OBTAINING OF LONG-LENGTH RODS WITH ULTRAFINE-GRAINED STRUCTURE BY THE RADIAL-SHEAR ROLLING

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Abstract. Improving the quality of metal products by modifying the structure is one of the main trends in materials science. However, the main problem of such materials is the small final size of the workpieces and low technological production. The paper presents data of the experimental production of ultra-fine-grained structure in a long rod of steel grade AISI 321 by radial-shear rolling. With a grain size of 300-600 nm, the mechanical properties and microhardness increase by more than 2 times while having a heterogeneity across the bar section.

Keywords: radial-shear rolling, ultrafine-grained structure, stainless steel, mechanical properties, microhardness, intensive plastic deformation, transmission electron microscopy

1 Introduction

Currently, progress in the production of new metal materials is focused on a deep change in the internal structure of the metal. The most effective way to improve the structure and properties of the metal is severe plastic deformation (SPD). Thus, bringing the metal microstructure into an ultra-fine-grained (UFG) state opens up great prospects in the field of materials engineering [1-2].

In the process of grinding the microstructure, with increasing the proportion of intergranular boundaries in the volume of the workpiece, along with changes in the mechanical properties of the material, its other physical properties also change, such as electrical resistance or radiation resistance [3]. The latter phenomenon is based on the fact that the grain boundaries serve as the drain surface for radiation defects of the grain crystal lattice, which are mass formed due to neutron irradiation in the reactor core. A large specific number of grain boundaries in UFG-structural materials significantly increase the number of such surfaces. The use of SPD will provide a new class of materials for nuclear power not only with improved mechanical properties, but also with increased resistance to neutron irradiation. This problem is very relevant, because a significant share in the cost of nuclear power plants is the replacement and disposal of structures operating in the core. The extension of the life cycle of such elements by manufacturing them from UFG materials can justify the relatively high cost of such products and make them commercially attractive, which in general is of high relevance for the UFG products market.

However, here the difficulties associated primarily with the lack of a reliable way to obtain a sufficient number of such materials with sufficient dimensions for commercial products. The most frequently used and studied methods, such as equal-channel angular pressing (ECAP) with good microstructure quality, have critical limitations on the length of the resulting workpiece, which
significantly complicates its industrial application [1]. The method of multi-axis forging allows you to get a relatively large workpiece. On the other hand it is very time-consuming and has its limitations. The problem of obtaining a long billet with UFG-structure is solved by means of ECAP-Conform and rolling-pressing, but only for non-ferrous metals and alloys. The method of accumulated roll bonding (ARB) for sheet materials is promising, but also still has a number of disadvantages for commercial use.

2 Experimental part
Radial-shear rolling (RSR) allows to obtain UFG structure of the long-length workpieces, but also has its disadvantages associated with the homogeneity of the structure and properties of the cross section of the workpiece (from the edge to the center). This method was invented by S. P. Galkin in ”MISIS” [4-5]. The difference from the usual cross-screw rolling, which is used in the tube rolling, is that a single round bar is rolled here along a three-roll scheme with increased feed angles of the rolls, which contributes to the intensification of shear deformation and non-monotonicity of the metal flow under the predominance of the hydrostatic compression scheme [1]. Such conditions are favorable for the formation of UFG structure, especially at low temperatures of deformation. Despite the lack of unevenness of the cross-section structure, this method has great potential, because unlike other methods it is as simple, efficient and technological as possible. And this drawback may be insignificant in the case of production of products having the shape of a pipe (for example, tubes of fuel elements of the reactor). It adds relevance to the question of obtaining UFG structure on the materials used in the nuclear power industry.

For the experiment, austenitic stainless steel AISI-321 (0.08% C; 17-19% Cr; 9-11% Ni; 2% Mn; 0.8% of Si; 0.5 to 0.7% Ti, all in wt. %) was chosen, since it is the main structural material of nuclear power. In particular, it is used for the manufacture of tubes of fuel elements of the most advanced fast neutron reactors. This steel is also used for the production of equipment operating in high temperature and aggressive environments (heat exchangers, pipes, parts of furnace and reactor valves, spark plug electrodes).

The experiment was conducted at Rudny Industrial Institute on the radial-shear rolling mill in-house marked 14-40. The mill is designed for hot and warm deformation of bars from almost any metal materials, including low-plastic, cast, composite and powder blanks. A special feature of the mill is the construction of the working stand of increased rigidity, which is a massive cylinder with grooves for the rolls cassettes. For expansion of assortment of mill two types of cassettes with rolls of a diameter of 90 mm and rollers with a diameter of 46 mm were used. Power of motors is 3×7.5 kW. Since one of the conditions for the formation of UFG structure is a reduced temperature of deformation, the temperature of the experiment 800 °C as the lowest technically possible value for rolling this steel at the mill 14-40 was chosen. The same temperature in the production of UFG structure on this steel by ECAP method in work [6] was used. The initial blank with a diameter of 30 mm and a length of 300 mm should be rolled in several passes to a diameter of 13 mm with an extraction equal to 5.

Before the experiment to determine the deformation parameters, in the software complex DEFORM-3D (SFTC, USA) finite element simulation of the process with the above conditions was carried out. The number of finite elements was 50 000, heat transfer and friction parameters recommended for hot deformation. Geometric and speed parameters of the model corresponding to the real process, except for the length of the workpiece, which was significantly reduced, because the real mill, unlike the model, successfully rolled short workpiece is technically difficult.

3 Results and discussion
The results of the model calculation are shown in figure 1. According to the obtained results, the degree of deformation of the peripheral zone of the sample by the end of rolling exceeds 15, while the axial zone receives the degree of deformation about of 5-6. Such deformation is already considered to be large and can lead, under other favorable conditions, to the formation of UFG structure. However,
the flow of metal in this zone is laminar, which should lead to the formation of highly elongated narrow grains such as rolling texture.

![Figure 1. Results of FEM-simulation](image)

Microhardness was measured on hardness testing HVS-1000B on the transverse microsection through every millimeter of cross section. For each point 5 measurements were made, the results are averaged and presented in the form of a graph in Fig. 1. The total level of microhardness is 290-320 HV, which is 2 times more than the initial one. The graph shows a smooth decrease in the microhardness of the axial zone by 10.2 % (33 HV). This phenomenon can be explained by the structural heterogeneity caused by different nature and degree of deformation of different areas of the workpiece. The microhardness drop in the center is also correlated with the calculated distribution of the degree of deformation in the cross section of the model below the graph. Further, according to the described scheme, a physical experiment on the mill 14-40 was carried out. Before rolling, samples were taken from the rod to determine the original structure and properties. The initial structure is equiaxed grains of size 60-80 microns, tensile strength is 493 MPa, Vickers microhardness is 160HV (load is 9.87 N, exposure is 15 sec), which generally corresponds to the known data [6-7].
Heating was carried out in a tubular furnace Nabertherm R 170/1000/13 to 800 °C with a heating time of 30 minutes. Then the heated billet was rolled in series in several passes to a diameter of 13 mm, after which it was intensively cooled with water. After rolling, from deformed rod in the longitudinal direction at a distance of half the radius from the center were made flat samples 30 x 3 x 0.3 mm for tensile testing on the machine Instron-1195. According to the test results of 5 samples, tensile strength is 1073 MPa, which is more than 2 times higher than the original.

Figure 2. Results of experiment: a – axial zone, b – peripheral zone
From the plates cut out along the longitudinal section of the rod, samples were also prepared for the study of the microstructure of the axial and peripheral zones on the transmission electron microscope JEM-2100. Photos of typical areas are shown in Fig. 2. The images show that in the peripheral zone formed equiaxial UFG structure with grains of 300-600 nm, while in the axial zone formed a completely different type of structure – a texture with elongated grains of 200-600 nm and a length of several microns. The resulting structure corresponds to theoretical expectations, and correlates with the structure of the obtained by other methods of SPD under similar conditions [6]. However, it is important to note that in this case, a long steel rod UFG was obtained at a lower cost.

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