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AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 15, 2015, No. 2

MULTISCALE MODELLING OF FERRITIC-PEARLITIC STEEL DEFORMATION IN ROD DRAWING PROCESS BY USING STATISTICAL REPRESENTATION OF MICROSTRUCTURE

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Abstract

Development of modelling method, which allows prediction of the properties distribution in the metal volume, was the objective of the paper. The behavioural features of the microstructure under the influence of the deformation during drawing of rods was considered. Multiscale model of this process was proposed. To save computing time, statistical representation of the microstructure was applied. Statistically Similar Representative Volume Element (SSRVE), representing ferritic-pearlitic steel microstructure, was developed. Simulations of the drawing process were performed and local deformation of each structural component was predicted. Selected results, as well as discussion of the effect of microstructure on the obtained stress and strain distributions, are presented in the paper.

Key words: rod drawing, multiscale model, statistically similar representative volume element

1. INTRODUCTION

The single pass drawing of rods (a range of diameters ranging from 5 mm to 40 mm) with small reduction (1-3 mm) is one of the most important processes for mechanical engineering, military and car industries. In this case the final products have different axes, shafts and rod constructions, which are usually used under the static and cyclic loads throughout all of their life period. Thus, the inhomogeneity of mechanical properties due to non-uniform deformation is crucial in prediction of the potential reliability of the finished product (Son et al., 2010; Sadok et al., 1994; Hasani et al., 2009). This problem plays particularly important role in case of rod drawing process of ferritic-pearlitic steels (Watanabe et al., 2012), since inhomogeneity of deformation can lead to large differences in mechanical properties in the workpiece layers. Numerical modelling of the rod drawing process can be a support for designing the best technologies for these steels. Thus, development of the model, which describes phenomena occurring in the microstructure of the ferritic-pearlitic steels during drawing, was the main objective of the work. Macro level models do not take into account complicated behaviour of the ferritic-pearlitic microstructure in the micro scale (Sarma et al., 1998). Therefore, development of modelling methods, which allow predicting the properties distribution in the metal volume with the behavioural features of the microstructure under the influence of the deformation, was needed (Wiewiorowska S., 2010a; 2010b; Castro et al., 1996; Campos & Cetlin, 1998; Park & Lee, 2003). It is an important theoretical problem which involves specific numerical solutions. Due to necessity of application very fine mesh

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with large number of elements these solutions are computationally very costly. Thus, numerical representation of ferritic-pearlitic steels microstructure does not allow using it directly in numerical simulations. Therefore, statistical methods were used to generate Statistically Similar Representative Volume Element (SSRVE), which simplifies original microstructure.

2. FORMULATION OF THE TECHNOLOGICAL PROBLEM

2.1. Rod drawing

In industrial conditions of rod drawing the deformation inhomogeneity may lead to cracking during the process (figure 1) or high degree of mechanical properties inhomogeneity (figure 2). The non-uniform distribution of the stress-strain state in the deformation zone (figure 3) is a key reason of these mentioned above problematic issues.

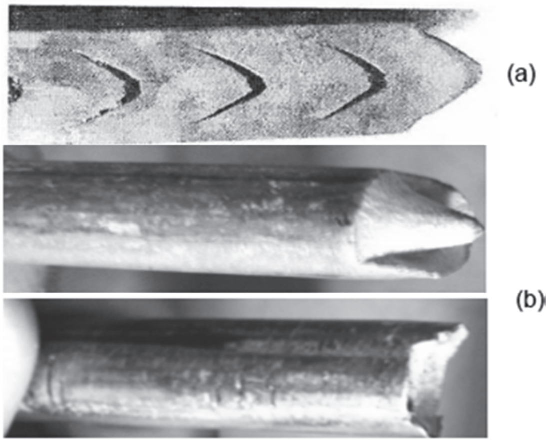


Fig. 1. Examples of cracking: (a) – chevron cracks: (b) - cup-and-cone crack.

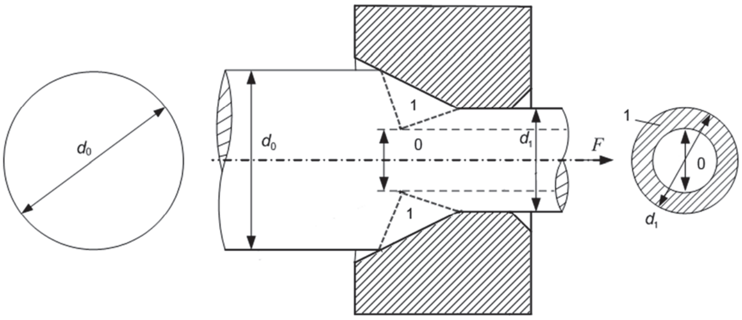


Fig. 3. The basic scheme of the metal flow in a conical deformation zone during rod drawing: 0 – tensile stress zone; 1- compressive stress zone.

Zone 1 in figure 3 is the slip cone. This is a zone in which plastic compression deformation occurs. At the zone 0 only tensile strains develop. According to this scheme, there are some borderline cases. If slip cones touch each other at the vertices, a homogeneous strain along the length of the rod cross-section is achieved. Contrary, if the cones do not touch each other, the inhomogeneous deformation occurs. In this case not only is the inhomogeneity in the distribution of properties at final product increased, but also risk of cracking during the process occurs. Therefore, the main aims of the rod drawing process optimization from a favorable stress-strain state point of view are as follows:

1. To increase level of compressive strain along the whole cross-section of the deformation zone.
2. To reduce tensile strain level in the central layers of the deformation zone.

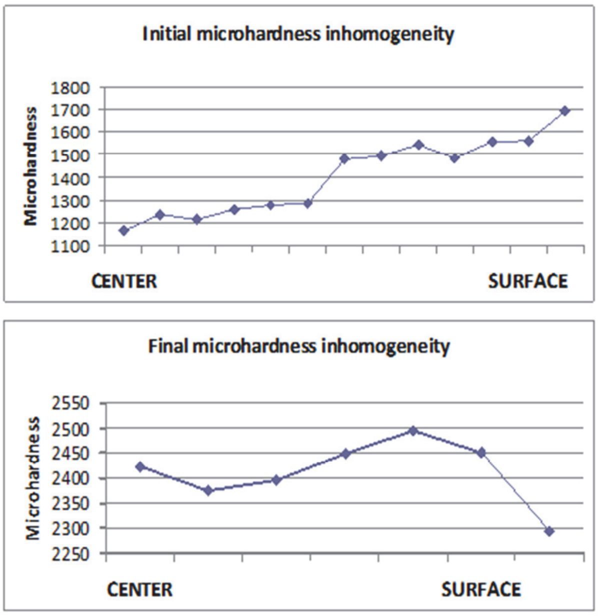


Fig. 2. Distribution of microhardness in cross-section before and after deformation

2.2. Problem of conventional simulation

Conventional modeling from the perspective of a homogeneous material does not provide a reliable prediction of the distribution of properties in the deformed metal volume. Typically, results of such simulations cannot fully explain the changes of the microhardness at the central layers rod. It leads to the fact that the drawing regimes, which were created by using such models, are rarely used in industrial processes. It should be noted that in general the most steels are "composites" of several micro elements, which often have very different behavior under load conditions. Thus, we can conclude that in the cold metal forming processes with a high degree of deformation inhomogeneity microstructure representation of the metal can be a crucial aspect in achieving accuracy of simulation.

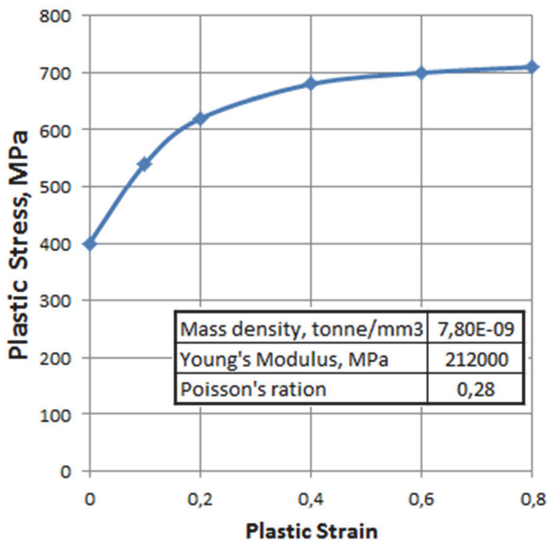
2.3. Model

2.3.1. Macro simulation

The drawing process of low-carbon non-alloyed steel grade 20 (table 1, figure 4) was selected as a basis of the research. It is an ordinary steel grade with ferritic-pearlitic microstructure

Table 1. *Chemical composition of steel grade 20.*

C	Si	Mn	Ni	S	P	Cr	Cu	As
0.17 - 0.24	0.17 - 0.37	0.35 - 0.65	<0.3	<0.04	<0.035	<0.25	<0.3	<0.08



Mass density, tonne/mm3	7,80E-09
Young's Modulus, MPa	212000
Poisson's ration	0,28

Fig. 4. *Material properties: steel grade 20.*

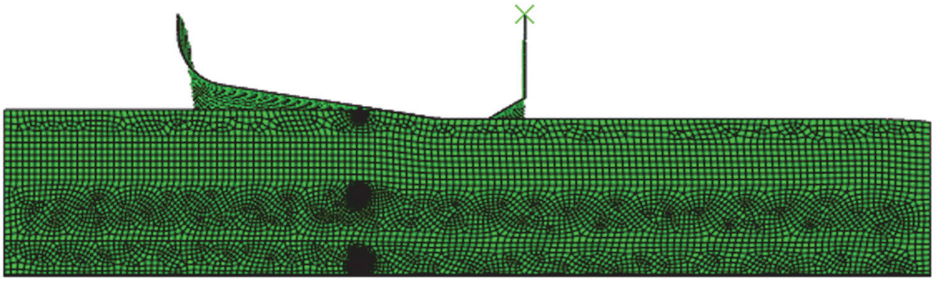


Fig. 5. *General view of the axisymmetric cross-section model with 3 places of high element concentration.*

The drawing was carried out with initial diameter of 38 mm, with different degrees of logarithmic strain (0.05, 0.1, 0.15, 0.2) and with different angles of the drawing tool (16, 18, 20, 22, 24 degrees). This process is currently used at OJSC "MMK-Metiz" (Russia, Magnitogorsk) for manufacturing steel rods.

A standards solver of software package Abaqus 6.14-1 was used for the calculations. The model was axisymmetric. The rheological model was elasto-plastic. The friction was described by the Amontons-Coulomb Law with friction coefficient value 0.05. The macro model mesh included 26,000 elements. Elements type was CAX4R (Standard Element Library): a 4-node bilinear axisymmetric quadrilateral, reduced integration, hourglass control. Drawing tool had type “Discrete rigid”.

The front end of the workpiece moved with a speed of 30 m/min. This speed is nominal for this mode in industrial production. To obtain required accuracy of data transfer between scale levels, 3 places with high concentration of elements (0.5x0.4 mm with 100 elements) were located in mesh of the rod cross section. The general view of the model is presented in figure 5.

2.3.2. Micro simulation (RVE)

According to the commonly used definition, Representative Volume Element (RVE) is the element of the microstructure with a minimum size, which can still accurately represent investigated microstructure. Square with the size of 0.5x0.4 mm was used to create a RVE picture of the steel 20 microstructure. Typical image segmentation and reconstruction algorithms like contrast aligning, adaptive binarization, connected-component labelling, dilation and erosion were used to obtain final image (figure 6), where black islands of perlite are located on the white ferritic background. Thereafter, the resulting image was covered with a triangular element mesh consistent with Abaqus software. Mesh grid was prepared based on approach proposed by Madej et al. (2012).

Plastic properties of structural components, which were used in simulations, are shown in figure 7 (Balzani et al., 2008).

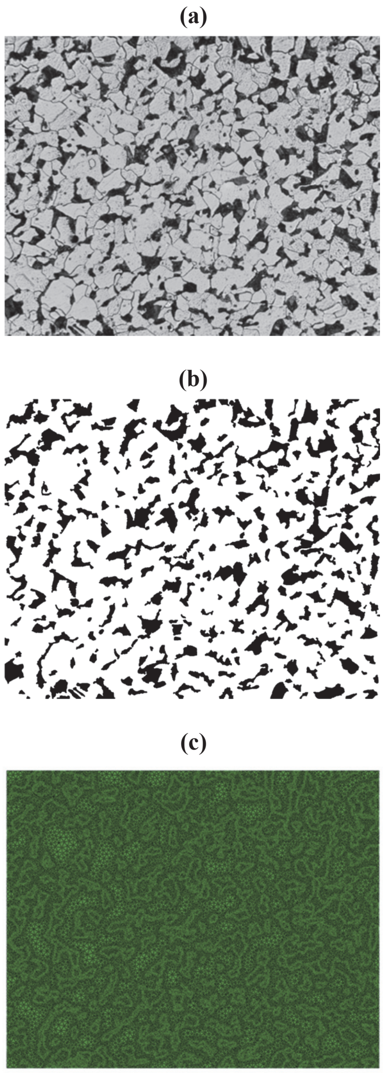


Fig. 6. Model creation stages: a) photo of microstructure; b) B&W version; c) meshed model for Abaqus.

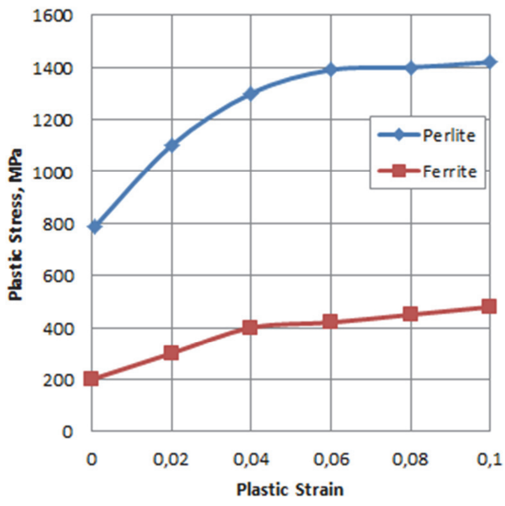


Fig. 7. Plastic properties of microstructure elements

2.3.3. *Micro simulation (SSRVE)*

However, the RVE itself and its preparing methodology have some serious drawbacks, which are summarized below:

1. The large number of elements in the model, resulting in high computing time.
2. Labor intensity and difficulty of creating such a model.
3. The lack of automation in creation of the model.
4. Availability of calculation errors in the individual elements.

All mentioned drawbacks make it difficult to perform calculations for a large number of variants that are needed for the analysis of a variety of technological processes. Therefore, SSRVE concept has been used to create a representative volume, which requires less computational resources. The idea of the SSRVE proposed by Schroeder et al. (2011) was used. The basic idea is to replace large representative volume (RVE) by statistically equivalent element (SSRVE) with similar morphology and stress-strain behavior under loading condition. This idea has already been successfully applied in the tests on the reconstruction of the DP-steels microstructure (Balzani et al., 2011a; 2011b; Rauch et al., 2011), but there are no works on the application of this concept to conditions of real industrial processes.

The process of SSRVE creation consists of the steps presented in figure 8 (Rauch et al., 2011).

The method is based on multicriteria optimization objective function. It is given by the equation composed of three internal elements responsible for identification of shape coefficients, statistical measures and rheological behaviour:

$$\Phi = \sqrt{\sum_{i=1}^{k} w_i \zeta_i^2 + \sum_{i=k+1}^{k+l} w_i \varphi_{i-k}^2 + \sum_{s=1}^{3} \left(w_s \sum_{j=1}^{p} \sigma_{sj}^2 (\varepsilon_j) \right)} \quad (1)$$

$$\zeta_i = \frac{\zeta_{iRef} - \zeta_{i\mathrm{SSRVE}}}{\zeta_{iRef}} \quad (2)$$

$$\varphi_i = \frac{\varphi_{iRef} - \varphi_{i\mathrm{SSRVE}}}{\varphi_{iRef}} \quad (3)$$

$$\sigma_{sj} = \frac{\sigma_{sjRef} - \sigma_{sj\,\mathrm{SSRVE}}}{\sigma_{sjRef}} \quad (4)$$

Where: equation (2) is a comparison of *i*-th shape coefficient, equation (3) is a comparison of statistical measures and equation (4) is a comparison of stresses obtained for three different deformations of referential microstructure and SSRVE, i.e. compression, tension and pure shear, w_i are parameters weights, k – number of shape coefficients, l – number of statistical measures, s – number of rheological curves, p – number of iterations in numerical simulations. Such approach allows comparison of not only individual numbers but also the whole rheological curves identified for microstructure and SSRVE. Rheological curves are created using following formulas:

$$\tilde{\varepsilon}_{ij} = \frac{1}{S}\int_S \varepsilon_{ij} dS \tag{5}$$

$$\tilde{\sigma}_{ij} = \frac{1}{S}\int_s \sigma_{ij} dS \tag{6}$$

Somewhat different situation was observed with radial stresses shown in figure 10. The average radial stresses in both models are generally identical. But macro model did not detect high compressive radial stresses and their distribution across the whole RVE. Moreover, the macro model did not detect zone of relatively high tensile stresses near the axis of symmetry. These facts are extremely important, because the numerical level of compressive stress corresponds to the plastic region of ferrite stress-strain curve. It helps to explain the growth of microhardness at the center of the rod. Thus, the micro level modeling has allowed not only to improve the accuracy of evaluation of parameter values, but also to detect new features of the stress-strain state.

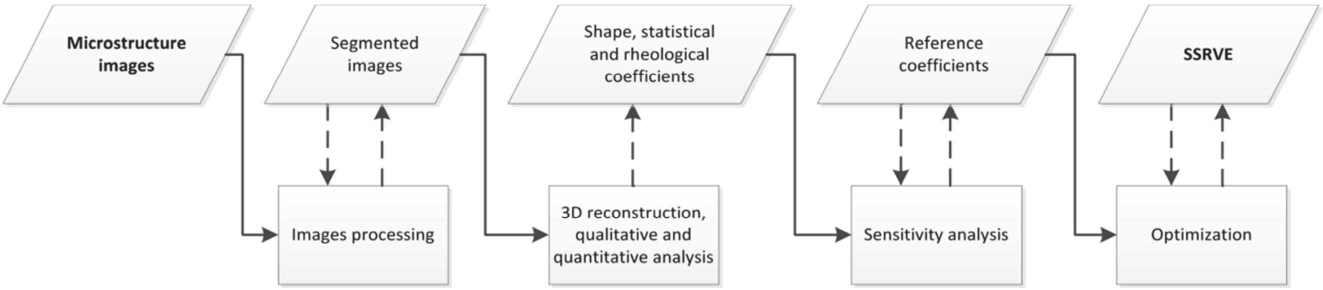


Fig. 8. SSRVE creation scheme

Equations (5) and (6) are calculated in each iteration of numerical simulation (S is the area of the microstructure or SSRVE sample). Non-uniform rational B-splines (NURBS) were chosen as grains representations. In this approach shapes can be easily modified by changing positions of control points on the restricted surface. The main goal of the optimization process was a modification of the position of control points to obtain the shape, which will give lower value of objective function (1). Modified genetic algorithm was used to solve the optimization problem.

4. RESULTS AND DISCUSSION

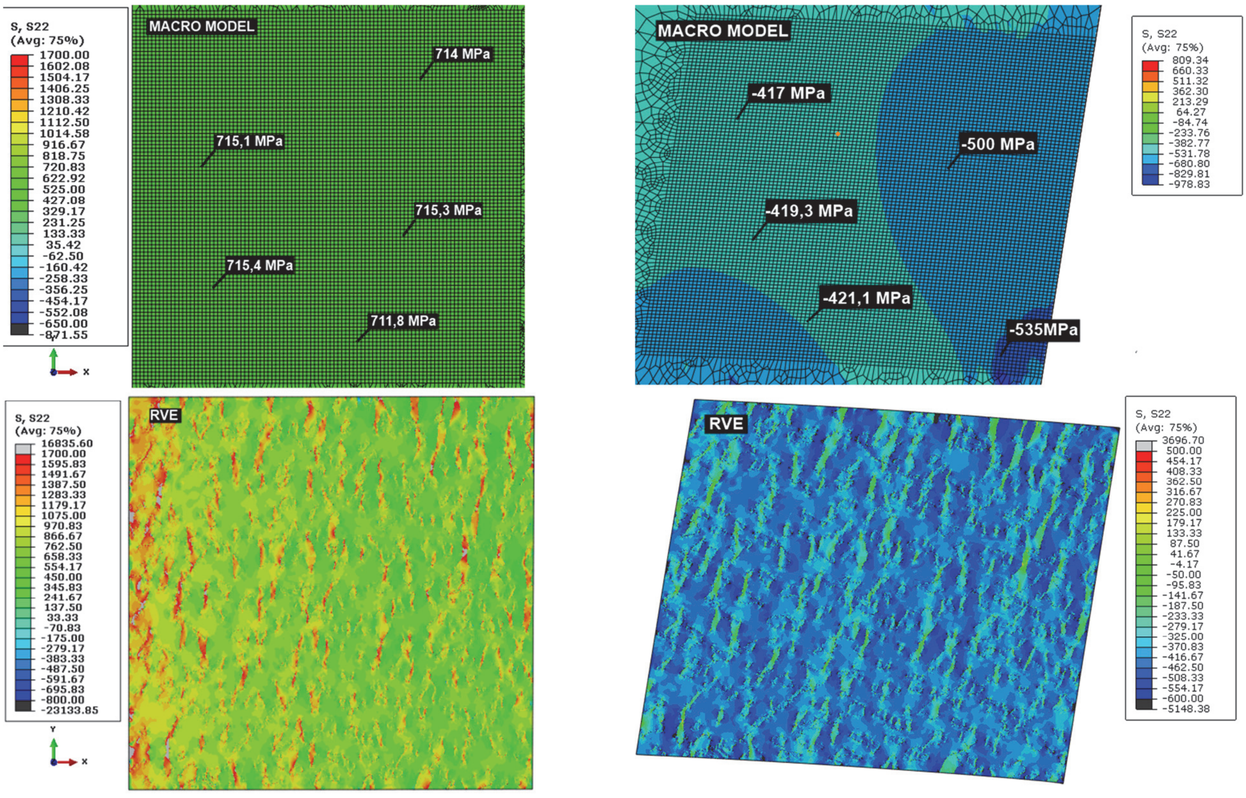
4.1. Results

4.1.1. Comparison of the macro and RVE models

The macro model showed similar average level of stress (figure 9). But RVE model has allowed to detect the localization of high longitudinal stresses at grains of perlite, as well as their very high localization near the axis of the rod. Thus, the RVE model showed more overall high accuracy of prediction and, therefore, it was considered more useful in predicting potential locations of chevron cracking.

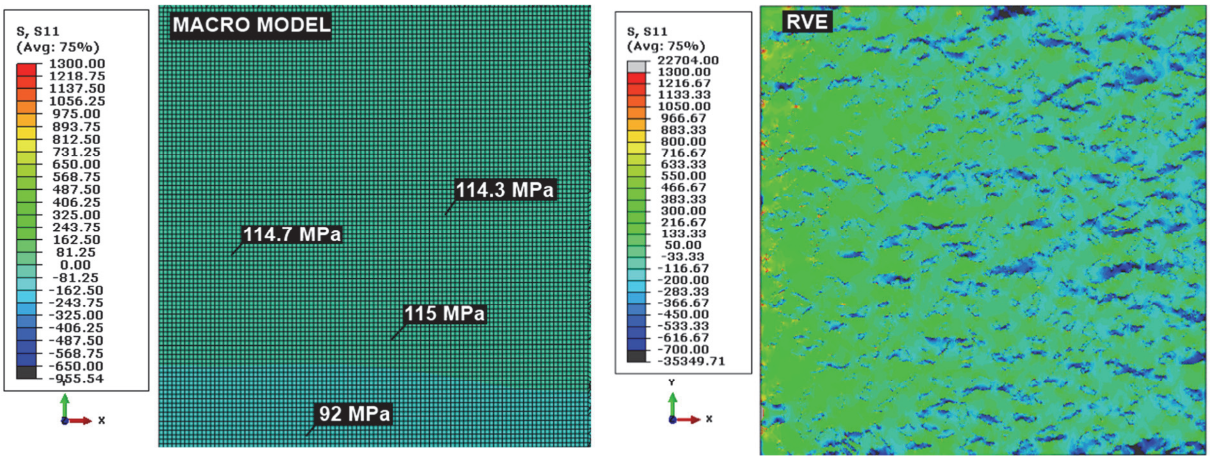
This behavior of the RVE can be explained by the fact that in modeling of micro volume we have to deal with a composite of extremely soft phase (ferrite) and much harder phase (perlite). Usually during metal forming processes, when simulation is performed at macro level only, such different behavior of each phase is homogenised. It explains why in case of rod drawing the macro model does not allow to justify the reasons of the microhardness increase in the center of the rod.

The influence of technological parameters (reduction ratio and die angle) on compressive radial stresses and strains was investigated by using RVE model and the results are shown in figures 11-14. The following method was used for the stress-strain state analysis. At each step of the calculation the values of compressive axial stress for all mesh elements of RVE were recorded. Following this, the values were sorted in the ascending order and selected 0.01% of the minimal values (0.01% of 285000 elements is about 28-30 elements) were selected. Finally, the average value of the resulting array was taken. In consequence, the process of data collection was automated and the risk of calculation errors due



(a) (b)

Fig. 9. The distribution of longitudinal stresses in the macro model and RVE: a) in the central layer; b) on the surface.



(a) (b)

Fig. 10. The distribution of radial stresses in the macro model (a) and RVE (b).

anomalous values in separate mesh cells was reduced. It means that figures 11-14 show the degree of the radial compressive strain, which was accumulated by RVE, and the corresponding level of stresses.

RVE allowed estimation of micro parameters and supplied information to discover new technological schemes of rod drawing that have not yet been applied in industrial production. At this point, in the real production at OJSC "MMK-Metiz" reduction of 1-2 mm and die angle of 18 degrees are used. But this choice of technological regime was carried out only from the standpoint of compliance with the requirements of the surface quality and dimensional accuracy for final product, without taking into account the deformation inhomogeneity in cross section. RVE shows the theoretical possibility of 1.5 times increase of reduction with relatively homogenous deformation of the whole rod cross-section. Classical macro simulations did not reveal the observed regularities.

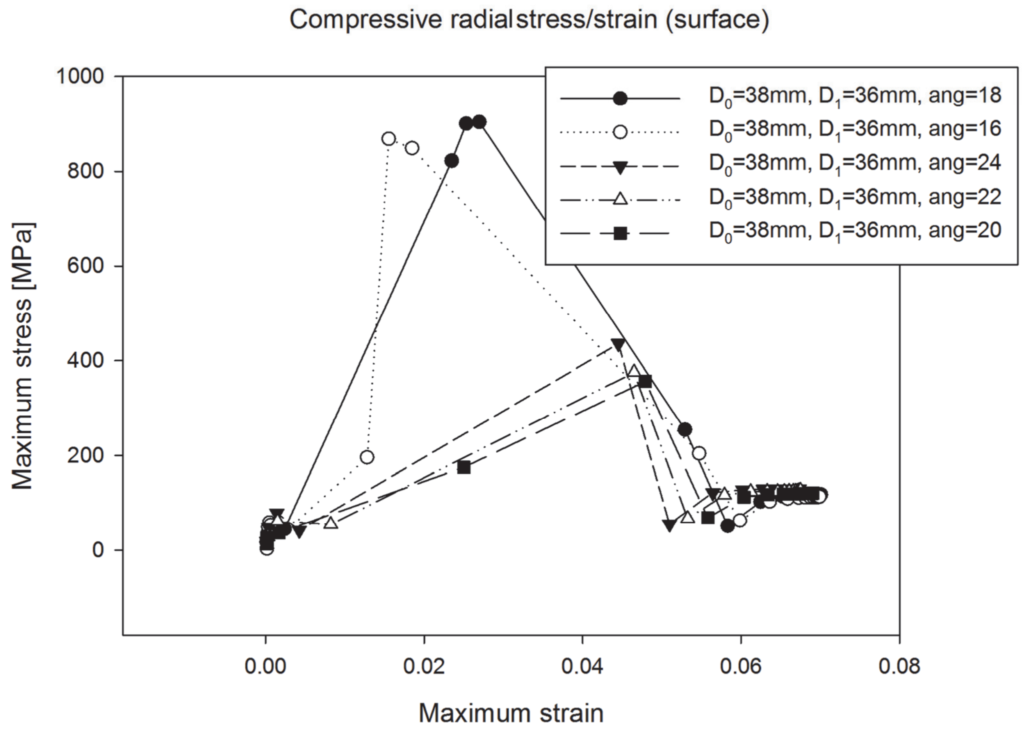


Fig. 11. *Influence of die angle on the distribution of compressive radial stresses and strains in the surface layer*

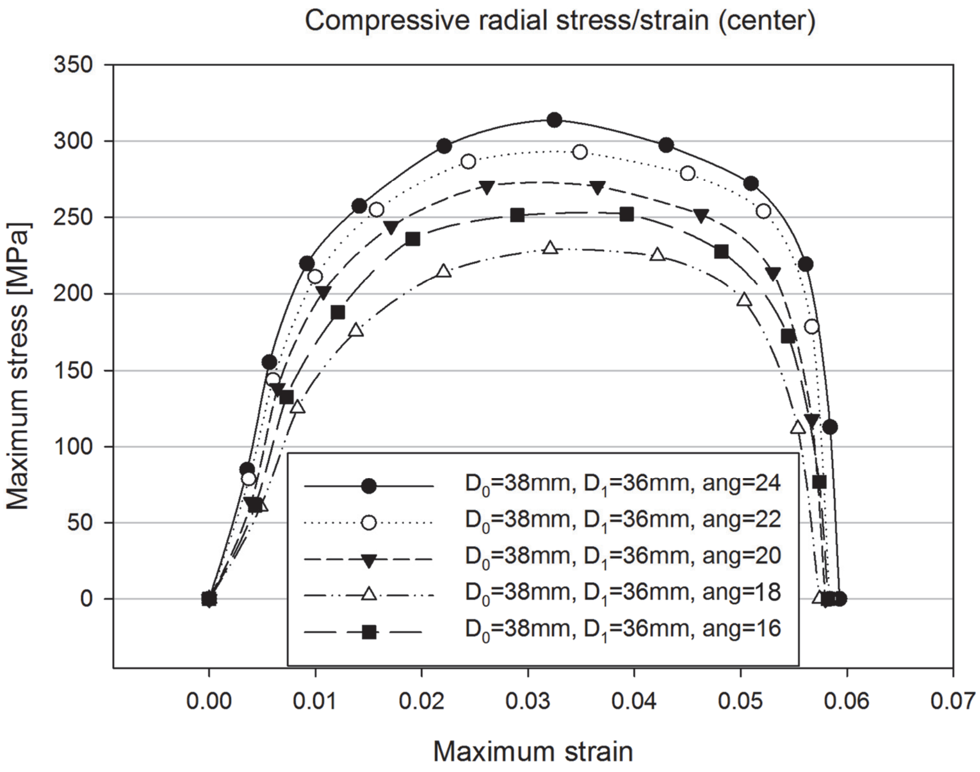


Fig. 12. *Influence of die angle on the distribution of compressive radial stresses and strains in the central layer*

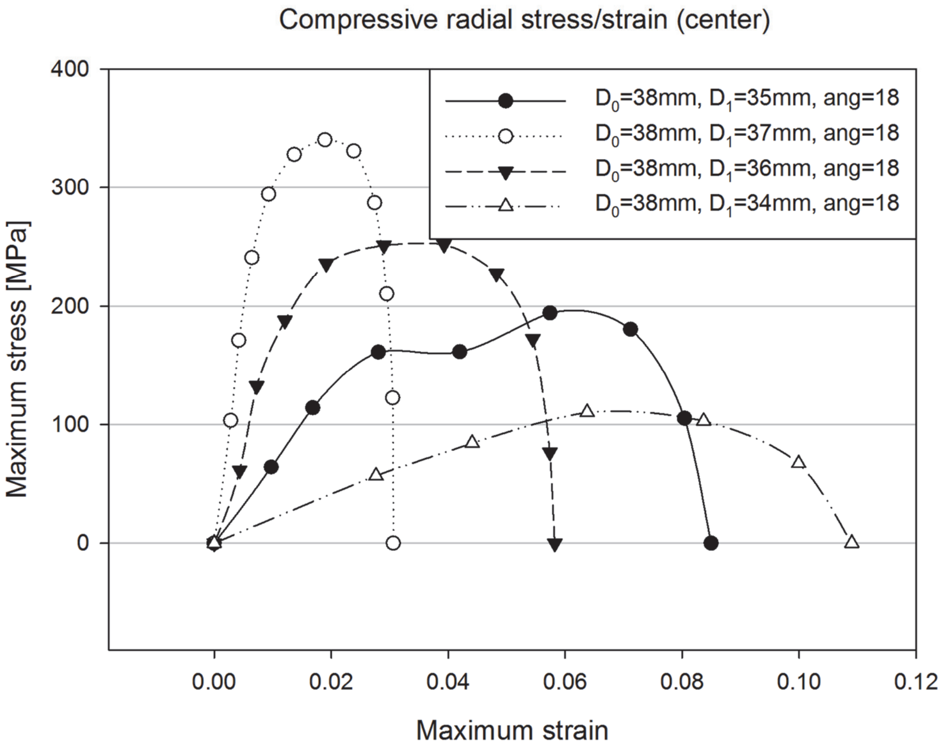


Fig. 13. *Influence of reduction degree on the distribution of compressive radial stresses and strains in the central layer*

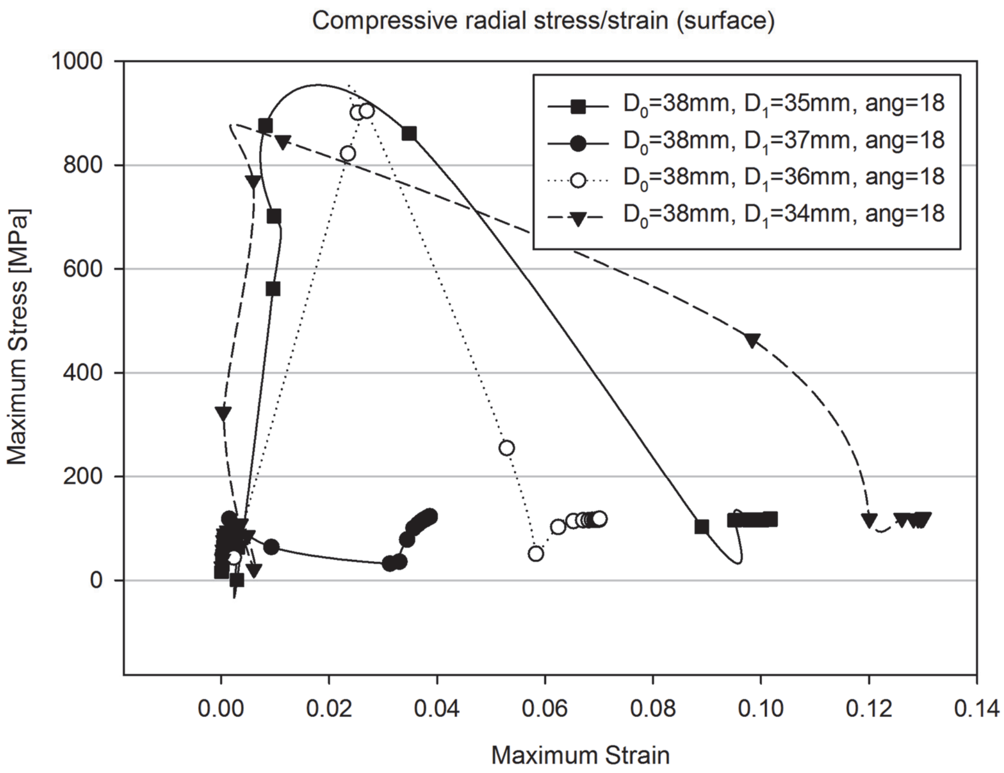


Fig. 14. *Influence of reduction degree on the distribution of compressive radial stresses and strains in the surface layer*

4.1.2. Comparison of RVE and SSRVE models

Statistically Similar Representative Volume Element, which was obtained during the optimization, is presented in figure 15. The size of this element was 0.02x0.02mm. The results of the load behaviour optimization are presented in the figure 16. The behaviour of the SSRVE under test loading conditions is almost identical to the behaviour of the RVE in the same conditions. The number of errors during optimization decreased below 2.5%.

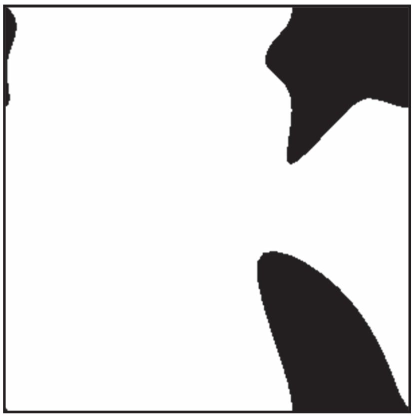


Fig. 15. Obtained Statistically Similar Representative Volume Element

Comparison of behavior of the SSRVE and the RVE in conditions of drawing process simulation is presented in figure 17. Analysis of the compressive radial stresses in the central layers of the rod allowed to conclude that SSRVE calculations gave identical character of the stress-strain state distribution with the minimum error in absolute values. The calculation time decrease was more than 60 times comparing to the RVE simulation.

5. DISCUSSION

The results showed that multiscale modeling has revealed new technological modes of rod drawing from position of favorable stress-strain state. But the

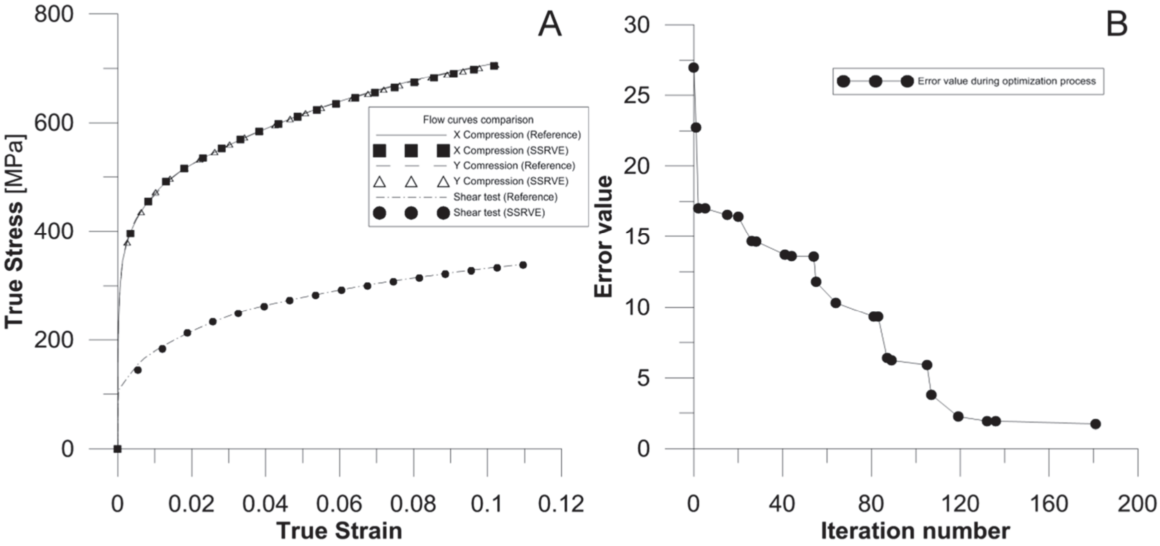


Fig. 16. Optimization results: a) comparison of stresses obtained for three different deformations of referential microstructure; b) changes of the error during optimization

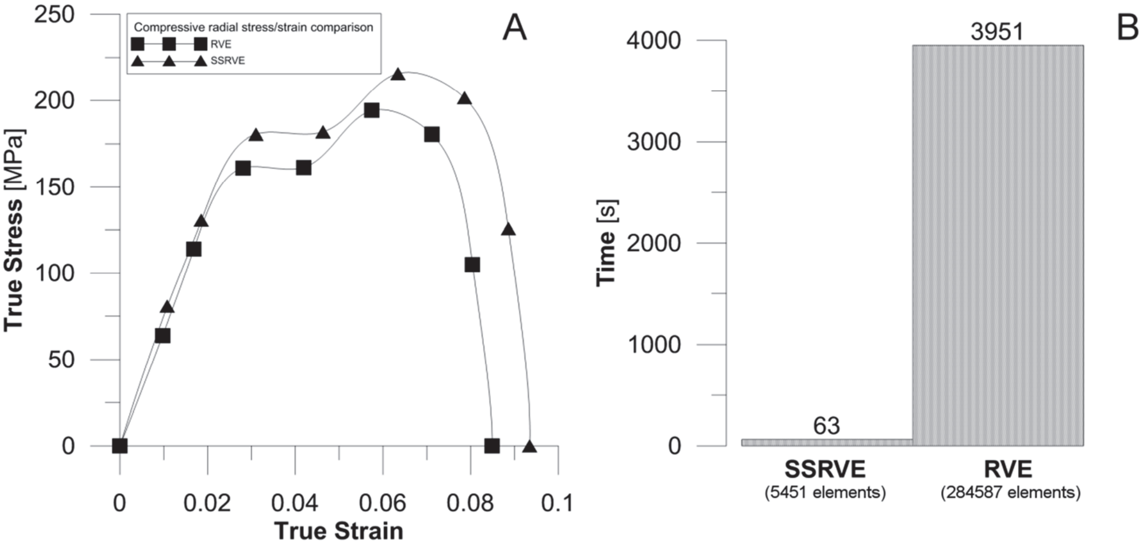


Fig. 17. Comparison of RVE and SSRVE: a) comparison of stress/strain ratio; b) calculation time (10 threads)

classical techniques of the multiscale simulations of phenomena occurring in the microstructure are not always optimal from the perspective of the required computational resources. Therefore, the SSRVE concept was applied in the present paper and the following goals were reached:

1. Simplifying and automating the process of microstructure model creation.
2. Reduction of the computing time.
3. Reduction of the required computational resources.

All these goals were reached while the accuracy of the prediction was kept on the reasonably stable level. Further prospective development of the SSRVE conception is its application for steels with more complex microstructure (such as TRIP-steel) and accounting for different deformation mechanisms.

ACKNOWLEDGEMENTS

The research is financed by the Ministry of Education and Science of the Russian Federation (2014-2015).

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WIELOSKALOWE MODELOWANIE Z ZASTOSOWANIEM STATYSTYCZNEJ REPREZENTACJI MIKROSTRUKTURY ODKSZTAŁCENIA STALI FERRYTYCZNO-PERLITYCZNEJ W PROCESIE CIĄGNIENIA PRĘTÓW

Streszczenie

Celem pracy jest rozwój metod modelowania, które pozwalają przewidywać rozkład własności w objętości wyrobu gotowego uzyskiwanego na drodze przeróbki plastycznej. Metody te uwzględniają cechy mikrostruktury w warunkach odkształcenia. Jako przykład rozważono proces ciągnienia prętów. Zaproponowany został wieloskalowy model dla tego procesu. W celu obniżenia czasu obliczeń wprowadzono statystyczną reprezentację mikrostruktury. Opracowany został statystycznie podobny reprezentatywny element objętości (ang. Statistically Similar Representative Volume Element - SSRVE), reprezentujący strukturę ferrytyczno-perlityczną. Przeprowadzono symulacje procesu ciągnienia prętów i wyznaczono odkształcenie każde fazy w mikrostrukturze. W artykule przedstawiono wybrane wyniki symulacji i przeprowadzono dyskusję uzyskanych rozkładów odkształceń i naprężeń w prętach.

Received: February 12, 2015
Received in a revised form: March 16, 2015
Accepted: April 1, 2015