

The effect of radial-shear rolling on microstructure and mechanical properties of stainless austenitic steel AISI-321

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Abstract. Improving the quality of metal products by crushing of the microstructure of material is one of the promising areas of modern metallurgy. The basic idea consists in refinement the grain structure of the material to sizes less than a micron, i.e. the obtaining of ultrafine-grained (UFG) materials, offering higher strength properties of the material under preservation or a small loss of ductility. Stainless austenitic steel AISI 321 is widely used in all the above areas as well as in chemical, vacuum and nuclear technology. For the obtaining of UFG structure in this material the method of radial-shear rolling is used. For the purpose of identifying the influence of radial-shear rolling on microstructure and mechanical properties of stainless austenitic steel AISI-321, the experiment was conducted where at the radial-shear rolling mill SVP-08 at 800 °C in several passes of the workpieces with a diameter of 30 mm rolled till a diameter of 13 mm with following cooling in water. The analysis of the microstructure of deformed samples showed the presence of equiaxed ultrafine-grained structure in the peripheral areas of the workpiece and the presence of elongated fibrous texture in the axial zone. The strength characteristics of the workpiece has increased more than 2 times, with a slight decrease of plasticity.

Keywords: metal forming, rolling, micro structure.

1 Introduction

Most of industrial processes of metal production are oriented to technological effectiveness of deformation process, and necessary level of mechanical properties is obtained by using appropriate steel grades. Generally, after traditional plastic processing metal products have coarse-grained structure. In the meantime, it is known that ultra-fine grain stage of metals and alloys with grain size less than 1 μm and special condition of edges can significantly (2-3 times) increase strength of pure metals and 1,5-2 times increase strength of alloys along with quite high plasticity [1-3].

From all kinds of severe plastic deformation which are used to receive long products with significant changes in microstructure and mechanical properties there is one that should be noted – cross rolling, particularly one of its kinds which is defined by its authors as a separate way called radial-shear rolling (RSR) [4-5]. Its difference from cross rolling (also known as a skew or helical rolling) used, for example, in pipe production [6-7] is that there is rolling of solid bar using three-high mill arrangement with large feed angles.

2 Peculiarities of cross rolling and used equipment

In process of cross rolling, stress state close to all-around pressure with big shear deformations appears in the deformation zone. The main peculiarity of cross rolling is non-monotony and turbulence of deformation; there are also differences in plastic flow and structure elaboration of different bar zones due to trajectory speed features of the process [8]. Because of this features of metal flow the most intensive shear deformations are concentrated in the metal flow lines crossing zone – the cross-section circle common for three-roll scheme. In the outer layer every small trajectory-oriented element is exposed to compression in direction of bar radius, compression in direction of metal flow (along cross rolling trajectory) and, accordingly, tensile strain across the cross rolling trajectory. It is important that there is constant radial gradient of velocity and flow direction which adds more shearing elements into overall complex strain-stress state. Metal structure composition elements exposed to dilatant flow with double-sided sinking strain (along the trajectory and along radius) obtain the form of isotropic insulated high dispersion particles [4].

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Speed of particles in axial grain and its length increases proportionately with elongation ratio in the same way as in longitudinal rolling. Cross section of central flow tubes decreases. Metal structure elaboration works in a way similar to longitudinal rolling in multisided grooves or compression. Structural composition elements become longer and thinner, obtaining distinctive structural streaky [9]. These peculiarities are described and illustrated in details in the works of S.P. Galkin [4-5, 8-9]. Based on that

works, family of radial-shear rolling mills using intensive plastic deformation for solid round bar rolling were created in Moscow Institute of Steel and Alloys. These devices were used for obtaining fine grain structure of pure magnesium in South Korea [10] and aluminium in Poland [11]. These family of mills include SVP-08 mill, which was purchased to Rudny Industrial Institute. The exterior view and stand scheme of this mill is shown at the Figure 1.

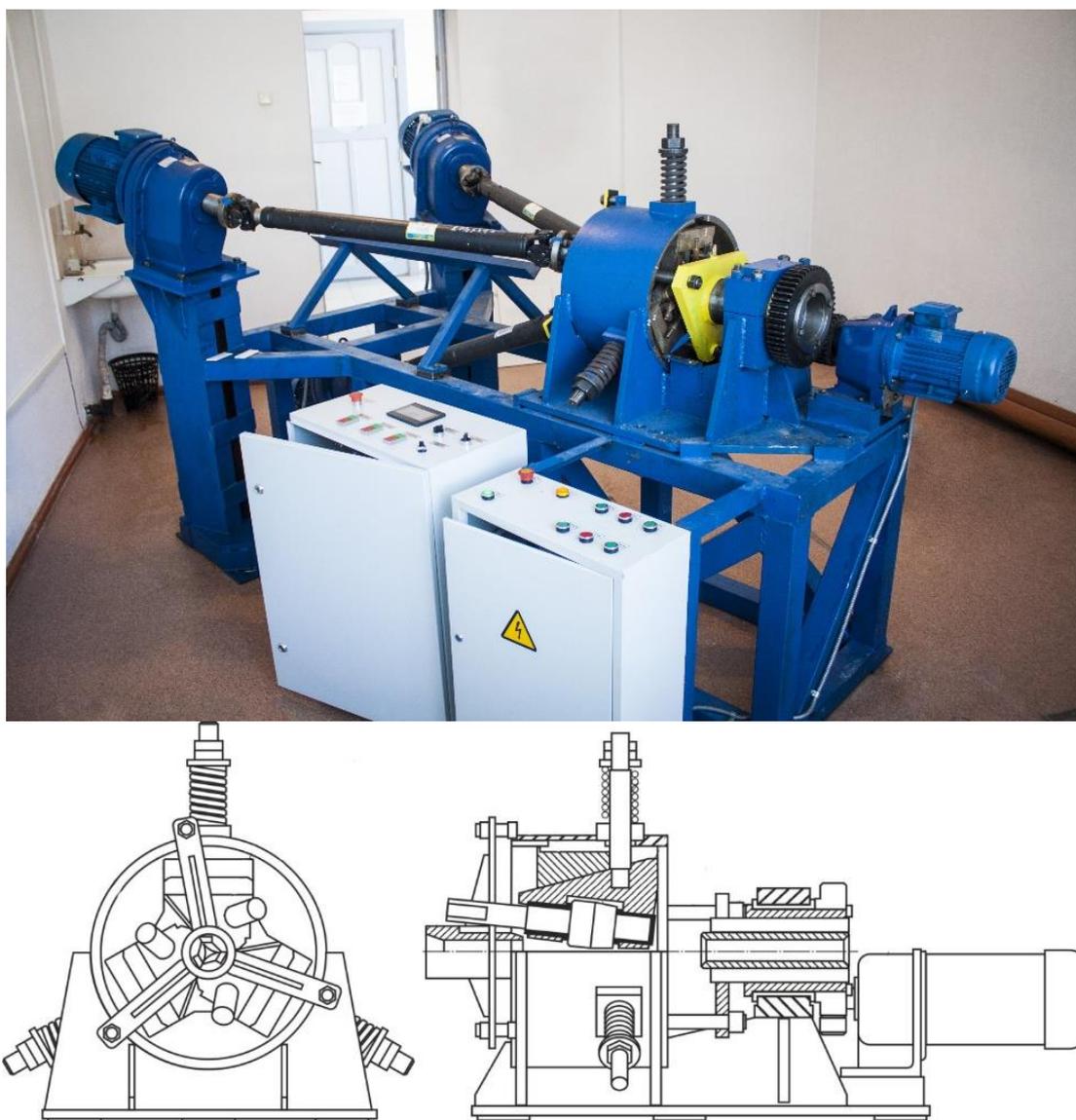


Fig. 1 Radial-shear rolling mill SVP-08

This mill is designed for hot deformation of solid round bars of practically any materials, including low-ductile, continuously cast and powder-metallurgical. Rolling of bars with 10-25 mm diameter is done in three-high mill of special rigid structure from 15-30 mm billets by means of their diametrical pressing in one or several passes using special calibrated rolls and, if necessary, with intermediate heating. Rolls diameter is 56 mm, elongation ratio reaches up to 1,1-5,0; mill capacity is 0,1-0,3 tons per hour; main drives power is $3 \times 7,5$ kW [5]. The main feature of the mill of this

design, as can be seen from fig 1 scheme, is extremely increased constructions stiffness. This is a favorable factor for experiments to obtain UFG materials, because it requires forming operations with reduced temperature and therefore increased deformation resistance.

This mill was selected for running experiments on looking into impact of cross rolling on steel microstructure because it provides wide range of sizes, rigid structure of the stand and is convenient to use.

3 Experimental part

For the experiment a bar of AISI-321 steel with 30 mm initial diameter was used. Chemical composition of AISI-321 steel - 0,08 % C; 17-19 % Cr; 9-11 % Ni; 2 % Mn; 0,8 % Si; 0,5-0,7 % Ti. It is used for making equipment working in extremely aggressive environment (heat-exchanging units, pipes, parts of furnace and reactor carcass, electrodes of spark ignition plugs).

Rolling temperature was chosen to be constant and equal to 800 °C. In several passes the billet was rolled from 30 mm to 15 mm with intensive water cooling of the bar. Similar temperature setting was used in works [12-13] for receiving ultra-fine grain structure of stainless steel. After the rolling some slices were cut off from the bar in longitudinal direction which were used

to make samples for investigating the structure using transmission electron microscope.

After rolling, cylinders 30 mm in length were cut from the rod. On a high-precision cutting machine Struers AccuTom-5 along the rod samples for mechanical testing were cut, in the form of strips 30x3x0.3 mm (Figure 2 (a), the bottom strip on the right). Dimensions of tensile sample were chosen according to internal standard of Institute of nuclear physics (Almaty, Kazakhstan) because tensile test was provided there and then it is planned to use such samples for neutron irradiation. The central (largest) section was used to prepare TEM samples for studying the fine structure. The places of sampling for microstructure research are shown in Figure 2 (B). The remaining massive half (Figure 2 (a) on the left) was used to measure the microhardness along the cross-section of the rod.

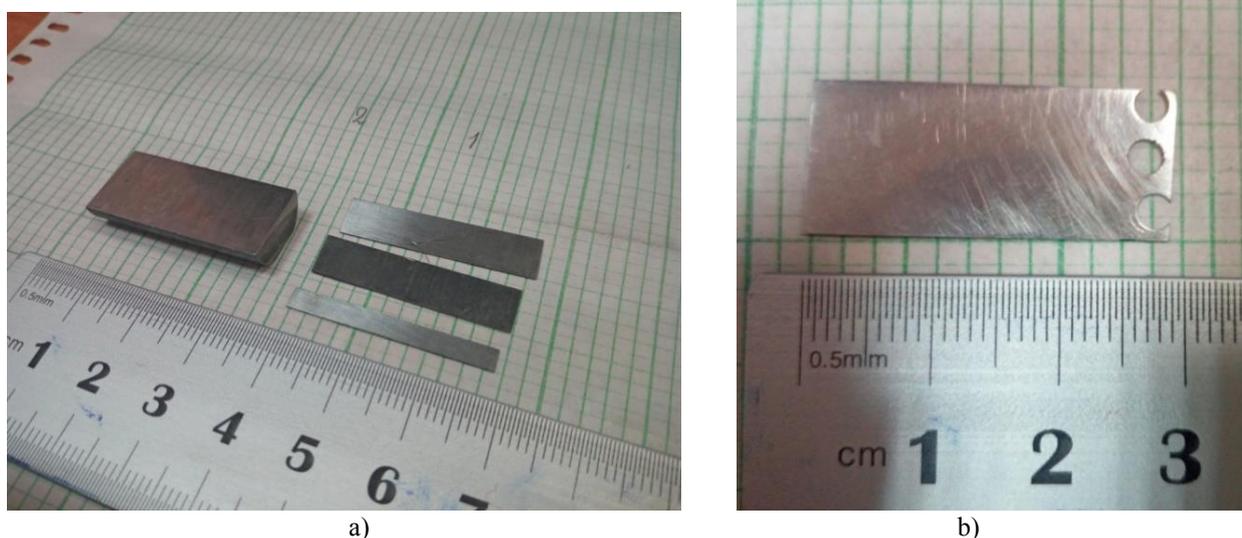


Fig. 2 Sample preparation for tensile testing (a) and for TEM-study (b)

4 Results and discussion

The samples were prepared by electrolytical method (solution composition 600 ml Methanol, 360 ml Butyl cellosolve, 60 ml Perchloric Acid) and examined on a transmission electron microscope JEM-2100 (JEOL, Japan) at an accelerating voltage of 200 kV. Photos of typical microstructure species in the center and on the periphery of the rod are shown in Fig. 3, 4.

The initial structure of AISI-321 steel in the delivery state has a coarse-grained structure with a grain size of about 40-60 μm . After deformation with total strain 11-

13 (according to known FEM-models [9, 14]) under favorable stress state, an ultrafine-grained microstructure was obtained in the peripheral part of the bar with a grain size (300-600 nm) comparable with the results of known studies [9, 12-13, 15-17]. In this case, it should be noted that the grains of the peripheral part are equiaxed. The structure of the central zone of the rod is the long and narrow grains that are elongated in the direction of rolling, resembling a texture of conventional rolling.

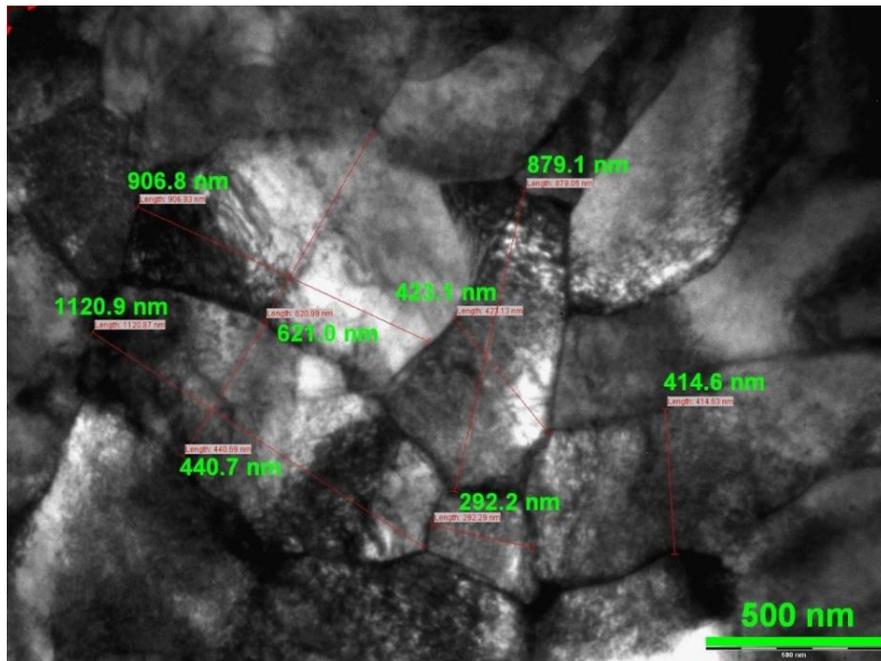


Fig. 3 Microstructure of the peripheral zone of the AISI-321 steel rod after radial-shear rolling

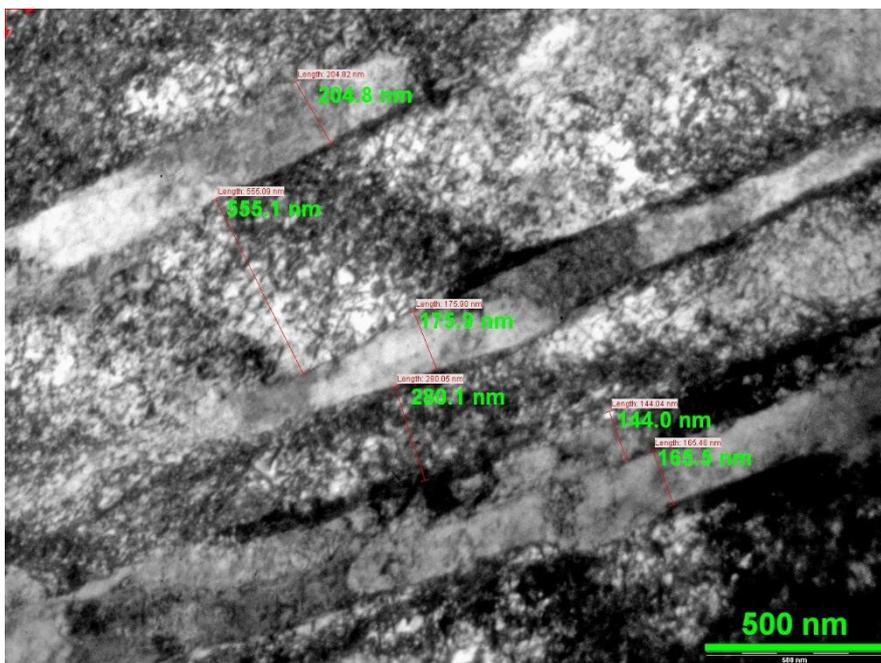


Fig. 4 Microstructure of the central zone of the AISI-321 steel rod after radial-shear rolling

The mechanical properties were determined by tensile testing flat samples on an Instron-1195 test machine. For the tests, strips were selected, by the next rule. The central line of sample located at a distance of 0.5 diameter of the rod, which will allow obtaining the most objective results, taking the detected heterogeneity of the microstructure along the cross-section of the rod. Based on the results of testing 5 samples, the average value of the tensile strength was 1073 MPa, which is approximately 2 times greater than the original value of 580 MPa. The elongation was 21%, which is approximately 2 times less than the initial value of 40%. The reduction in plasticity in this case is within the limits of the norm for materials that have undergone

similar processing. One of the stress-strain curve is shown in Figure 5.

The microhardness was measured on a HVS-1000B testing machine. Microhardness testing was providing by Vickers method with a force of 9.87 N for 15 seconds exposition. Taking the heterogeneity of the microstructure, it was decided to investigate the change in microhardness along the cross-section of the rod. For this purpose, measurements were made through each millimeter of the sample cross section, 3 times at each point of the graph. The results for each point were averaged. The microhardness graph in the rod cross section is shown in Figure 6. The initial microhardness is 160 HV. After radial displacement rolling, the microhardness level rose to 288-321 HV and as a whole

increased 2 times compared to the initial one. In this case, due to the structural inhomogeneity along the cross-section of the rod, the microhardness level of the central zone of the rod is smoothly reduced by 10.2% (33 HV). This fact according to theoretical expectations and correspond to the received data on microstructure in different zones of bar. Receiving graph suggest that

changing of microstructure type across the sample section from equiaxed UFG grains on periphery to elongated fibrous structure of central zone take place also without sharp borders. Small symmetrical decreasing of microhardness level (less than 1 %) on the bar edge probably caused by thermal decarburization.

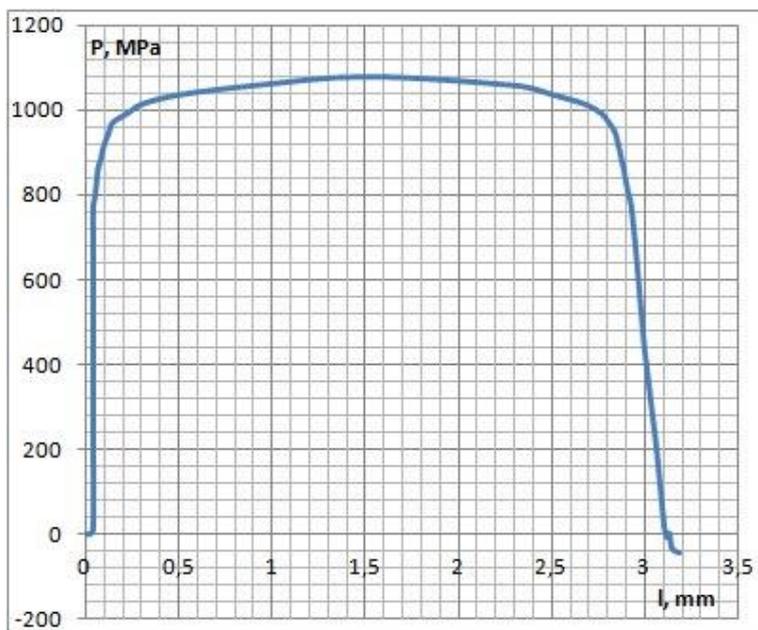


Fig. 5 The stress-strain curve of a sample of AISI-321 steel after radial displacement rolling

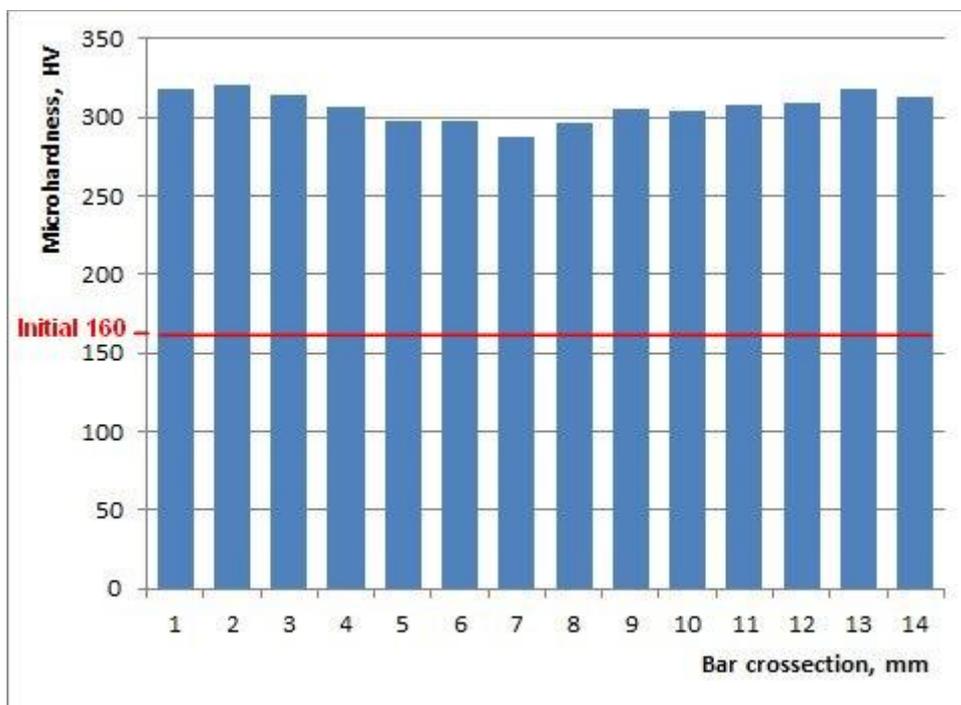


Fig. 6 Microhardness changing over the section of the bar of AISI-321 steel after radial-shear rolling

5 Conclusions

A radial-shear rolling with a total stretching of 4, in a single rod with initial grain size of 60 μm, a microstructure of two different types was obtained. On the periphery of the rod was a more and less equiaxed

ultrafine-grained structure with a grain size of 300-600 nm, while in the central zone of the rod there was an oriented texture, similar with conventional rolling.

The obtained microstructure was made first time for this material on the radial-shear mill of SVP-08 design. Results correlate with the data of the other studies on

radial-shear rolling for other materials [4-5, 7, 9] and with the data on this material for other severe plastic deformation (SPD) processes conducted at same temperature and deformation conditions [10]. Obtaining such a structure by one of the most common SPD methods – equal channel angular pressing (ECAP), requires at least 6-8 pressing cycles [1, 3, 12, 13] and is possible only for short workpiece, while at the mill of radial displacement rolling it is obtained for 3-4 passes for rods of unlimited length. The problem is in the heterogeneity of the structure in the central and peripheral zones of the rod.

Further improvement of cross rolling ways with purpose of receiving more homogeneous structure in bar cross section will provide an opportunity to get large amounts of ultrafine-grain materials with the least time and energy consumption, which will make commercial efficiency and cheapening of UFG materials production available.

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