of SEM allows to understand the fracture mechanism in special magnesium alloys and to determine the empiric coefficients of yield stress and fracture models.

In the chamber of SEM the material was stretch with 100 μm tool displacement and then tool were stopped. Scaning electron microscope was used to made photo in macro scale (as in figure.1b, c) and in micro scale with zoom 500x and 1000x (as in figure 2 and figure 3). This process was repeat until the moment when fracture was appeared. Results of tensile test for both magnesium alloys in macro scale are shown in figure 1b and figure 1c. During tensile test the stretching force and displacement of tools were measured. Those data allow constructing diagram force dependence on tool displacement. This diagram is shown in figure 1d. Both materials cracked by different tool displacement – AZ80 after 1.423 mm and CaMg08 after 1.490 mm.

Fracture mechanism in micro scale is shown in figure 2 for CaMg08 and in figure 3 for AZ80. For the magnesium alloy CaMg08 the centers of fracture are localized on the grain boundaries, figure 2b. In case of AZ80 magnesium alloy, the fracture mechanism has a mixed type - the fracture accured in grains and, partially, in boundaries. Probably, at AZ80 there are two mechanism of fracture phenomena, – intercrystal fracture and transcrystal fracture, figure 3b.

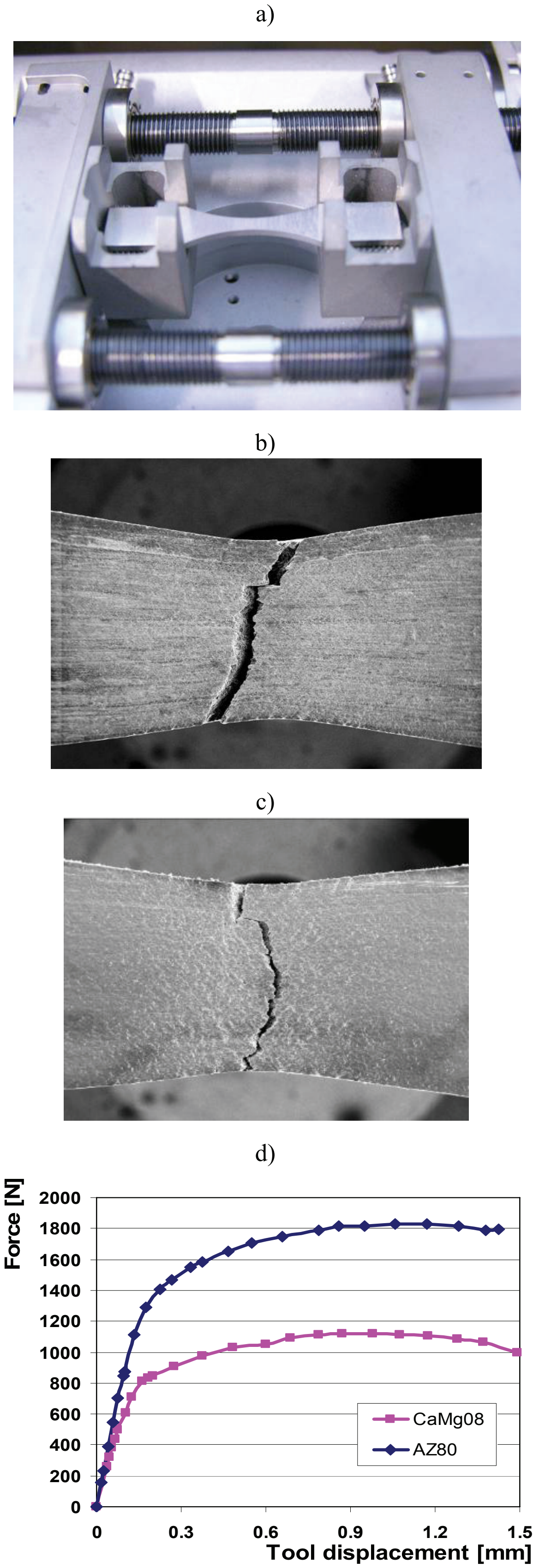


Fig. 1. Experimental research: a) testing machine – tensile/compression stage and sample; b) example of fracture in macro scale for AZ80 alloy, x20; c) example of fracture in macro scale for CaMg08 alloy, x20; d) diagram force - displacement for CaMg08 and AZ80.

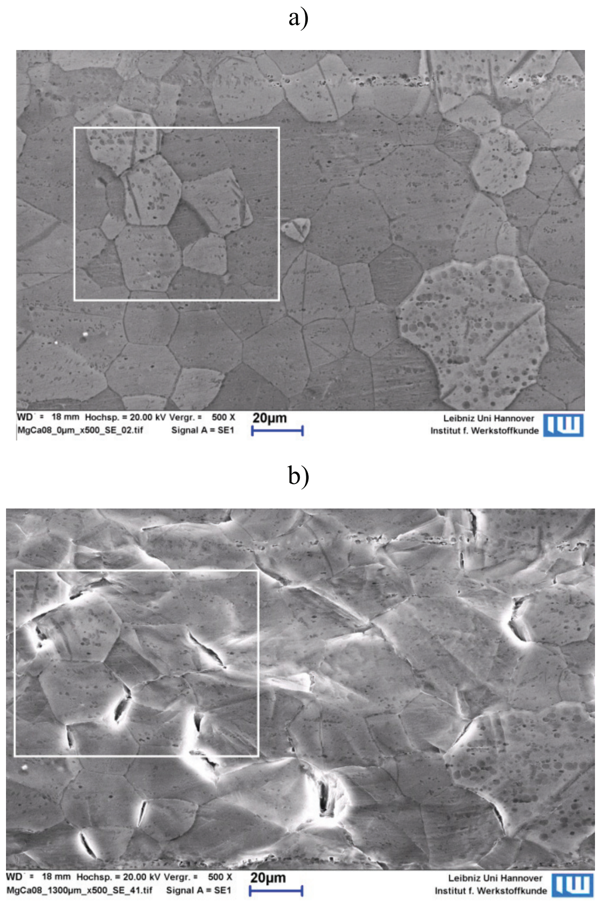


Fig. 2. *Fracture mechanism in micro scale for CaMg08; a) before tensile test, b) during tensile test (tool displacement is 1.2 mm), the rectangles are selected area of RVE.*

3. FRACTURE MODEL

Modeling of fracture phenomena in macro scale was done witch following equation [8]:

$$\psi = \frac{\varepsilon_i}{\varepsilon_p(k)} < 1 \tag{1}$$

where ψ – the resource of plasticity; ε_i – the intensity of deformation in metal working processes; ε_p – the critical deformation before fracture of metal as function of triaxity factor $k = \frac{\sigma}{\sigma_s}$; σ – mean stress.

If the resource of plasticity ψ is equal 1.0, the material will experience fracture. The function $\varepsilon_p(k)$ is obtained through experiments. In this work the following form for this function is used:

$$\varepsilon_p(k) = [d_1 \exp(-k)], \tag{2}$$

where: d_1 is a empirical parameter.

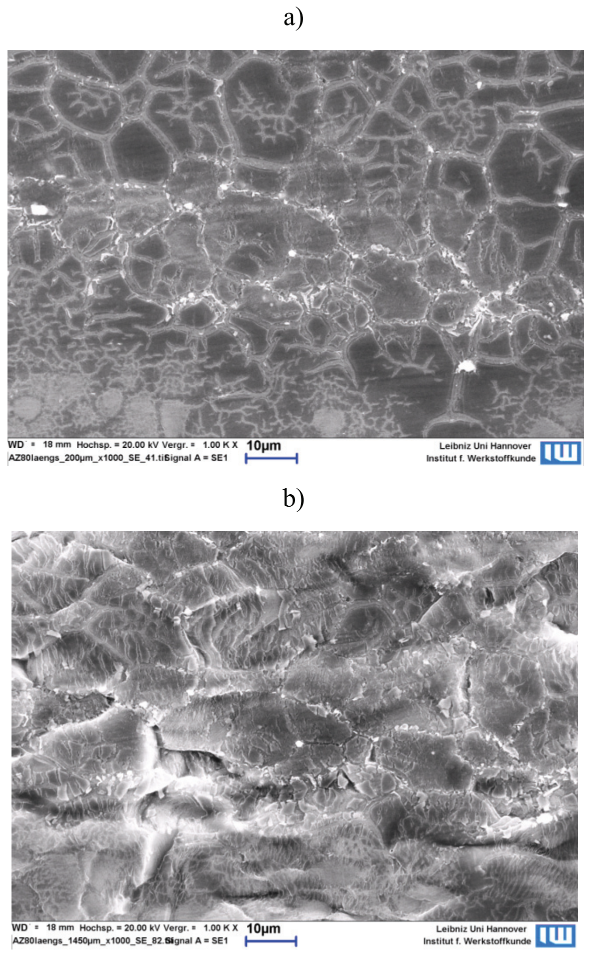


Fig. 3. *Fracture mechanism in micro scale for AZ80; a) before tensile test, b) before breakage (tool displacement is 1.423 mm).*

If the deformation process is multi – step, then equation (1) is describe by the integral:

$$\psi = \int_0^{\tau} \frac{\xi_i}{\varepsilon_p(k(\tau))} d\tau < 1, \tag{3}$$

where ξ_i – the strain rate; τ – the time of deformation.

The FEM code Drawing2d [9] and ABAQUS [10] program uses integration procedure to evaluate the above integral. This results in:

$$\psi = \sum_{m=1}^{m=m_\tau} \frac{\xi_i^{(m)}}{\varepsilon_p(k(\tau))} \Delta\tau^{(m)}, \tag{4}$$

where: $\Delta\tau^{(m)}$ – the current time increment, $\xi_i^{(m)}$ – the values of the strain rate in the current time, m – is a index number of time step during numerical integration.

4. NUMERICAL MODEL OF TENSILE TEST AND FRACTURE PHENOMENA IN MACRO SCALE

The numerical model of tensile test was design in ABAQUS software, on figure 4,a the mesh of FEM model of sample is present. The follow equation was use for flow stress approximation:

$$\sigma_p = a\varepsilon^n , \tag{5}$$

where: σ_p – yield stress, a – equation parameter, ε - strain, n – hardening coefficient.

According method of inverse analyze [11] for determination of reological parameters the cost function is use in the follow form:

$$\phi = \sqrt{\frac{1}{N_s}\sum_{i=1}^{N_s}\left(\frac{F_{im}-F_{ic}}{F_{im}}\right)}, \tag{6}$$

where F_{im} and F_{ic} is measured and calculated load, respectively.

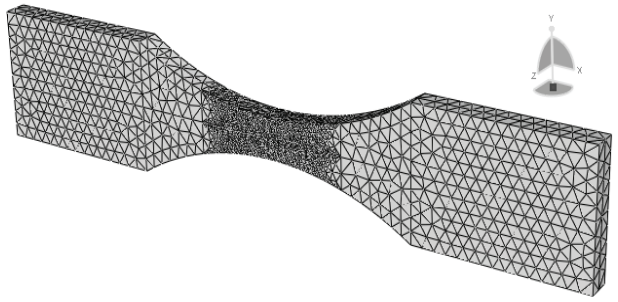


***Fig. 4.** Mesh of numerical FEM model of tensile test in macro scale.*

The results of inverse analysis are shown in figure 5. The follow equations for reologycal properties was obtained by inverse analyses:

$$\sigma_p = 440\varepsilon^{0.12} \tag{7}$$

for AZ80 and

$$\sigma_p = 230\varepsilon^{0.08} \tag{8}$$

for CaMg08 magnesium alloy.

Coefficient in the damage model was determined next. The example of calculated stress-strain parameters evolution during the test in center point of sample is shown on figure. 6 for AZ80 alloy. In moment of crack the follow parameters in this point of sample are obtain: $k = \frac{p}{q} = 0.35713$, $\varepsilon_p = 0.2347$. The empirical coefficient d_1 of equation (2) were determined by processing of ε_p and k in moment of crack for AZ80 and CaMg08 alloys. The follow functions $\varepsilon_p(k)$ is obtained:

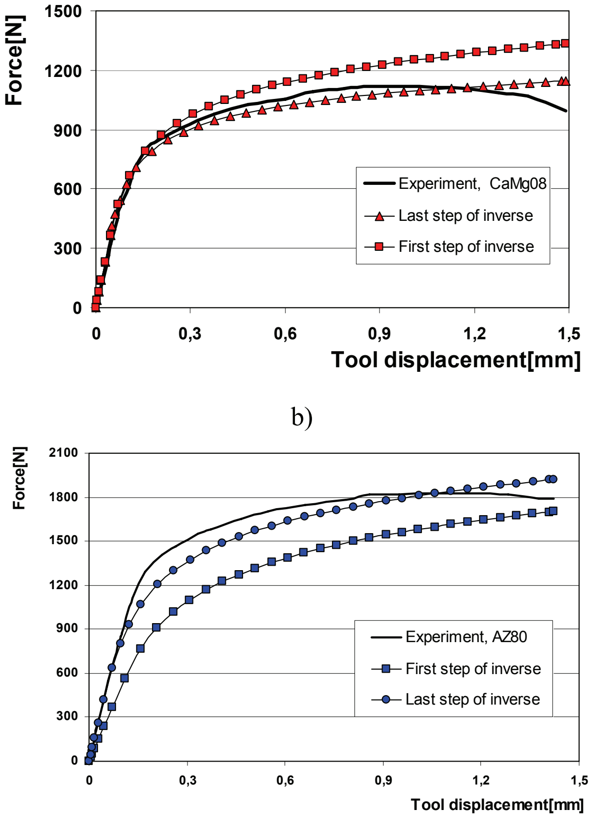
$$\varepsilon_p = 0.334\exp(-k) \tag{9}$$

for AZ80 and

$$\varepsilon_p = 0.306\exp(-k) \tag{10}$$

for CaMg08.

a)



b)

***Fig. 5.** Results of inverse analysis, force dependence on tool displacement; a) for CaMg08 alloy, b) for AZ80 alloy.*

The reological properties and functions $\varepsilon_p(k)$ are shown in figure. 7. Distribution of stress-strain parameters and recourse of plasticity in longitudinal dimension of sample are shown in figure. 8.

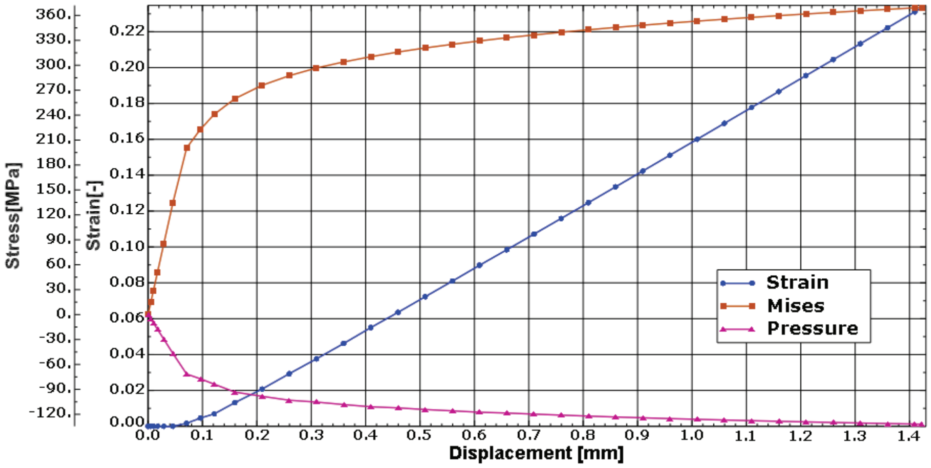


Fig. 6. *Results of numerical analysis of tensile test. Value of pressure, strain and stress in center of sample neck during tensile process of AZ80 magnesium alloy.*

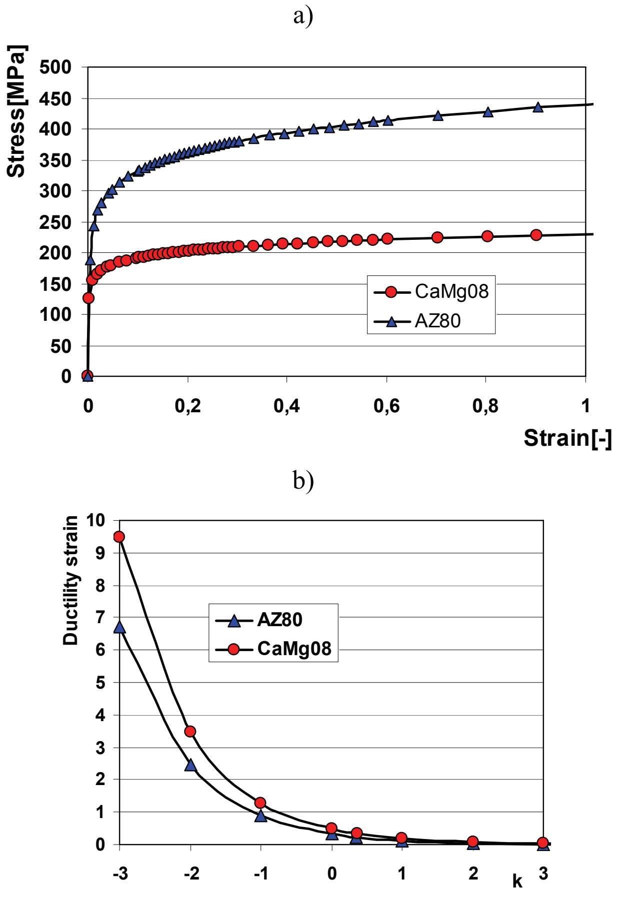


Fig. 7. *Flow stress curve (a) and ductility strain dependence on coefficient k (b) for CaMg08 and AZ80 alloys.*

5. NUMERICAL SIMULATION OF FRACTURE IN MICRO SCALE

In experimental investigation of damage in micro scale the different mechanism of damage for AZ80 and CaMg08 was shown. For AZ80 damage process to fulfill in grains and application of macro scale damage model (1)-(4) is well-heeled. For CaMg08 damage process to fulfill only in boundary of grains and for verification of macro model of damage in this case the micro model of damage is needed. Using ABAQUS system the numerical model of tensile test in micro chamber was obtain. The RVE (representative volume element) for CaMg08 is shown on figure.2,a (before test) and on figure.2,b (before damage). The geometrical model of RVE is shown on figure.9,a and the FEM mesh for RVE is shown on figure. 9,b. The boundary condition of RVE model (deformation in longitudinal direction) was transfer from macro model of test. The yield stress model (8) was used for grain. The model of fraction in micro scale was used only for inter grain material (boundary). The follow model for CaMg08 was proposed:

$$\varepsilon_p = K_{grad}\, 0.306 \exp(-k), \qquad (11)$$

where K_{grad} is empirical coefficient for take into account the gradient of deformation in RVE. For CaMg08 value of K_{grad} was

$$K_{grad} = \frac{\varepsilon_{\max micro}}{\varepsilon_{\max macro}} = 1.144\,. \qquad (12)$$

Results of numerical analysis is shown in figure 9,b,c,d.

The moment of damage in RVE is corresponded with moment of damage in experiment. The agreement between prognosis by macro scale damage model and micro scale fracture model is reasonably good.

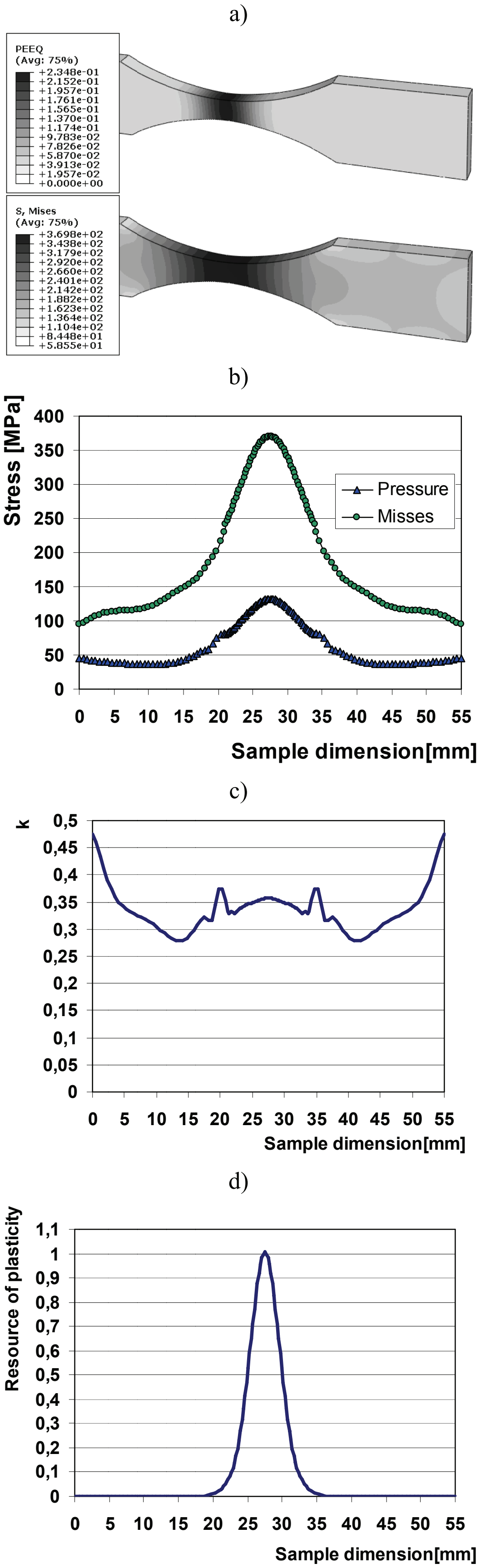


Fig. 8. *Results of numerical tensile test simulation for AZ80 alloy: a) distribution of strain intensity and Mises stress in last moment before damage; b) pressure dependent on sample dimension; c) parameter k dependence on sample dimension; d) resource of plasticity dependence on sample dimension.*

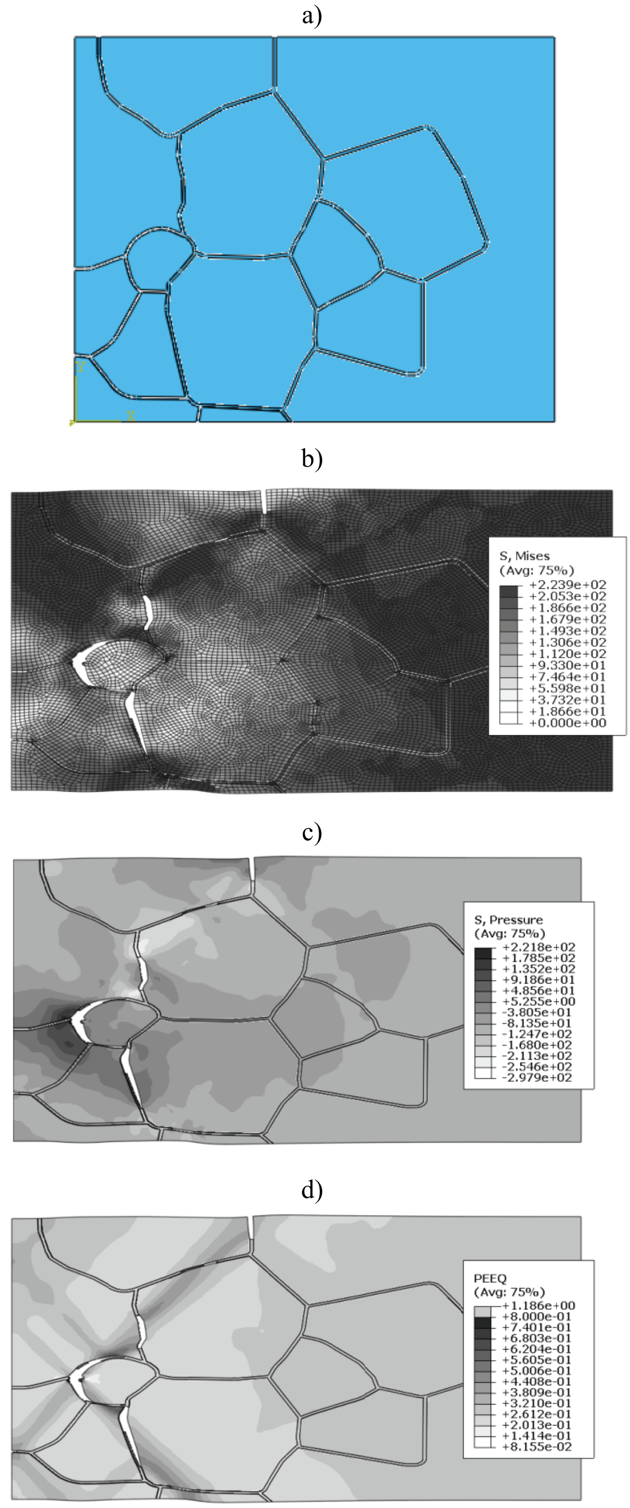


Fig. 9. *Results of RVE modeling in final step of test before damage: a) graphic model of RVE for CaMg08 magnesium alloy structure from figure 2,a; b) Misses stress distribution; c) main stress distribution; d) effective strain distribution.*

6. DRAWING PROCESS SIMULATION IN MACRO SCALE

The models of yield stress and functions of critical deformation were implementing to Drawing2d software [9]. Drawing process was simulate for initial wire diameter 2 mm and final diameter of wire

1.8 mm. Process was done in room temperature with friction coefficient 0.03. Two drawing angle were used – 6° and 7°. Calculated distributions of recourse of plasticity for AZ80 alloy are shown in figure 10. It is seen in this figure that, value of maximum of recourse of plasticity for drawing angle 7° is more than for drawing angle 6°. The maximum of recourse of plasticity is localized in surface on wire. After implementation development models to Drawing2d software the optimization procedures for magnesium drawing processes is possible.

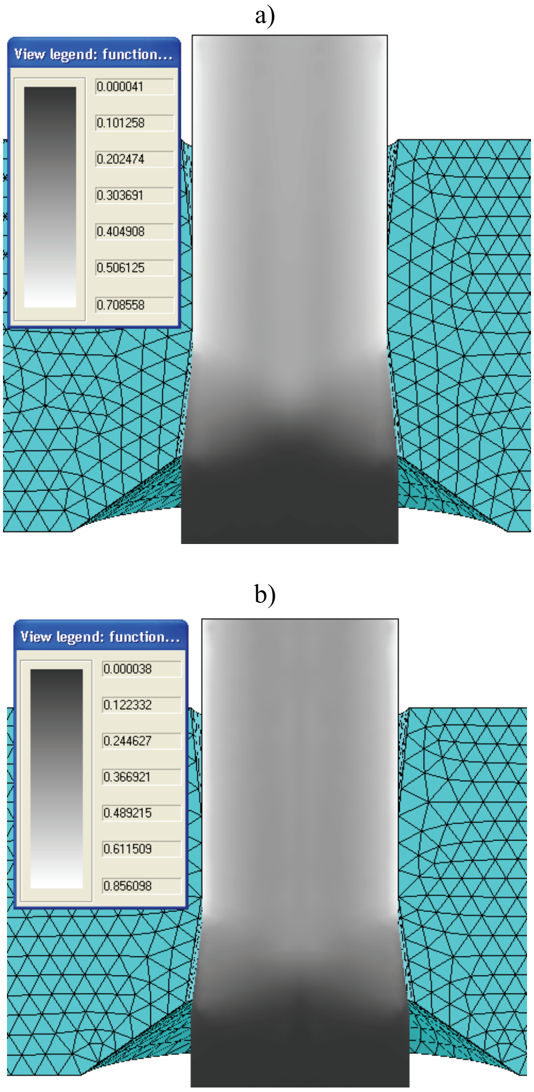


Fig. 10. Distribution of resource of plasticity after drawing process: a) drawing angle 6°, b) drawing angle 7°.

7. CONCLUSIONS

1. In experimental investigation of fracture in micro scale the different fracture mechanisms for AZ80 and CaMg08 alloys was shown. For AZ80 damage process accured in grains. For CaMg08 fracture accured only at boundary of grains and for verification of macro model of damage in this case the micro model of damage is need.
2. The flow stress and fracture models in macro scale were obtain by inverse method.
3. The micro scale model of fracture process was suggested for CaMg08 alloy. The accordance between prognosis by macro scale fracture model and micro scale fracture model is reasonably good.
4. The elaborated models in macro scale were implemented to Drawing2d software and examples of simulations are shown.

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WIELOSKALOWE MODELOWANIE ORAZ INTERPRETACJA PRÓBY ROZCIĄGANIA W MIKROKOMORZE DLA SEM STOPÓW MAGNEZU

Streszczenie

W niniejszym artykule rozpatrzono proces ciągnienia stopów magnezu dla zastosowań w chirurgii. Stopy magnezu mają niską plastyczność w temperaturze pokojowej dlatego proces ciągnienia na zimno jest trudny, a nawet praktycznie niemożliwy. Dlatego przewidywanie procesu pękania jest istotne z technologicznego i praktycznego punktu widzenia. Analiza próby rozciągania w mikrokomorze "10000N Tensile/Compression Stage for the SEM" w skali makro oraz skali mikro, pozwoliła na zrozumienie procesu pękania tych stopów. Celem niniejszej pracy jest opracowanie krzywych płynięcia oraz modelu matematycznego procesu pękania rozpatrywanych stopów magnezu oraz implementacja tych modeli do kodu metody elementów skończonych.

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