Features of a severe plastic deformation method for threaded steel reinforcing bars used in construction

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Abstract. Enhancing the mechanical properties of products by developing new technologically advanced SPD methods, as the most efficient for strengthening of materials due to deep refinement of the initial structure, is an urgent task. For this purpose, a method was developed for the continuous forming of threaded rods with the required properties, using successive operations of rolling and transverse shear. The produced rods with a threaded profile can be used in construction as reinforcing bars for the reinforcement of concrete structures. The studies were conducted using mathematical modeling and physical experiments. We analyzed the stress-strain state of the produced billets. In one processing cycle, the strength of the initial billet from low-carbon steel 10 was raised from 350 to 530-550 MPa and simultaneously a threaded profile was formed. The obtained parameters comply with the Russian state standard GOST for steel reinforcing bars of the A500 class used in construction.

1. Introduction
For producing construction reinforcing bars, the hot rolling of steel rods with special rolls of complex design is predominantly used. It is evident that the operating, engineering and energy costs of such a technology are very high [1]. In the present study, we propose an alternative technology for producing construction reinforcing bars (rebars) that employs the principles of severe plastic deformation (SPD) [2-4] and is based on the use of successive forming operations of rolling and transverse shear (by free torsion) (figure 1). As the initial billets, we used the most common round rolled sections (rods, coils). In the process of rolling, a square cross section is formed from a round section, the initial billet becomes strengthened and during the second operation it is subjected to shear. It is known that shear deformation is less energy-consuming than other types of deformation (compression, tension). Shear provides not only the forming of a threaded profile with an inclination angle of 45-60°, but also additional deformation and strengthening of a rod. In this connection, the task is to verify experimentally the proposed technology using laboratory devices and a physical experiment. To solve the set task, at the first stage it is necessary to evaluate the stress-strain state of the deformed billets using computer simulation, which will reduce the costs at the experiment stage and provide scientific and technical information on the process parameters.

2. Material and experimental procedures
To perform the experiment by means of numerical simulation, we used the software package DEFORM-3D. Using a CAD software Kompas-3D, we designed the 3D models of the deforming tool and the billet under study.
As the material for the investigation, we selected from the Deform-3D material library the low-carbon steel AISI1010, an analogue of steel 10.

Figure 1. Principle of the method of rolling with forming: 1- rolling rollers, 2-guide, 3-twisting mechanism [5].

The following boundary conditions were used in the simulation:
1) The initial material is ductile and isotropic.
2) The experimental temperature is 20 °C, deformational heating is not considered.
3) The tool is rigid.
4) The initial material’s diameter is 10 mm, and the length is 500 mm.
5) The simulation includes 500 steps.
6) The billet is divided into 70000 elements.
7) The coefficient of friction between the billet and the tool, calculated according to Zibel’s formula, is 0.12.
8) The number of passes - 1 pass
9) The size of the bar after deformation - 8.6 mm in diameter
10) Sample twist angle - 45 ° +/- 2 °
11) Linear speed during deformation - 1.8 m / min

The simulation results were used to find the variation in the intensity of accumulated plastic strain and the average stresses of the billets produced by the proposed method.

To produce the experimental samples of reinforcing bars, we developed and manufactured a laboratory die-set (figure 2).

Figure 2. Experimental die-set for implementing the operation of transverse shear and the appearance of the produced samples.

3. Experimental results and discussion
The computer simulation results show that during the deformation by rolling, the largest strain is accumulated in the surface layers of the billet, where strain reaches a value of \(e=1.4\). Further deformation
by transverse shear raises the level of accumulated strain which reaches values of about \( \varepsilon = 2 \) in the surface layers of the billet (figure 3). As a rule, such a level of cold non-monotonic strain ensures a rather intensive refinement down to the ultrafine sizes [6].

Figure 3. Strain state of the billet after the operations of rolling and transverse shear: a – the pattern and diagram of accumulated strain distribution after rolling, b – the pattern and diagram of accumulated strain distribution after transverse shear.

Figure 4. Pattern of damage distribution across the section of the deformed rod.
Studies of the damage parameter, conducted in the software system Deform-3D on the basis of the Cockroft-Latham criterion, reveal its low values not exceeding 0.3, which indicates a rather large operational safety margin of the produced rods (figure 4).

Studies of the mechanical properties of the produced billets demonstrate that after rolling the billet is strengthened to 420-430 MPa, and after transverse shear – to 530-550 MPa.

4. Conclusions
1. With the use of computer simulation, we studied an end-to-end process for producing threaded reinforcing bars of the A500 class, analyzing the stress-strain state parameters and the damage parameters of the deformed billets during their processing by the strengthening and forming operations of rolling and transverse shear. A gradient strain distribution has been found in the bulk of the finished product. The strain accumulated in the peripheral layers reaches $e \sim 2$, while the central layers it reaches $e \sim 0.7$.
2. The obtained damage parameter based on the Cockroft-Latham criterion does not exceed 0.3, which indicates a rather large operational safety margin of the produced reinforcing bars.
3. In one processing cycle, the strength of the initial billet from low-carbon steel 10 was increased from 350 to 550 MPa, and simultaneously the required threaded profile with an inclination angle of 50° was formed. Both parameters comply with the Russian state standard GOST for construction reinforcing bars of the A500 class.

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