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THE MULTI-SCALE NUMERICAL AND EXPERIMENTAL ANALYSIS OF COLD WIRE DRAWING FOR HARDLY DEFORMABLE BIOCOMPATIBLE MAGNESIUM ALLOY

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Abstract

The problem of determination the drawing schedule of the cold drawing of thin (less than 0.1 mm) wire from the hardly deformable magnesium alloy Ax30 with the aid of the multi-scale mathematical model is examined in the paper. The special feature of the alloy Ax30 is the mechanism of fracture on the grain boundaries. It is experimentally proven that the microscopic cracks during the tension tests occurs long before the complete fracture of samples. The state of metal, which directly precedes the appearance of these microscopic cracks, is proposed to consider it as optimum from the point of view of the restoration of plasticity with the aid of the annealing. The simulation of this state in the wire drawing process and development on this basis regimes of wire drawing is the purpose of paper. Solution of problem required the development of the fracture model of alloy in the micro scale, identification of the fracture model and its implementation into the FEM model of wire drawing. Two schedules of wire drawing are examined. The first of them is according to the results of simulation allowed the appearance of microscopic cracks. The second regime was designed so that the microscopic cracks would not appear during wire drawing. Experimental verification is executed in laboratory conditions on the specially developed device. The annealing was carried out before each passage. The initial diameter of billet was 0.1 mm. In the first regime it was possible to realize only 2-3 passages, after which the fracture of wire occurred. The cracks on the grain boundaries were observed in this case on the surface of wire. The second regime made it possible to carry out 7 passages without the fracture, the obtained wire with a diameter of 0.075 mm did not contain surface defects, it had high plastic characteristics and allowed further wire drawing. Thus, the validation of the developed multi-scale model is executed for two principally different conditions of deformation.

Key words: drawing process, multi-scale modeling, magnesium alloys

1. INTRODUCTION

This paper is devoted to the new magnesium alloys used in medicine as a soluble implants (Heublein et al., 1999; Haferkamp et al., 2001; Thomann et al., 2009). Typically, these alloys contain lithium and calcium supplements. The production of thin surgical threads to stitching tissues may be an example of application of these alloys (Seitz et al. 2011; Milenin et al, 2010b). Feature of these alloys is a low technological ductility during cold forming. As shown in the previous works (Kustra et al., 2009; Milenin et al., 2010a), a technological ductility of these alloys during cyclic processes based on a combination of a cold deformation and annealing is significantly lower than for most known magnesium alloys. The reasons of this fact are explained in the (Milenin et al., 2011) that there are fractures on the grain boundaries long before the fracture of the sample in the macro-scale in these alloys during cold deformation. These microcracks considerably make worse the restoration of plasticity using annealing.

Solution of the problem is proposed in the works (Milenin et al., 2010b; Milenin & Kustra, 2010). It is

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based on drawing by a hot die. Studies show that this method is effective for more than 0.1 mm wire diameter. Obtainment a thin wire is difficult because of the strong sensitivity to the velocity of drawing process. Another disadvantage is that the biocompatible lubricant cannot be used what becomes to be important in medical application. Thus the solution of listed problems requires in-depth study of cold drawing process for these alloys.

The aim of this work is to determine the parameters of the cold drawing of thin (less than 0.1 mm) wires by using a multi-scale modeling of wire drawing process and experimental verification of the results.

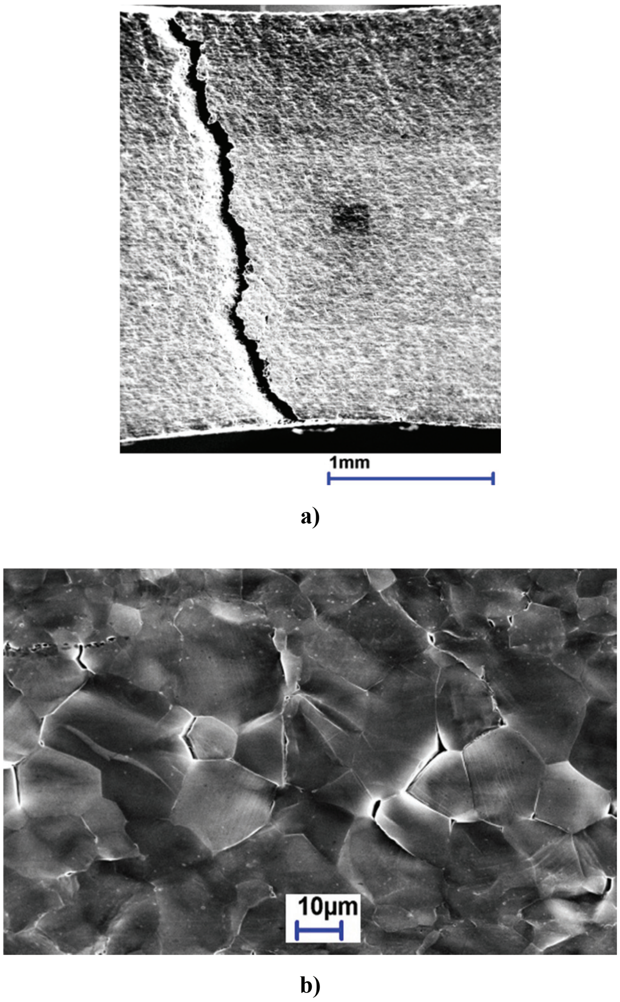
2. MECHANISM OF FRACTURE

The MgCa0.8 (0.8% Ca 99.2%Mg) alloy and its modification Ax30 (0.8%Ca, 3.0%Al, 96.2% Mg) were selected as a material for the study. The technique of research of the fracture mechanism is based on stretching sample in microscope's vacuum chamber. During the process of stretching changes of microstructure and microcracks nucleation are monitoring. The experiment is described in detail in the works (Milenin et al., 2010a; Milenin et al., 2011). The test shown that these alloys crack mainly on grain boundaries. A porosity in sample appears long before the moment of fracture in macro-scale. An example of cracks for alloy Ax30 is shown in figure 1 in macro-scale (figure 1a) and micro-scale (figure 1b).

The porosity values in the stretching sample characterize the technological plasticity during multi-pass drawing. It is proved that if the microcracks do not appear in a current pass, the annealing allows restoring the plasticity (Milenin et al., 2011). Otherwise, the effectiveness of annealing is much reduced and reaching of large deformation in a multi-pass process is impossible.

In figure 2 the values of porosity in a center of sample during tensile test of MgCa0.8 and Ax30 alloys are shown. The values for Az80 alloy, used in mechanical engineering, are also shown for comparison purpose. The figures show that in these alloys microcracks appear much earlier than in the typical magnesium alloy Az80. Thus, the increase of porosity in the early stage of deformation is a fundamental difference between considered alloys and known magnesium alloys.

It follows from this that the development of the drawing technology should be made in such a way that in an every pass the material does not have microcracks. The multi-scale model of wire drawing process was proposed to solve this problem in the works (Milenin et al., 2010a; Milenin et al., 2011). For micro-scale modeling of the fracture processes the boundary element method (BEM) was used, which allows to easily simulate of the fracture of grain boundaries.



a)

b)

Fig. 1. The examples of microcracks during tensile test of Ax30 alloy: a) on the surface of the sample in macro-scale, b) in micro-scale

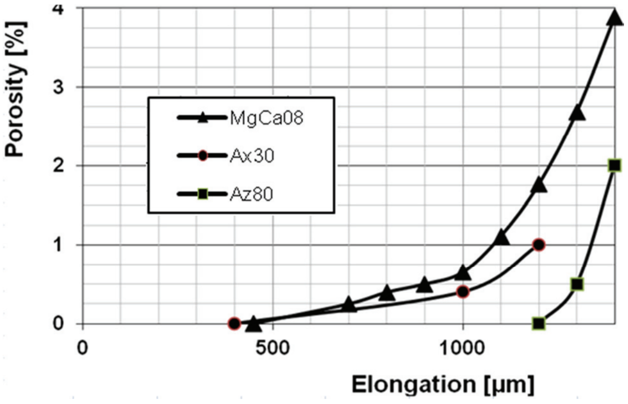
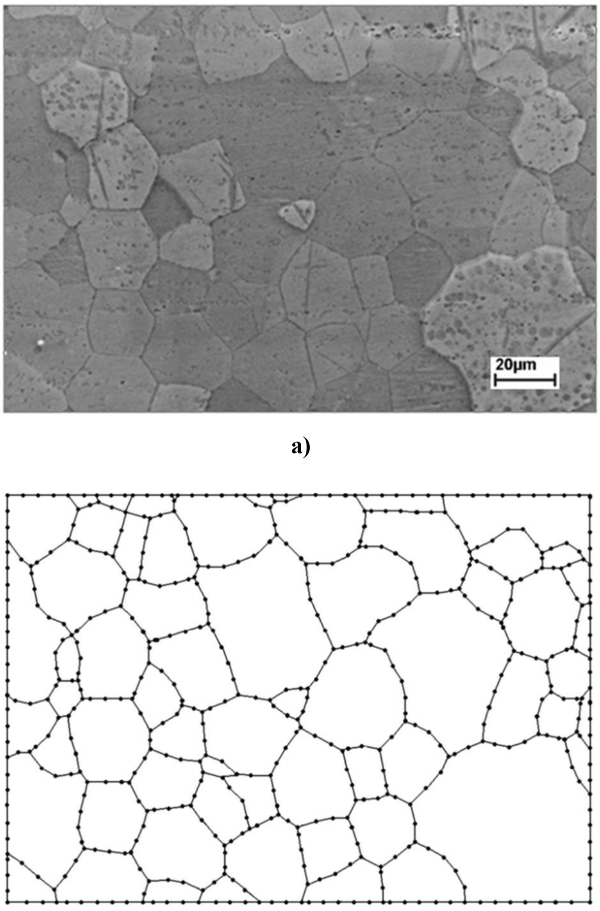


Fig. 2. The porosity dependence on a total sample elongation

3. THE MULTI-SCALE MATHEMATICAL MODEL OF A DRAWING PROCESS

The macro-scale numerical model of drawing process is based on finite element method (FEM) and described in paper (Milenin, 2005). The micro-scale model of deformation is based on boundary element method. The macro-scale and micro-scale models are coupled in a such way that the results of simulation on macro-scale, especially stress and displacements, are the boundary conditions at the micro-scale. At the micro-scale the displacements, strains and stresses on grains boundary are computed, but the most important parameter in micro-scale simulation is the damage parameter D, which is explained below.

The digital representation of the microstructure in a micro-scale model in proposed BEM code is considered as a two-dimensional representative volume element (RVE) which is divided into grains (figure 3). The model at the micro-scale includes the BE mesh generation based on images of a fragment of real microstructure and numerical solution at the micro-scale level.



a)

b)

***Fig. 3.** Photo of microstructure (a) and BE mesh (b)*

The crystallographic orientation is included in the developed program by a random parameter k, which refers to change of elastic-plastic properties due to the various orientations of grains. The effective plastic modulus of the material for each grain is calculated as follows:

$$E_{eff} = k\frac{\bar{\sigma}}{\Delta\bar{\varepsilon}} \tag{1}$$

where: k is the random parameter, $\Delta\bar{\varepsilon}$ – increment of mean equivalent strain in grain; $\bar{\sigma}$ – yield stress of material in grain.

The Saint-Venant-Levy-Mises theory is used for relation between stresses and increments of strains for plastic deformation:

$$\sigma_{ij} = \delta_{ij}\sigma_0 + \frac{2\bar{\sigma}}{3\Delta\bar{\varepsilon}}\Delta\varepsilon_{ij} \tag{2}$$

where δ_{ij} – the Kronecker delta, σ_0 – the mean stress, $\Delta\varepsilon_{ij}$ – the increment of strain components.

The solution of boundary problem is based on the Kelvin's fundamental solution (Crouch & Starfield, 1983) for the two-dimensional tasks and incompressible material. The solution of boundary problem and fracture criteria are described in detail in previous works (Milenin et al., 2010a; Milenin et al., 2011).

The proposed criteria of crack initiation are based on the theory by L. M. Kaczanov and Y. N. Rabotnov (Rabotnov, 1969). This theory was successfully used in (Diard et al., 2002) for modeling of grain boundary cracking in the case of the deformation of the polycrystals. This model was modified to describe the crack initiation at the grain boundary:

$$D = \int_0^{\tau} \dot{D}\,d\tau = 1, \tag{3}$$

$$\dot{D} = b_1\left(\frac{\sigma_{eq}}{E}\right)^{b_2}(1-D)^{b_3}, \tag{4}$$

$$\sigma_{eq} = \sqrt{\sigma_n^2 + b_0\sigma_S^2}, \tag{5}$$

where: D – damage parameter; E – Young modulus; σ_n – tensile (positive) component of normal stress at the boundary between two grains; σ_S – shear stress at the boundary between two grains; b_0-b_3 – empirical coefficients.

According to the equation (3)-(5), the damage parameter is computed at micro-scale for all boundary elements and depends on the material and stress state. The value of parameter D varies from 0 to 1. When the value of parameter D reaches the value 1 for boundary element, the fracture criteria is met.

The crack initiation is allowed only for the internal boundaries in the developed model. The outer boundaries of the domains were assigned to boundary conditions and, in spite of a possible fulfillment of condition, they cannot be destroyed.

The determination of empirical parameter of fracture model at the micro-scale is based on inverse analysis of experimental data. The purpose of this analysis is to minimize the difference between the empirical and calculated moment of crack initiation and the empirical and calculated porosity in micro-scale of sample during deformation (Milenin et al., 2012).

As a result of experimental data processing, which are shown in figure 2, the following coefficients of equations (4) and (5) for alloy Ax30 are received: $b_0 = 0.02$, $b_1 = 0.43$, $b_2 = 0.30$, $b_3 = -0.50$.

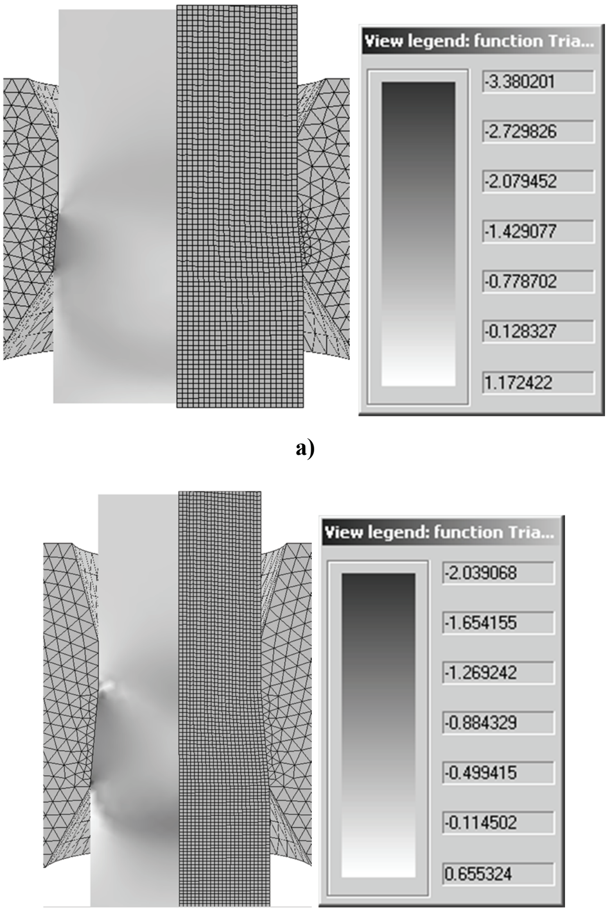
4. THE MULTI-SCALE MODELING OF TWO VARIANTS OF DRAWING PROCESS

For the purpose of proposed technique validation two variants of wire drawing process were simulated.

Diameters of wires in variant 1: 0.1→0.0955→ 0.0912→0.087→0.0831→0.0794→0.0758 (elongation per pass 1.096).

Variant 2: 0.162→0.147→0.135→0.123→0.112 (elongation per pass 1.20).

Angle of die in each pass was 5^0. The drawing speed was 10 mm/s and was chosen in such a way that the annealing could be done in a furnace, which was installed before the device for drawing. All passages in each variants was geometrically similar, so results of stress and strain for all calculated passages are close. For this reason, simulation only first passage for each variant was performed. In figure 4 the results of simulation (triaxility factor) of the first pass for variant 1 (figure 4a) and variant 2 (figure 4b) are shown. The present data shown, that stresses and strains in variants 1 and 2 are significantly different. From the point of view of experience in a drawing of magnesium alloys and based on the results of the simulation in macro-scale the variant 2 is preferred because in this case deformation is more homogeneous and value of tensile stresses is lower (Yoshida, 2004). However, this refers to alloys without high propensity to microcracks in the early stages of deformation. Thus, when the experimental verification of numerical simulation finds that preferable to variant 1, this may be the proof of theoretical conclusions about the major impact of micro cracks on technological plasticity.



a)

b)

Fig. 4. Distribution of triaxility factor: a – for variant 1; b – for variant 2

In figure 5 the distribution of strain in the drawing direction and vertical stresses along the centre line of the deformation zone are shown. These parameters are used as boundary conditions for the micro-scale simulation of microstructure deformation. Results of simulation in micro-scale are shown in figure 6. As can be seen from the results (figure 6), in the variant 1 the cracks on the grains boundaries did not appear. The maximum value of the parameter D is reached for passage amounted to 0.89. However, in variant 2 there is the emergence of microcracks (figure 6b). This suggests that in this case the ductility restoration for alloy after pass will not be possible and the number of passes before the fracture of the wire will be less then in variant 1.

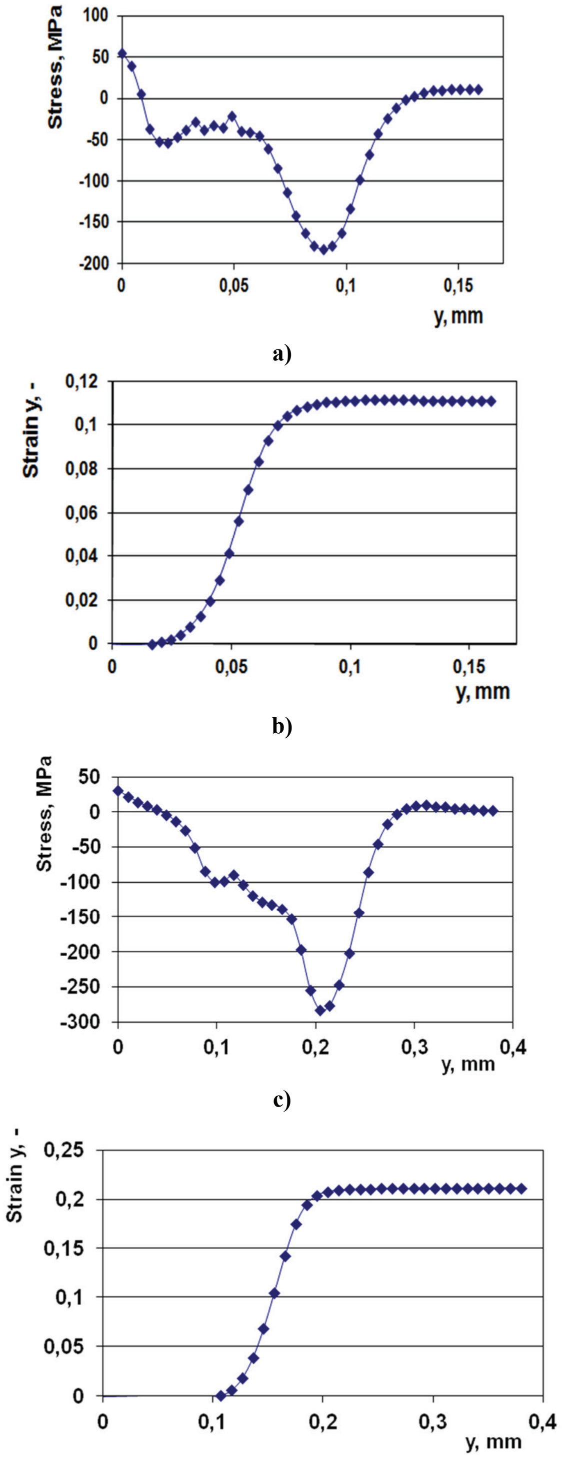


Fig. 5. The distribution of strain in the direction of drawing (b, d) and vertical stresses along the centre line of the deformation zone (a, c) for variant 1 (a, b) and variant 2 (c, d)

5. THE EXPERIMENTAL VALIDATION OF RESULTS

The experimental validation of the results of calculations was performed in the context described above. The Ax30 alloy was used. As a lubricant sunflower oil was proposed and the temperature of drawing was 30° C. The methodology of receiving the billet by hot wire drawing process is presented in the work (Milenin & Kustra, 2010). The surface of the workpiece does not contain defects observed on the optical microscope.

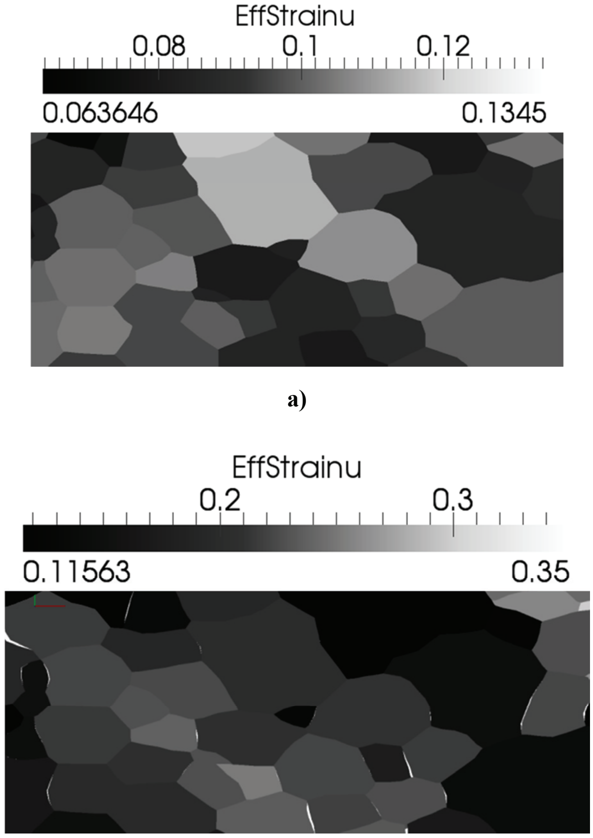


Fig. 6. Results of simulation (effective strain in grains) in micro-scale for variant 1 (a) and for variant 2 (b)

In the variant 2 only 4 passage was perform. The hairline fractures on the grains boundaries after passage 2 on the surface of the wire can be observed using an optical microscope. The received wires were fragile and crumble and after 2 pass tie the knot is impossible. Developed network of cracks after 4 pass is shown in figure 7. Further attempts of annealing and drawing were unsuccessful.

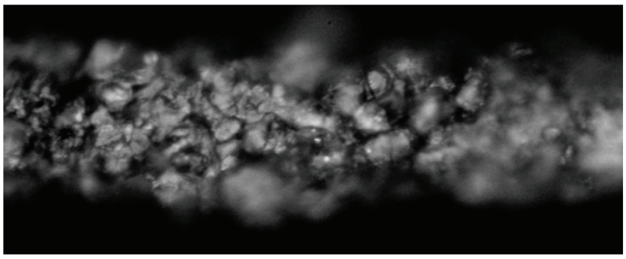


Fig. 7. Network of cracks after 4 pass, wire diameter is 0.112 mm, variant 2

Much higher wire quality (figure 8) and mechanical properties which allow further drawing were achieve in variant 1. Study of mechanical properties in INSTRON machine showed that the tensile strength R_m of wire for all passages is not significantly different (diameter 0.0955 mm - R_m = 250.7 MPa, diameter 0.0758 mm - R_m = 252,9 MPa).

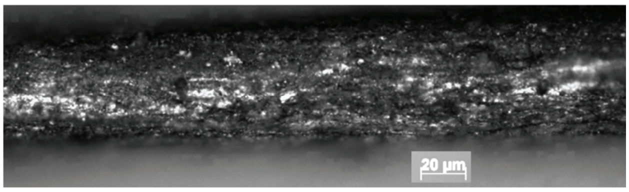


Fig. 8. *Surface of wire after drawing according variant 1, wire diameter 0.0758 mm*

6. CONCLUSIONS

1. The prediction of the microcracks using multiscale model coincided with the results of the experiment. Based on the developed schema of drawing the wire diameter 0.0758 mm for Ax30 alloy by cold drawing could be reached.
2. It is shown that microcracks on grains boundaries have influence on parameters of wire drawing technology of thin wire from Mg-Ca alloys.

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WIELOSKALOWE NUMERYCZNE MODELOWANIE ORAZ ANALIZA EKSPERYMENTALNA PROCESU CIĄGNIENIA NA ZIMNO TRUDNO ODKSZTAŁCALNYCH BIOZGODNYCH STOPÓW MAGNEZU

Streszczenie

Praca poświęcona jest opracowaniu procesu ciągnienia na zimno cienkich (o średnicy mniejszej niż 0,1mm) drutów z trudno odkształcalnego biozgodnego stopu magnezu Ax30 przy wykorzystaniu wieloskalowego modelu numerycznego. Cechą charakterystyczną stopu Ax30 jest mechanizm pękania po granicach ziaren. Udowodniono eksperymentalnie, że mikropęknięcia w trakcie próby rozciągania pojawiają się na długo przed pęknięciem próbki w skali makro. Stan metalu, który bezpośrednio poprzedza pojawienie się mikropęknięć, jest uznany za optymalny pod względem możliwości odzyskania plastyczności za pomocą wyżarzania. Głównymi celami pracy są symulacja takiego stanu materiału oraz opracowanie procesu ciągnienia na tej podstawie. Rozwiązanie przedstawionego problemu wymaga opracowania modelu pękania stopu w skali mikro, identyfikacji parametrów pękania oraz implementacji modelu w skali mikro do modelu MES procesu ciągnienia. Dwa przypadki procesu ciągnienia zostały zbadane. Pierwszy z nich, zgodnie z wynikami obliczeń, prowadzi do powstania mikropęknięć. Drugi rozpatrywany schemat ciągnienia został dobrany tak, by nie pojawiły się mikropęknięcia w ciągnionym drucie. Eksperymentalna weryfikacja wyników obliczeń została przeprowadzona w warunkach laboratoryjnych w specjalnie do tego celu opracowanym narzędziu. Wyżarzanie było wykonywane przed każdym przepustem. Początkowa średnica drutu wynosiła 0,1 mm. W pierwszym przypadku możliwe było przeprowadzenie 2-3 przepustów, po których w materiale wystąpiły pęknięcia. W tym przypadku pęknięcia po granicach ziaren były obserwowane na powierzchni drutu. Drugi rozważany schemat ciągnienia pozwolił na przeprowadzenie 7 przepustów bez pojawienia się pęknięć, otrzymano drut o średnicy 0,075 mm bez defektów na powierzchni o plastyczności pozwalającej na dalsze ciągnienie. Tak więc, przeprowadzono walidację modelu na dwóch zasadniczo różnych przypadkach procesu ciągnienia.

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