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MULTI-SCALE FEM SIMULATION OF THE DRAWING PROCESS

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Abstract

In this paper the wire drawing process is investigated in two levels. They are a steady-state solution using the 2-dimensional rigid-plastic finite element method (macro-level) and a modeling of microstructure changes (micro-level).

In the macro level the joint deformation-temperature problem is considered. It is shown that the model based on the theory of the flow of rigid-plastic continuum allows for calculating of drawing force with good accuracy.

In the micro-level the process of deformation of a representative volume element (RVE) is considered. The grain deformation and an orientation of cementite lamellas changes in RVE are modeled with a help of the FEM. The micro-level model is implemented into finite element code Drawing2d.

Key words: wire drawing, grain deformation, finite element method, microstructure, cementite lamellas

1. INTRODUCTION

The properties of the wire are dependent on the micro and macrostructures of the steel. Recently (Muskalski, 2004; Muskalski & Milenin, 2006) a close connection between properties of the wire and the orientation of the cementite lamellas in the grains was shown. The orientation of the cementite lamellas in the grains is dependent on the parameters of the multi-pass drawing process (direction of the drawing, friction, shape of dies etc.).

The objective of the present work is to develop a thermomechanical finite element model that can by applied to receive an information about an influence of the technological parameters of the drawing on the microstructure of the wire.

2. EXPERIMENTAL RESEARCH

In the experimental research the process of the drawing of the high carbon steel wires (steel grade GD76A) with a diameter from 4.0 mm after lead patenting has been performed with a laboratory bull block drawing machine in six draws to the wire with a diameter 1.70 mm; speed of drawing is 1.6 m/s. The chemical composition of steel is shown in table 1 and the schedule of total and single reductions is shown in table 2. Wires were made according to two variants of the drawing process. Variant A6 – drawing direction was constant and in variant B6 the direction was changed before the last pass.

The analysis of experimental result shows: the change of a drawing direction in the last draw doesn't influence R_m (tensile stress) and $R_{0,2}$ (yield stress) statistically significant way but has an essential influence on L_z (number of torsions), L_s (number of bends) and fatigue strength N (figure 1).

The change of the mechanical properties of the wire are connected with microstructures of the wire and especially with the orientation of the cementite lamellas (figure 2).

In the experimental research the degree of orientation of the cementite lamellas have been determined for both variants with the use of the measurement method of the electrical resistance at the

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ambient and liquid nitrogen temperature. The relative change of an ideal electric resistance $\Delta\rho_i/\rho$ proportional to the degree of the orientation of cementite lamellas show the increase of electric resistance for variant B6 about 8.6%.

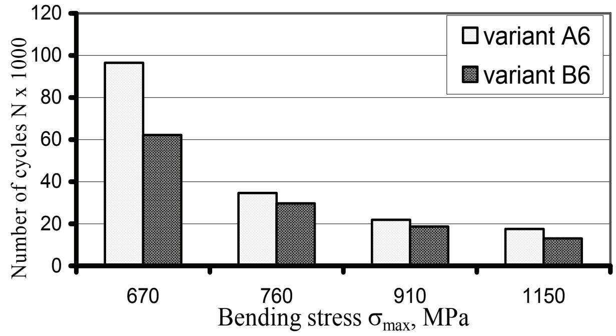


Fig. 1. *The number of fatigue cycles N at the different level of bending stresses for wires ϕ1.7 drawn according to variants A6 and B6.*

Table 1. *Chemical composition of GD76A steel.*

Contents of elements, %									
C	Si	Mn	P	S	Cu	Cr	Ni	Al	Cu+Cr+ Ni
0.76	0.21	0.60	0.005	0.009	0.09	0.03	0.06	0.002	0.18

Table 2. *Schedule of single (G_p) and total reductions (G_c) in process of drawing.*

Draw's number		1	2	3	4	5	6
Wire diameter, mm	4.00	3.40	2.93	2.53	2.18	1.90	1.70
G_p, %	-	27.8	25.7	25.4	25.8	24.0	19.9
G_c, %	-	27.8	46.3	60.0	70.3	77.4	81.9

For computer modeling of the cementite lamellas orientation change during the drawing a new mathematical model is proposed. The wire drawing processes is modeled in two levels: steady-state solution using the 2-dimensional rigid-plastic finite element method (macro-level) and a modeling of the microstructure change (micro-level).

3. FEM MODEL OF DRAWING

Theoretical analysis of drawing process has performed with a help of the Drawing 2d software (Milenin, 2005), which has been elaborated specially for the solving of the drawing problem. In this FEM model a boundary problem has been solved considering other phenomena: plastic deformation, heat transfer, wire heating due to deformation and friction. In the model, the strain tensor distribution obtained in previous pass is transferred to the next one. A change of the direction of the drawing is also possible in the elaborated software.

a)

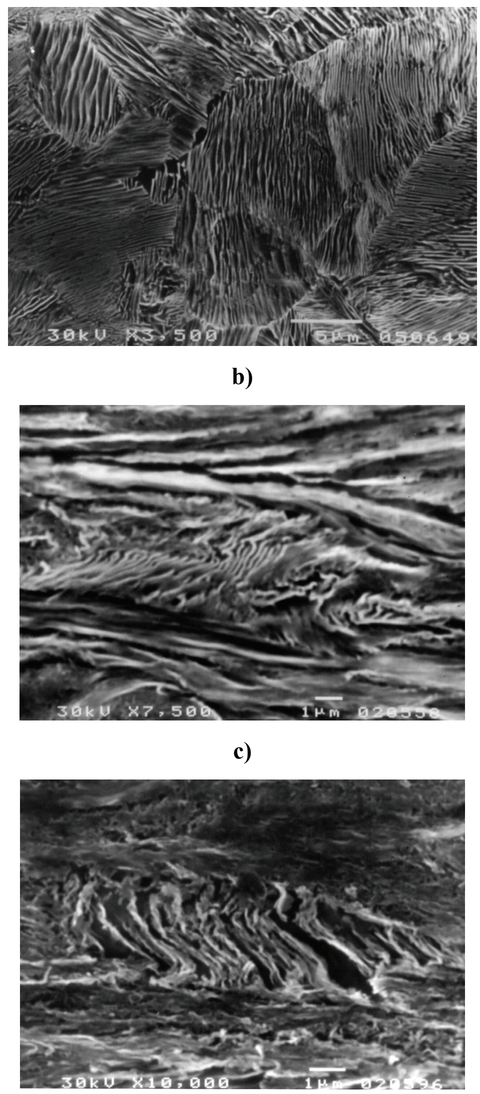


Fig. 2. *The initial microstructure (a) and the final orientation of the cementite lamellas in variant A6 (b) and B6 (c).*

For obtaining the solution of the boundary problem, the variation principle of rigid-plastic theory is used:

$$J = \int_V \int_0^{\xi_i} \sigma_S(\xi_i) \mathrm{d}V + \int_V \sigma_0 \xi_0 \mathrm{d}V - \int_F \sigma_\tau v_\tau \mathrm{d}F, \quad (1)$$

where: σ_S – yield stress, ξ_i – the intensity of strain rate, V – volume, σ_0 – mean stress, ξ_0 – volumetric strain rate; F - the metal contact area with the die, σ_τ – the stress of the friction, v_τ – the metal slip velocity along the surface of the die.

The friction stress was determined according to the law proposed by Levanov et al. (1976):

$$\sigma_\tau = f_{tr}\frac{\sigma_S}{\sqrt{3}}\left(1-\exp\left(-\frac{1.25\sigma_n}{\sigma_S}\right)\right), \qquad (2)$$

where: f_{tr} – the friction coefficient, σ_n – the normal stress on the metal contact with the tool.

The components of the stress tensor σ_{ij} are calculated with dependence on components of strain rate tensor ξ_{ij} according to the follow equation:

$$\sigma_{ij} = \delta_{ij}\sigma_0 + \frac{2\sigma_S}{3\xi_i}\xi_{ij}. \qquad (3)$$

The components of the deformation tensor ε_{ij} are calculated through integration of each component of the strain rate tensor along the flow line:

$$\varepsilon_{ij} = \int_0^\tau \xi_{ij}(\tau)d\tau = \sum_{k=1}^{k=k_\tau}\xi_{ij}^{(k)}\Delta\tau^{(k)}, \qquad (4)$$

where: $\Delta\tau^{(k)}$ – the current time increment, $\xi_{ij}^{(k)}$ – the values of the components of the strain rate tensor determined according to the follow equation:

$$\xi_{ij}^{(k)} = \sum_{n=1}^{n_{nd}} N_n\xi_{ijn}, \qquad (5)$$

where: N – the finite element shape functions, ξ_{ijn} – the nodal values of the components of the strain rate tensor for the current finite element, n_{nd} – the number of nodes in element.

A determination of the next points of the flow line is based on the calculation of the components of metal velocity for current point **k** according to the follow equation:

$$v_i^{(k)} = \sum_{n=1}^{n_{nd}} N_n v_{in}, \qquad (6)$$

and the integration of coordinates:

$$x_i^{(k+1)} = x_i^{(k)} + v_i^{(k)}\Delta\tau. \qquad (7)$$

In that way the flow lines are estimated, which give the possibility to make easy the visual analysis of the deformation states during the drawing processes. The scheme of calculation of the point location of the flow lines is shown in figure 3.

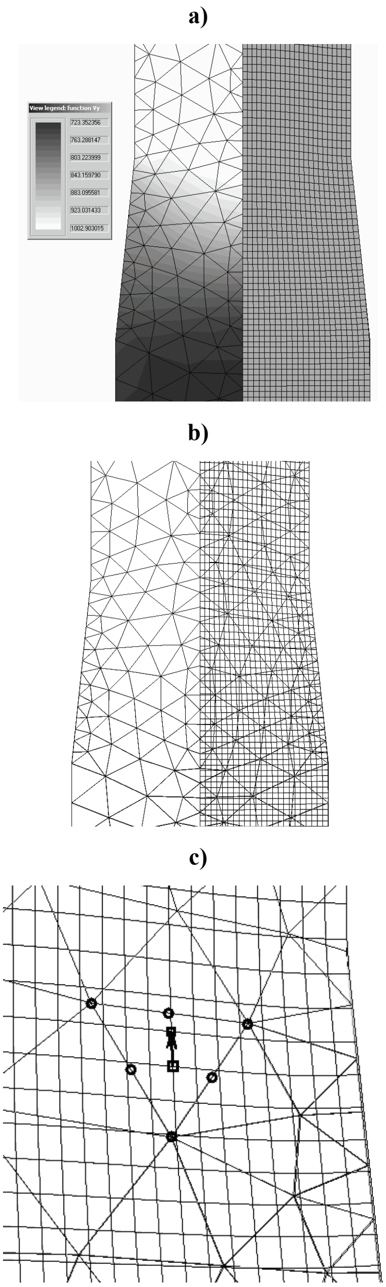


Fig. 3. *The scheme to the determination flow lines point location; a – velocity field in drawing direction and flow lines mesh; b – the flow line mesh placed on FEM mesh; c – the scheme to the determination the next point of current flow lines.*

For the solution of the thermal problem the following method has been used. The passing of the wire by the die deformation cone with the solution the follow nonstationary thermal problems on each step has been analyzed. The equation of heat conduction shown below is calculated for every time step and temperature distribution is obtained:

$$k\left(\frac{\partial^2 t}{\partial r^2}+\frac{1}{r}\frac{\partial t}{\partial r}\right)+Q = c\rho\frac{dt}{d\tau}, \qquad (8)$$

where: Q – the deformation power, $Q = 0.9\sigma_s\xi_i$; c – specific heat; ρ – metal density; k – thermal conductivity coefficient.

The heat exchange on the contact metal with the die is written as equation:

$$q_{conv} = \alpha(t - t_{\infty}), \tag{9}$$

where: t_{∞} – the die temperature, α – the heat exchange coefficient.

The thermal flux generated on the friction surface is determined by the equation: $q_{fr} = 0.9\sigma_s v_{\tau}$.

4. VERIFICATION OF THE FEM MODEL OF DRAWING

The verification of the model was based on a comparison the experimental and theoretical data of drawing stress σ_c. Results obtained by Pilarczyk et al. (1997) are considered as examples of experimental data. The parameters of the drawing and the results of the measurement and calculation of the drawing stress are shown in tables 3 and 4.

The comparison experimental and numerical result shows a good accuracy of the model for different dimensions of deformation zone and friction conditions.

Table 3. *The experiment and simulation results for friction coefficient f_{tr} = 0.07.*

No	D_0, mm	D_1, mm	P_{ekp}, kN	P_{MES}, kN	δ_F, %	$\sigma_{c\ exp}$, MPa	σ_c MES, MPa	δ_σ %
1	5.5	4.73	11.0	11.34	3.1	626	645	3.0
2	4.73	4.00	10.3	10.58	2.7	816	837	2.6
3	4.00	3.39	7.4	8.400	13.5	822	932	13.4
4	3.39	2.89	6.9	6.470	6.2	1040	987	5.1
5	2.89	2.5	4.9	4.809	2.01	1002	979	2.3

Table 4. *The experiment and simulation conditions for friction coefficient f_{tr} = 0.03.*

No	D_0, mm	D_1, mm	P_{ekp}, kN	P_{MES}, kN	δ_F, %	$\sigma_{c\ exp}$, MPa	σ_c MES, MPa	δ_σ %
1	5.50	4.73	9.3	9.127	1.9	530	519	2.1
2	4.73	4.00	8.8	8.472	3.7	699	674	3.6
3	4.00	3.39	6.6	6.778	2.7	726	751	3.4
4	3.39	2.89	5.5	5.207	5.3	829	793	4.3
5	2.89	2.5	3.9	3.848	1.3	801	784	2.1

5. MODEL OF THE MICROSTRUCTURE CHANGE

The micro-level model of the grain deformation process is based on the following assumptions:

- the grain is considered as a multi-phase representative volume element (RVE). Properties of phase (ferrite and cementite) are presented by the flow curves;
- boundary conditions (nodes velocities on the grain boundary) for micro-level problem are obtained from the macro-model according the equation (6);
- for numerical imposition of the boundary conditions on grain boundary the penalty method is used. The alteration of the actual methods (for example, presented by Thibaux at al. (2000)) is based on an idea of the non-rigid boundary conditions for the RVE. It increases the numerical stability and accuracy of the solution.

For obtaining the solution of the boundary problem for the RVE, the modified variation principle of rigid-plastic theory is used:

$$J = \frac{1}{2}\int_V \mu\, \xi_i^{\,2} dV + \int_V \sigma_0 \xi_0 dV + K_\tau \int_F (v_\tau)^2 dF + K_n \int_F (v_n)^2 dF, \tag{10}$$

where K_n – a penalty coefficient on impenetrability condition of the grain boundary, $v_n = a_r v_r + a_z v_z$; K_τ – a penalty coefficient on sliding between the grain boundaries:

$$K_\tau^{(p)} = \frac{\sigma_\tau^{(p-1)}}{v_\tau^{(p-1)}}, \tag{11}$$

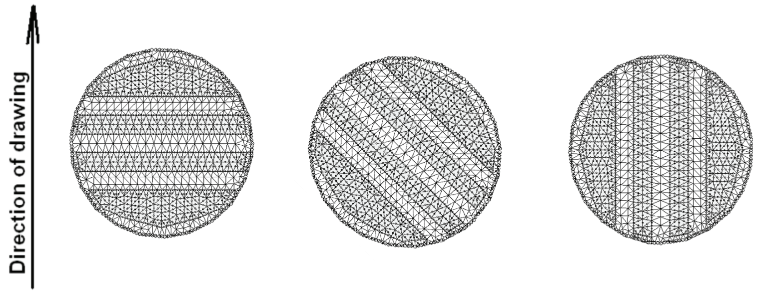
where p – number of iteration, v_x – slip velocity of grains boundaries, σ_z – friction stresses between the boundaries of the grains.

For numerical analyses of the deformation of the multi-phase grain, a following variants of initial cementite lamellas orientation are used:

1 – lamellas are perpendicular to the drawing direction (figure 4, a);

2 – an angle between the cementite lamellas and the drawing direction is of 45^0 (figure 4, b);

3 – lamellas are parallel to the drawing direction (figure 4, c).



a) b) c)

Fig. 4. Variants of the initial cementite lamellas orientation (a – the lamellas are perpendicular to the drawing direction, variant 1; b – the angle between the cementite lamellas and the drawing direction is 45^0, variant 2; c – lamellas are parallel of drawing direction, variant 3).

The first pass from table 2 is considered. For variant 2 the two values of the die angle are considered (variant 2a – 6^0, variant 2b – 3^0). The friction factor between metal and die is 0.03 and between grains is 0.8. The start position of modeling grains is in the center of the sample. The ratio between yield stresses of the cementite and ferrite is set to be 5.

The results of the simulations are shown in figure 5 (macro-level) and figure 6 (micro-level).

As show in figure 5, the strain rate distribution in the deformation zone has two extremes in surface zone of metal for all variants of simulations. In the centre of the deformation zone for die angle 6^0 we can observe one extreme of the strain rate distribution. It's a consequent of the geometrical conditions of the drawing (the longest of the deformation zone for the die angle of 3^0). This distribution of the strain rate is transferred to the grain in the micro-level model.

The significant difference of the strain rate between the ferrite and cementite is observed for the variant 2a and 2b (for canting positions of the cementite lamellas). It is shown in figures 7-9. For the variant 2,b, distribution of the strain rate in the ferrite and cementite (figure 9) has two extremes according to the solution in the macro-level (figure 5,b).

As show in figure 7-8 and figure 5, the maximal strain rate in the grid (in the ferrite phase) is above the mean value of macro-level solution.

a)

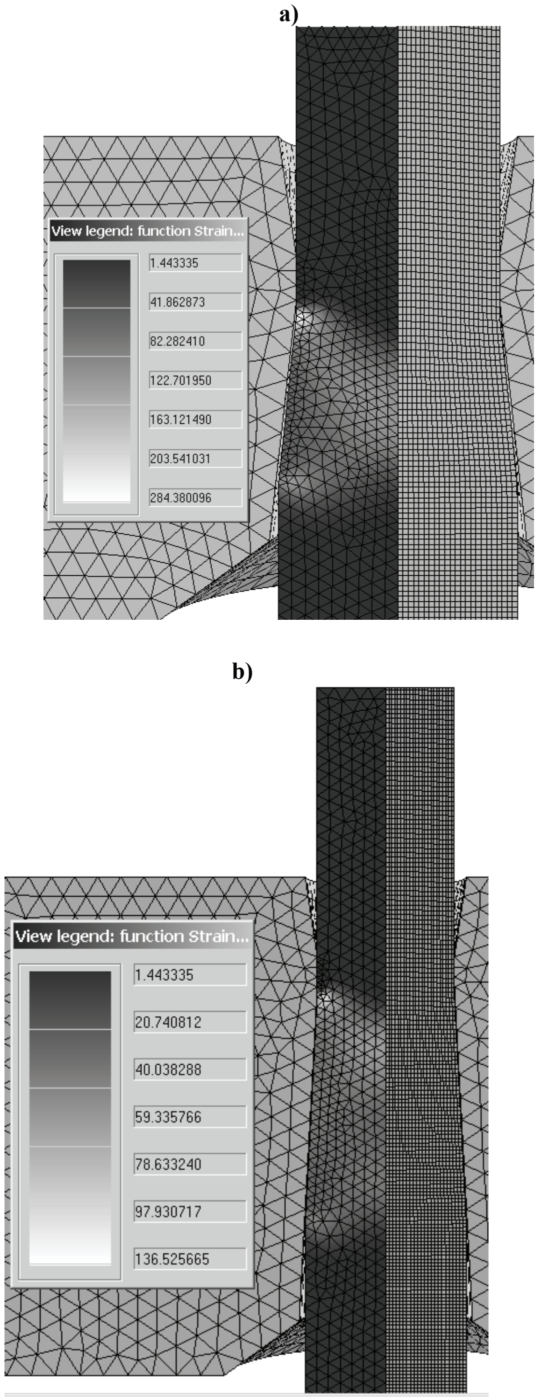
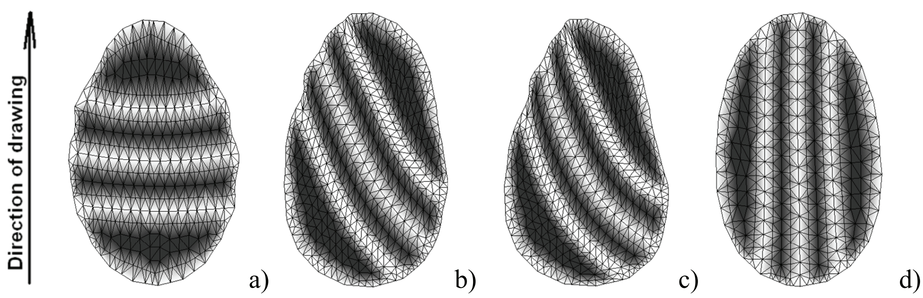


Fig. 5. The results of the simulations of the strain rate fields during the drawing process on the macro-level (a – die angle is 6^0 ; b – die angle is 3^0).



a) b) c) d)

Fig. 6. Results of the simulations on the micro-level (a – variant 1, b – variant 2a, c – variant 2b, d – variant 3, white – cementite, gray – ferrite).

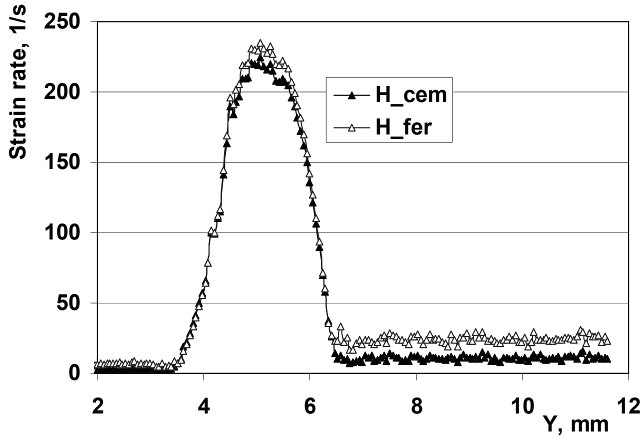


Fig. 7. Change of the strain rate in the cementites lamella (▲) and ferrite (△) in the center of grain, variant 1.

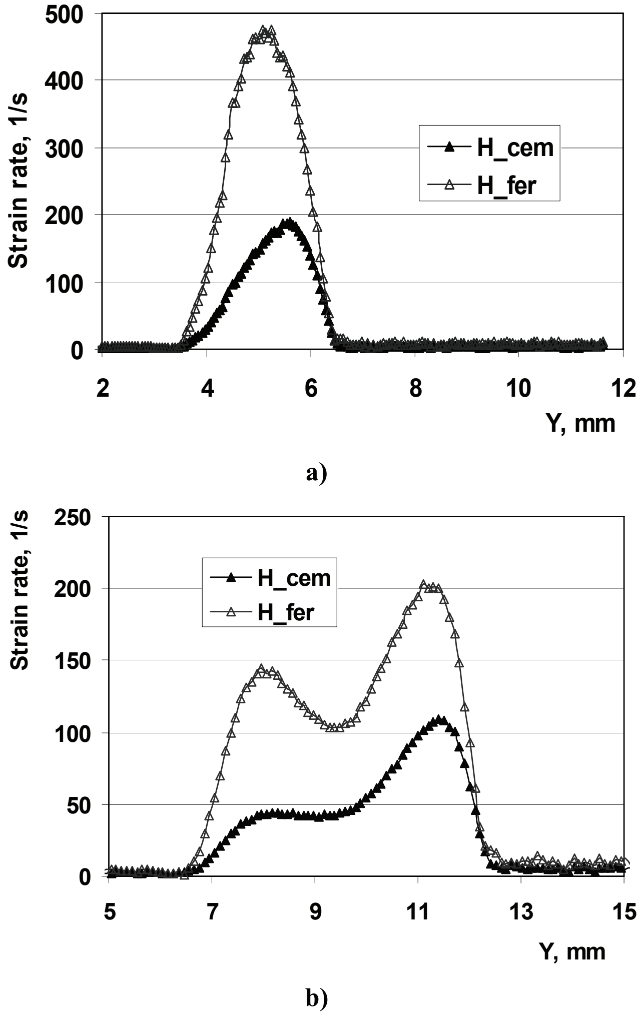


Fig. 8. Change of the strain rate in the cementite lamellas (▲) and ferrite (△) in the center of the grain, a – variant 2,a, b – variant 2,b.

6. CONCLUSIONS

1. A new model of two-phase grain deformation for wire drawing is proposed. The new conception of simulation of the boundary conditions for the representative volume element is based on the penalty method and uses a solution of the problem on macro-level.
2. The numerical simulation is shown a maximal non-uniform deformation of grain phases for the canting positions of the cementite lamellas relative the drawing direction.
3. The geometrical parameters of the deformation zone are influenced from the change of the cementite lamellas orientation during the drawing.

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WIELOSKALOWA SYMULACJA PROCESÓW CIĄGNIENIA ZA POMOCĄ METODY ELEMENTÓW SKOŃCZONYCH

Streszczenie

W pracy przeanalizowano proces ciągnienia drutu na dwóch poziomach. Na poziomie makro wykorzystano rozwiązanie 2-wymiarowego, stacjonarnego, sztywno-plastycznego zadania brzegowego odkształcenia ciała, natomiast na poziomie mikro wykonano modelowanie zmian mikrostruktury. Na poziomie makro rozpatrywano problemy związane z polami odkształceniem i temperatury. Stwierdzono, że model oparty o teorię sztywno-plastycznego odkształcenia ciała pozwala na obliczenia siły ciągnienia z dużą dokładnością. Na poziomie mikro rozpatrzono proces odkształcenia reprezentatywnego objętościowo elementu (ROE). z Stosując metodę elementów skończonych modelowano odkształcenie kolonii perlitu i zmiany ułożenia płytek cementytu. Model otrzymany na poziomie mikro został zaimplementowany do programu Drawing2D symulującego proces ciągnienia.

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