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The multi-scale FEM simulation of the drawing processes of high carbon steel

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Analysis and modelling

ABSTRACT

Purpose: The influence of cementite lamellas orientation on mechanical and technological properties of wire experimentally show up during investigation of drawing processes with change the direction of drawing between passes. The purpose of this paper is to develop a mathematical model of cementite and ferrite deformation during drawing processes and receive an information about transformation of a pearlitic structure of wire during drawing.

Design/methodology/approach: The wire drawing processes was investigated in two levels - using the 2-dimensional rigid-plastic finite element method (macro-level) and modelling of a microstructure change (micro-level). In micro-level the process of deformation of representative volume element (RVE) is considered. The pearlitic colony deformation and stress-strain state in RVE is modelled with help of the FEM.

Research limitations/implications: The influence of initial cementite lamellas orientation on triaxity factor and localization of deformation in micro-level is investigated. The numerical simulation is shown a maximal non-uniform deformation of pearlite phases for the canting positions of the cementite lamellas relative the drawing direction.

Practical implications: The results of article will be helpful for a fundamental understanding of pearlitic deformation during development of high strength steel wires for tire cord applications.

Originality/value: A new model of two-phase grain deformation for wire drawing is proposed. The new conception of simulation of the boundary conditions for the RVE is based on the penalty method and uses a solution of the problem on macro-level.

Keywords: Computational material science; Wire drawing; Pearlitic steel; Multi-scale simulation

1. Introduction

The properties of the wire are dependent on the micro and macrostructures of the steel. Recently [1] 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 pearlitic colony is dependent on the parameters of the multi-pass drawing process. Development of high strength steel wires with a breaking strength of 4000 MPa, particularly, for tire cord application [2,3], exemplifies importance of such a fundamental understanding of pearlite deformation.

The purpose of this paper is to develop a mathematical model of cementite and ferrite deformation during drawing processes and receive an information about transformation of a pearlitic structure of wire during drawing. Therefore, it is evident that there is a need for modelling of steel in different scales [4-9] and monitoring their behaviour simultaneously.

2. The multi-scale mathematical model and experimental researches of drawing processes of pearlitic steel

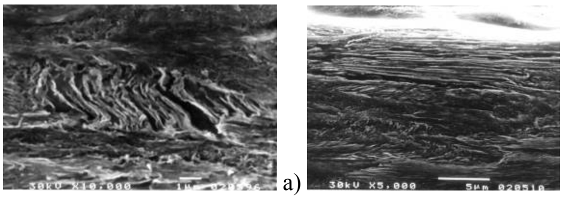
2.1. The experimental researches

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 has been performed with a laboratory bull block drawing machine in six passes to the wire with a diameter 1,70 mm. Wires were made according to two variants of the drawing process. Variant A6 where drawing direction was constant and in variant B6 where the direction was changed before the last pass [1].

The analysis of experimental result shows: the change of a drawing direction in the last draw doesn't influence on tensile stress and yield stress in statistically significant way but has an essential influence on number of torsions, number of bends and especially on fatigue strength N (from 14,5 to 35,6%). The research of a fatigue durability of wires carried out in the rotary bending conditions on the machine built according to the machine scheme DRABI SCHENCK.

The change of the mechanical properties of the wire is connected with microstructures of the wire and especially with the orientation of the cementite lamellas (figure 1). 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 ambient and liquid nitrogen temperature. The relative change of an ideal electric resistance (Δρi/ρ) proportional to the degree of the orientation of cementite lamellas show the increase of electric resistance for variant B6 about 8.6% (figure 2). It exemplifies importance of analysis the pearlitic colony deformation during drawing.

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).



a) b)

Fig. 1. The examples of the final orientation of the cementite lamellas in variant A6 (a) and B6 (b)

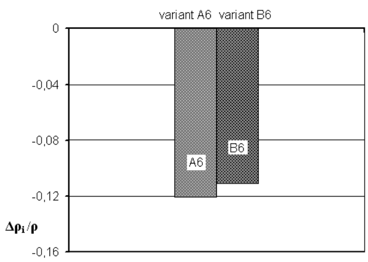


Fig. 2. The relative change of an ideal resistance $\Delta\rho_i/\rho$ proportional to the degree of orientation of cementite lamellas

2.2. The FEM macro-model of drawing processes

Theoretical analysis of drawing process was performed with a help of the Drawing 2d software [10], which has been elaborated especially for the solution 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. For obtaining the solution of the boundary problem, the variation principle of rigid-plastic theory of plasticity is used [11]:

$$J = \int_V \int_0^{\xi_i} \sigma_i(\xi_i)\mathrm{dV} + \int_V \sigma_m \xi_0 \mathrm{dV} - \int_F \sigma_\tau v_\tau \mathrm{dF}, \qquad (1)$$

where: σ_S – intensity of stresses, ξ_i – strain rate, V – volume, σ_m – 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 components of the deformation tensor ε_{ij} are calculated through integration of each component of the strain rate tensor along the flow line:

$$\varepsilon_{ij} = \int_0^\tau \xi_{ij}(\tau)d\tau = \sum_{k=1}^{k=k_\tau} \xi_{ij}^{(k)} \Delta\tau^{(k)}, \qquad (2)$$

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:

$$\xi_{ij}^{(k)} = \sum_{n=1}^{n_{nd}} N_n \xi_{ijn}, \qquad (3)$$

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.

In the model of drawing processes in macro scale the information from micro scale is not used.

2.3. The model of the pearlitic colony deformation

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

- the grain was 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 were obtained from the macro-model;
- for numerical imposition of the boundary conditions on grain boundary the penalty method is used. The alteration of the actual methods (for example, presented in paper [12-13]) is based on an idea of the non-rigid boundary conditions for the RVE and increases the numerical stability and accuracy of the solution.

For obtaining the solution of the boundary problem for the RVE, the modified variation principle is used [10].

2.4. The modelling conditions

The example of initial microstructure of wire is shown in figure 3. For numerical analyses of the deformation of the pearlitic colony, a following variants of initial cementite lamellas orientation are used:

- lamellas are parallel to the drawing direction (figure 4, a);
- an angle between the cementite lamellas and the drawing direction is of 45^0 (figure 4, b);
- lamellas are perpendicular to the drawing direction (figure 4, c).

The drawing of wire from ∅4 mm to ∅3.4 mm was considered.

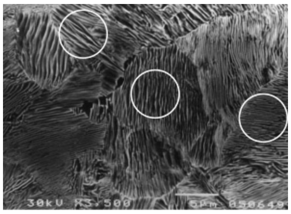


Fig. 3. The examples of the initial microstructure in wire

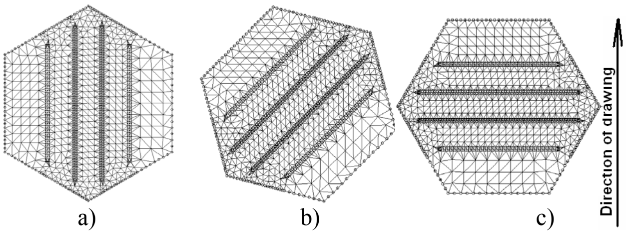


Fig. 4. The variants (a, b and c) of the initial orientation of the cementite lamellas in wire

3. The results and discussion

3.1. Modelling in macro-level

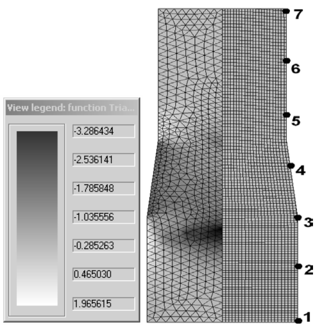


Fig. 5. The triaxity factor distribution on macro-level of drawing process and points (1-7) of RVE deformation analysis

The result of triaxity factor ($k = \sigma_m / \sigma_i$, where σ_m – mean stress, σ_i – intensity of stresses) simulation in macro-level is shown on figure 5. The positions from 1 to 7 on figure 5 are a points of RVE deformation analysis. The distribution on figure 5 shown a monotonic change of *k* in deformation zone and change of *k* sign from "-" to "+" in calibration zone. During modeling on macro level the flow curves for GD76A steel from plastometric research was used [14]. For cementite was accepted [15]: $\sigma_{sc} = 10\sigma_{sf}$.

3.2. Modelling in micro-level

The result of triaxity factor simulation in micro-level is shown on figures 6-8. For all variants (*"a"*-*"c"*) was observed a non-uniform distribution of *k*.

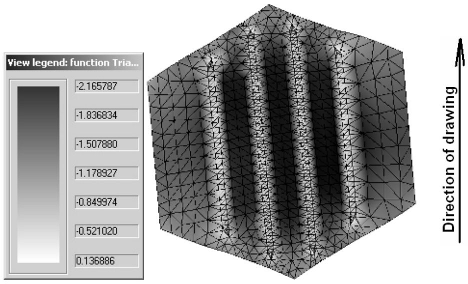


Fig. 6. The triaxity factor distribution in RVE for variant "*a*" of initial cementite lamellas orientation in point 3 on figure 5

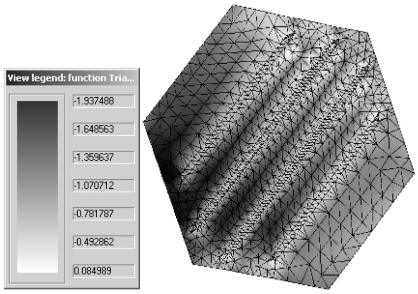


Fig. 7. The triaxity factor distribution in RVE for variant "*b*" of initial cementite lamellas orientation in point 3

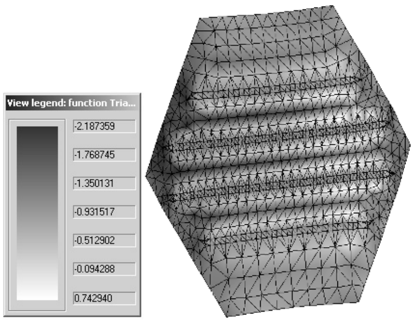


Fig. 8. The triaxity factor distribution in RVE for variant "*c*" of initial cementite lamellas orientation in point 3

For variant *"a"* the values of *k* for cementite lamellas is positive (spread) and for ferrite phase is negative (contractile). The maximum values of *k* is observed in variant *"c"* (figure 8). But in variant *"c"* the maximum of spread stresses is localized near cementite lamellas, in ferrite phase (figure 8).

In figures 9-11 the distribution on strain intensity in RVE is shown. The significant localization of strain intensity in ferrite phase was observed for the canting positions of the cementite lamellas (figure 10) relative the drawing direction.

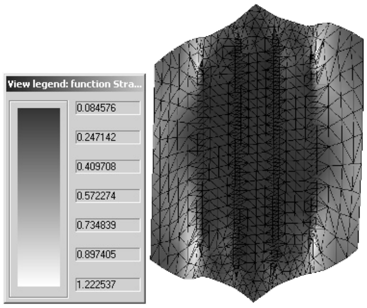


Fig. 9. The strain intensity distribution in RVE for variant "*a*" of initial cementite lamellas orientation in point 5

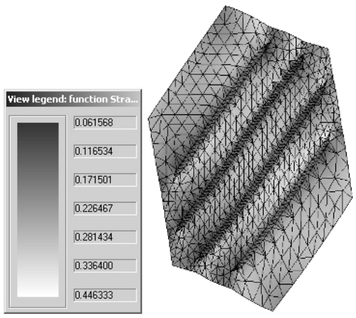


Fig. 10. The strain intensity distribution in RVE for variant *"b"* of initial cementite lamellas orientation in point 5

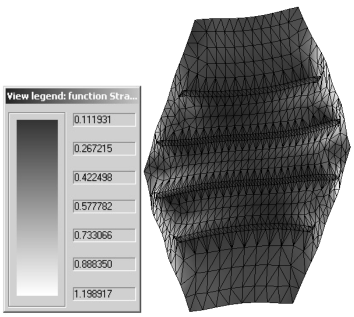


Fig. 11. The strain intensity distribution in RVE for variant *"c"* of initial cementite lamellas orientation in point 5

4. Conclusions

A 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.

The numerical simulation is shown a maximal non-uniform deformation of pearlite phases for the canting positions of the cementite lamellas relative the drawing direction. The maximum values of a triaxity factors is observed in perlitic colony with a perpendicular direction of cementite lamellas relative the drawing direction.

Acknowledgements

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