MICROSTRUCTURE-BASED COMPUTER SIMULATION OF PEARLITIC STEEL WIRE DRAWING

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Abstract

Cold-drawn high-carbon steel wire with pearlite microstructure is one of the most popular raw material for modern reinforcing ropes. Lamellae thinning, changes in interlamellar interface and metallographic texture, strain localization are the main property-forming phenomena in the wire drawing process. However, the experimental study of these phenomena dynamics is difficult and time-consuming. Drawing process of pearlitic steel wire was investigated. Behavior of pearlite colonies on the surface and the central layer of the wire was researched based on the multiscale computer simulation. Cementite lamellae orientation in relation to the drawing axis, interlamellar spacing and shape of cementite inclusions were key factors. Regularities of the pearlite colonies reorientation, changing the shape and size of cementite lamellae and strain localization in the ferrite were established on the basis of FEM. It was established that the cementite lamellae, that are parallel to the drawing axis, had the maximum thinning. Interlamellar distance in pearlite colonies with such lamellae changed most intensively. Cementite lamellae, that are perpendicular to the drawing axis, are the most susceptible to fracture. It found that for certain values interlamellar distance this effect can be reduced. Intensive reorientation of pearlite colonies in relation to the drawing axis was observed in the case of their location at an angle to the drawing direction. At the same time there were a significant bending of cementite lamellae and their susceptibility to fragmentation. Estimated values of the wire mechanical properties were compared with a real experiment. The simulation results were verified by metallographic analysis.

Keywords: Wire drawing, pearlitic steel, multiscale simulation, cementite lamellae orientation, interlamellar interface

1. INTRODUCTION

Steel with a pearlite structure is a classic example of a nanostructured metallic material. Due to its strength properties and crack resistance, pearlite steel is rightly called one of the strongest metallic bulk materials at the moment [1-5]. Traditionally, this steel type is used in the wire production. In this case it is possible to archive 5-7 GPa strength level of such steel by drawing after preliminary heat treatment [6]. For this reason, cold-drawn wire from steel with pearlite structure is popular raw material for the production of modern reinforcing ropes, metal cord, ropes, etc. [7]. The combination of high strength, non- complex alloying and the possibility of small diameters obtaining allows reducing steel consumption of the structures in the mining industry, production of constructive elements, elevators, etc. However, the main property-forming processes during wire drawing are lamellae thinning, changes in interlamellar interface and metallographic texture, strain localization [8-11]. These parameters dynamically change during the drawing process and determine the processability of the wire at the next stages of production. Few papers devoted to multiscale computer simulation of pearlite steels drawing clearly demonstrate the expediency and relevance of studies of microstresses and microdeformations at the level of pearlitic colonies [12-14]. It was observed that the stress-strain state, even at the scale level of individual perlite colonies, is characterized by a high degree of inhomogeneity. Therefore, the development of these ideas for practical-oriented prediction of the wire properties after the drawing process has great importance for the design of multi-stage industrial technologies.

2. MATERIALS

The initial billet was made from steel with the chemical composition given in **Table 1**. The initial billet was subjected to the patenting process [15] under industrial conditions.

Table 1 Chemical composition of the studied steel grade (wt. %)

C	Si	Mn	Cr	Ni
0.81-0.82	0.31-0.32	0.55-0.56	0.02	0.02-0.03

The initial microstructure of patented samples consisted of ferrite-carbide mixture with average interlamellar spacing 0.147 µm. The interlamellar spacing on the surface of the sample is 0.098 µm. The mechanical properties of the initial billet after patenting are given in **Table 2**. The mechanical properties of individual microstructural components were chosen on the basis of previously published studies [16].

Table 2 Mechanical properties of the patented billet for drawing

Yield stress $\sigma_{0.2}$, MPa	UTS σ_B, MPa	Percent elongation δ_{10}, %	Reduction in area ψ, %
820	1196	10.6	30.3

3. METHODS

The process of pearlite steel nine-pass drawing according to the following reduction schedule with the total strain degree ~88 % was researched:

$12.00 \xrightarrow{24.6} 10.42 \xrightarrow{23.6} 9.11 \xrightarrow{22.5} 8.02 \xrightarrow{21.6} 7.10 \xrightarrow{20.0} 6.35 \xrightarrow{20.8} 5.65 \xrightarrow{19.8} 5.06 \xrightarrow{19.1} 4.55 \xrightarrow{18.8} 4.10$

The basic principles of simulation creation are described in papers [17-18]. The microstructure of the initial billet has few distinctive aspects (**Figure 1**): A) cementite lamellae which are parallel to the axis of drawing; B) cementite lamellae which are perpendicular to the axis of drawing; C) cementite lamellae which are located at a certain angle relatively to the axis of drawing; D) finely dispersed inclusions of predominantly ellipsoidal shape; E) elongated curved plates in areas of ferrite accumulation. For further research, the following representative volumes were prepared (**Figure 2**).

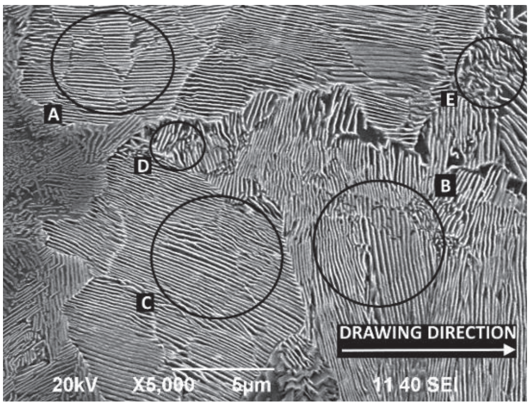


Figure 1 Microstructure of initial billet before wire drawing process

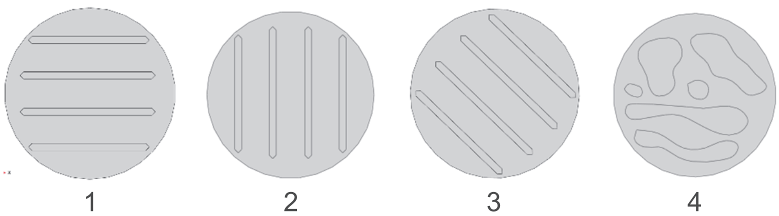
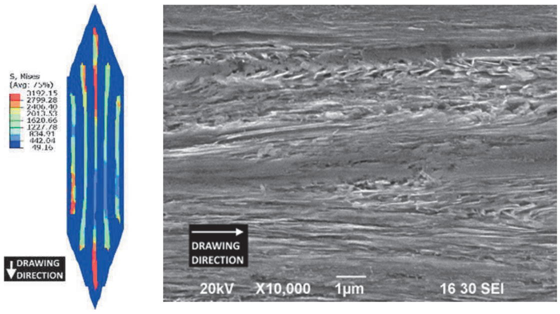


Figure 2 General view of RVEs: 1 - cementite lamellae are parallel; 2 - cementite lamellae are perpendicular; 3 - cementite lamellae at 45°; 4 - cementite with the shape of fine inclusions and curved plates

4. RESULTS

The micromodels analysis of pearlite colonies oriented parallel to the drawing axis showed that for this orientation cementite lamellae are most prone to thinning. At the same time, the thinning of cementite lamellae was relatively inhomogeneous with the formation of "neck". Such pearlite colonies were stretched as far as possible in the direction of the drawing axis. The interlamellar spacing in such colonies changed most intensively. Approximately after the fifth drawing pass (total strain degree 0.65), initialization of partial fracture of individual cementite lamellar is observed, which is confirmed by metallographic experiment (**Figure 3**).



a b

Figure 3 Distribution of Mises stresses in pearlite colonies parallel to the axis of drawing (a), and the picture of the microstructure (b) in the center of the wire

The described features of the interlamellar spacing changes most typically occur on the surface of wire. On the surface of the wire, cementite lamellar oriented parallel to the drawing axis acquired additional distortion and lost parallel orientation (**Figure 4**). Absolute values of Mises stresses and Equivalent strains in the center and on the surface of wire were commensurably the same: the maximum value is 3100 MPa,the minimum value is 1500 MPa. However, the distribution of the stress-strain state parameters in the pearlitic colonies in the center of the wire was more inhomogeneous. With a twofold decrease in the interlamellar spacing the stress-strain state of the cementite lamellar became more uniform (**Figure 5**). The stress-strain state of a pearlite colony with a bigger interlamellar spacing is characterized by multitude of localized Mises stresses on the level 3000 - 3200 MPa, with an average stress value of 2000 - 2200 MPa. With a decrease in the interlamellar spacing the stresses and strains localizations number also decreases (in 1.3 - 1.5 times), and therefore the perlite colony tends to deform as a single whole. Through simulations it was found that the colonies, which are oriented perpendicular to the axis of drawing, the most susceptible to deformation and fracture (**Figure 6**).

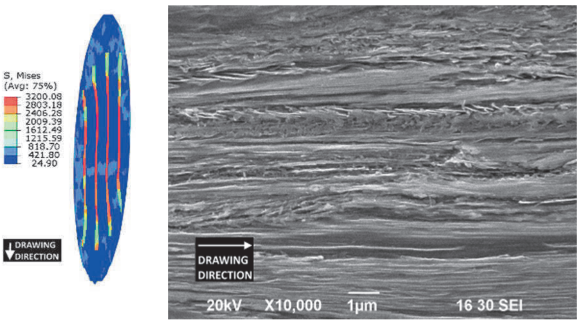


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Figure 4 Distribution of Mises stresses in pearlite colonies parallel to the axis of drawing (a), and the picture of the microstructure (b) on the surface of the wire

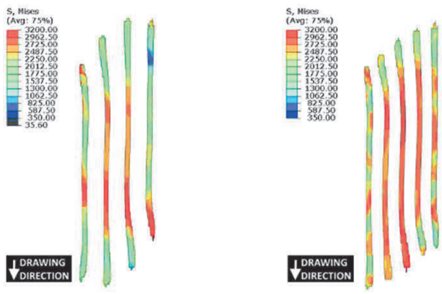

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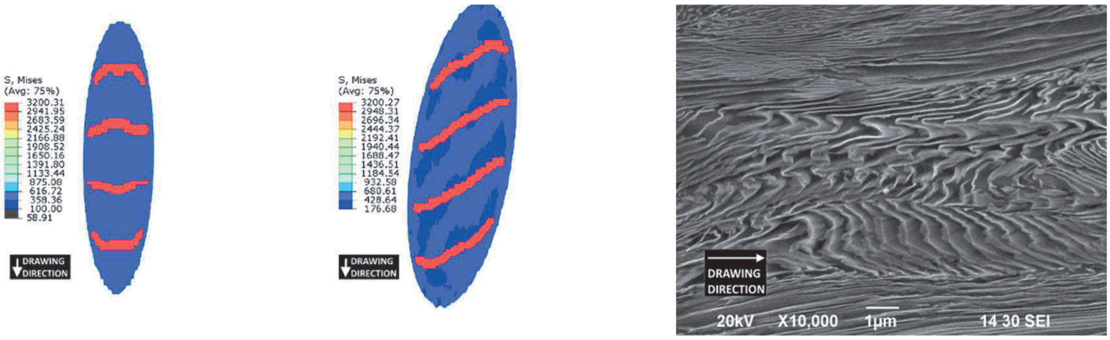
Figure 5 Comparison of the Mises stresses distribution in colony with different interlamellar spacing: 100 % (a) and 50 % (b)

The interlamellar spacing in these colonies varies insignificantly, but the fragmentation of these lamellar with the formation of submicrocrystalline structure is most intense. At the same time, these areas are the most probable places for the initialization of various microcracks, what agrees with the previously published results [19-23].



a b c

Figure 6 Mises stresses distribution in pearlitic colonies perpendicular to the axis of drawing in the center (a) and on the surface (b) of the wire and the microstructure picture (c)

Another situation is observed in pearlite colonies oriented at an angle to the axis of drawing. In the micro-simulation the initial angle was taken as equal to 45 ° (**Figure 7**). The quantitative values of the parameters of the stress-strain state at this orientation of the cementite lamellar were the same on the surface and in the center of the wire. In this case, as the strain degree increases, the cementite lamellar change their orientation angle, tending to parallel with the direction of drawing. This is consistent with metallographic researches [24-26]. Such an initial orientation in space makes it possible to realize much greater strain degrees in local volumes than parallel or perpendicular.

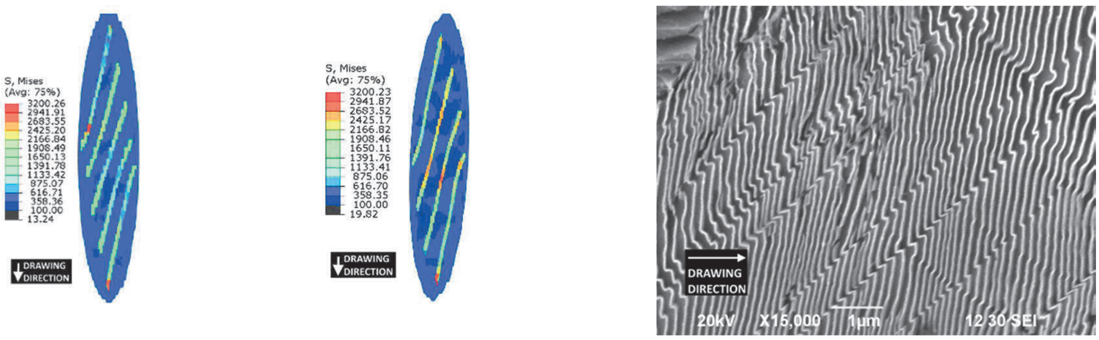


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Figure 7 Mises stresses distribution in pearlitic colonies with orientation angle 45° to the axis of drawing in the center (a) and on the surface (b) of the wire and the microstructure picture (c)

However, with the accumulation of a strain degree (more than 0.70), fracture or bending of cementite lamellar begins. The individual parts of the lamellar are deformed by shearing in places with a locally high stress concentration in the ferrite. Fine inclusions with predominantly ellipsoidal form slightly change their shape and size. In this case, significantly curved in the initial state cementite lamellar can be distorted up to a loop-like state with uniform deformation along the entire length of the lamellar [7]. Further, in accordance with paper [25], a comparative analysis of the mechanical properties of real wire samples and their calculated values was carried out according to the dependence (**Figure 8**):

$$\sigma_R(i) = \sigma_0 + k\left(\frac{\bar{s}_0(i)}{\cos\beta_0(i)}\right) \quad (1)$$

In the approach used in the present work (based on the Embury-Fisher equation) the constant k depends on chemical composition, the value remaining constant during the whole drawing process.

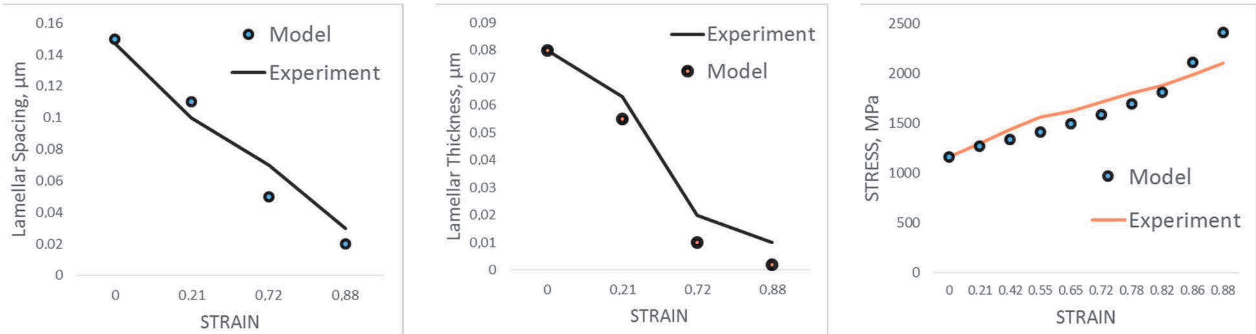

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Figure 8 Comparative analysis of mechanical properties and parameters of microstructure in real wire samples and their calculated values

5. CONCLUSION

It was found that the cementite lamellae, that are parallel to the drawing axis, had the maximum thinning. Interlamellar distance in pearlite colonies with such lamellae changed most intensively. Cementite lamellae, that are perpendicular to the drawing axis, are the most susceptible to fracture. Intensive reorientation of pearlite colonies in relation to the drawing axis was observed in the case of their location at an angle to the drawing direction. The high predictive power of the proposed models is proved by comparison with the results of an industrial experiment.

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