REFINEMENT OF THE MICROSTRUCTURE OF STEEL BY CROSS ROLLING

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ABSTRACT

One of the most effective ways for refinement of metal microstructure is a severe plastic deformation. The cross rolling is the one of most perspective methods of severe plastic deformation, because it allows to get the long billets, unlike equal angular pressing and other popular methods. This fact provides some industrial expectation for this method. However, deformation and motion path of the metal is very heterogeneous across the section of the rolled piece. This paper presents the finite element modeling of hot cross rolling of steel in the software package DEFORM-3D features implemented and studied the stress-strain state. An experimental study of the effect of the cross rolling on a three-roll mill on the microstructure of structural alloy steel and stainless steel AISI321 in different zones of the bar. Analysis of microsections made after rolling with high total stretch and the final pass temperature 700ºC, shows the formation of equiaxial ultrafinegrain structure on the periphery of an elongated rod and "rolling" texture in the central zone. The resulting microstructure corresponds to that obtained in models of stress-strain state.

<u>*Keywords*</u>*: cross rolling, ultra-fine grain structure, steel.*

INTRODUCTION

Obtaining materials with high and well-balanced physical and mechanical properties continues to be one of the main aims of Metallurgy and Materials Science. Among the most promising ways of improving the properties of metallic materials without changing and complication of their chemical and phase composition is to obtain them in an ultrafine-grained (UFG) state. The ultra-fine grain metals and alloys with grain size of about 1 micron and special condition of edges can significantly (2 - 3 times) increase durability of pure metals and 1,5 - 2 times increase durability of alloys along with quite high plasticity [1 - 2]. Such properties of UFG materials come from their unusual structure: due to the small size of the grains they contain a large amount of grain

boundaries, which play a crucial role in the formation of their physical and mechanical properties. At the same time, the special state of grain boundaries having high angle character, a high level of stress, significant distortion of the crystal lattice in the border area and a high density of grain boundary dislocations are important.

There are two main methods of obtaining UFG products. First is the sintering of ultradisperse powders [2]. Second is severe plastic deformation of a macroobject with the aim of grinding it up to the required structure. The second method of grinding structures often involves shorter and therefore more economical production cycle by eliminating the step of grinding the starting material in ultrafine powder specified fraction. This fact allows to avoid residual porosity and, therefore, low plasticity of bulk product obtained after sintering of the powder. Us-

ing severe plastic deformation (SPD) for the grinding of grain metal structure avoids many disadvantages of the processes based on the principles of powder metallurgy. However, even the most common and effective methods of severe plastic deformation, such as equal channel angular pressing [3 - 5] and the torsion under high pressure [6], also have their specific disadvantages related to the inability to obtain lengthy billets and the need to make a large number of processing cycles in order to achieve the proper conversion degree of the original structure and its sufficient even spreading throughout the volume of the treated piece. These problems hinder the wide application the described processes in industry, and this work focuses on solving some of these problems.

There are several ways to get long-length rods with improved structure and properties of a continuous process. For example, there is known [7] method ECAP-Conform, or [8] rolling-pressing. Both of them are in fact continuous modifications of the known equal-channel pressing process, involve a large number of cycles and are applicable only to non-ferrous metals and alloys.

Among 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-displacement rolling (RDR) [9-10]. Its difference from cross rolling [11] used, for example, in pipe piercing is that there is rolling of solid bar using three-high mill arrangement with large feed angles [9]. However, in order to avoid confusion, later the more common name - cross rolling - will be used.

PECULIARITIES OF CROSS ROLLING AND EQUIPMENT USED

In the process of cross rolling in the deformation zone scheme is implementing the stress state close to hydrostatic compression with high shear deformations, which conducive for obtaining UFG structure.

The main peculiarity of cross rolling is nonmonotonicity and turbulency of deformation; there are also differences in plastic flow and structure elaboration of different bar zones due to trajectory speed features of the process. 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 triaxial scheme, which is confirmed by the model. 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 dilatable flow with double-sided sinking strain (along the trajectory and along radius) obtain the form of isotropic insulated high dispersion particles [10].

The speed of particles in axial grain and its length increases proportionately with elongation ratio in the same way as in longitudinal rolling. The cross section of central flow tubes decreases. Metal structure elaboration works in a way similar to longitudinal rolling in multisided grooves or compression. The structural composition elements become longer and thinner, obtaining distinctive structural streaky [12]. These peculiarities are described and illustrated in details in the works of S. P. Galkin [9, 10, 13, 14].

Based on the works named above, cross rolling mills using intensive plastic deformation of solid round bar rolling were created in Moscow Institute of Steel and Alloys. Different countries have this type of work in a number of research organizations and industrial enterprises of Russia, South Korea, Germany, Poland and other countries. These mills include RSP «10-30» mill [12, 13] delivered to Karaganda State Industrial University. The exterior view of the mill is shown at Fig. 1.

The RSP «10-30» mill is designed for hot deformation of solid round bars of practically any materials,

Fig. 1. RDR "10-30" mill.

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 $3 \times 5,5$ kW [6]. The design features of the mill and power parameters are described in detail and illustrated in [15].

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.

FINITE-ELEMENT MODELING OF CROSS ROLLING

In order to look into the scheme of strain-stress state implemented by RDR "10-30" mill finite-element modeling of steel bar rolling from 25 mm to 15 mm diameter in several passes was done using DEFORM-3D software complex (SFTC company, USA). The material of the bar was chosen AISI-5140 steel (equivalent of 40X grade) as one of the most common worldwide alloyed construction steel grades. The rolling temperature was 800ºC as corresponding to low limit of rolling temperature for steel grades of this class.

The other parameters of the model were as follows: the number of the finite element model was made 300 000, so that the average size of the element should be about 0.7 mm to ensure sufficient accuracy of the calculation. The rotational speed of the rolls was 100 rev/min. All the tools in the model had a temperature of 20°C. The heat transfer coefficient accepted 5 N/sec/mm/K according to the recommended program. The coefficient of friction was assumed constant and with a value above normal - 0.8. This assumption was dictated by the special conditions in the capture screw rolling and the results of measurements of the maximum axial force in the selected mill in [15], which indirectly refined friction necessary for an adequate model.

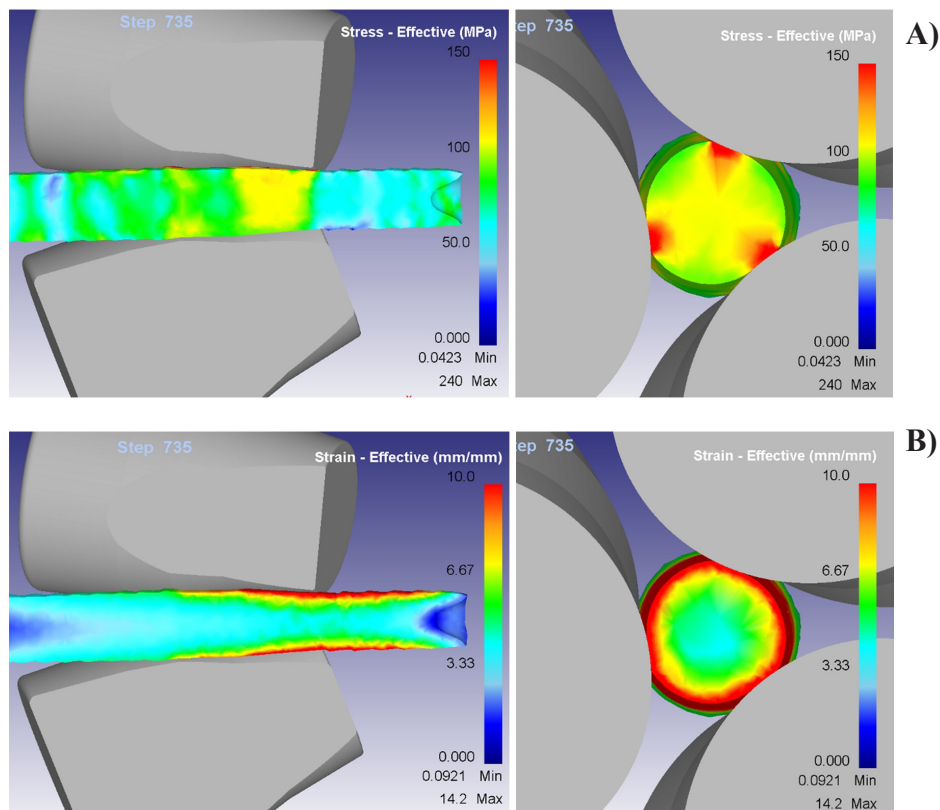To achieve the diameter of 15 mm, 2 models were

Fig. 2. Stress and strain state of the deformation in the last pass (A - Equivalent stress; B - Equivalent strain).
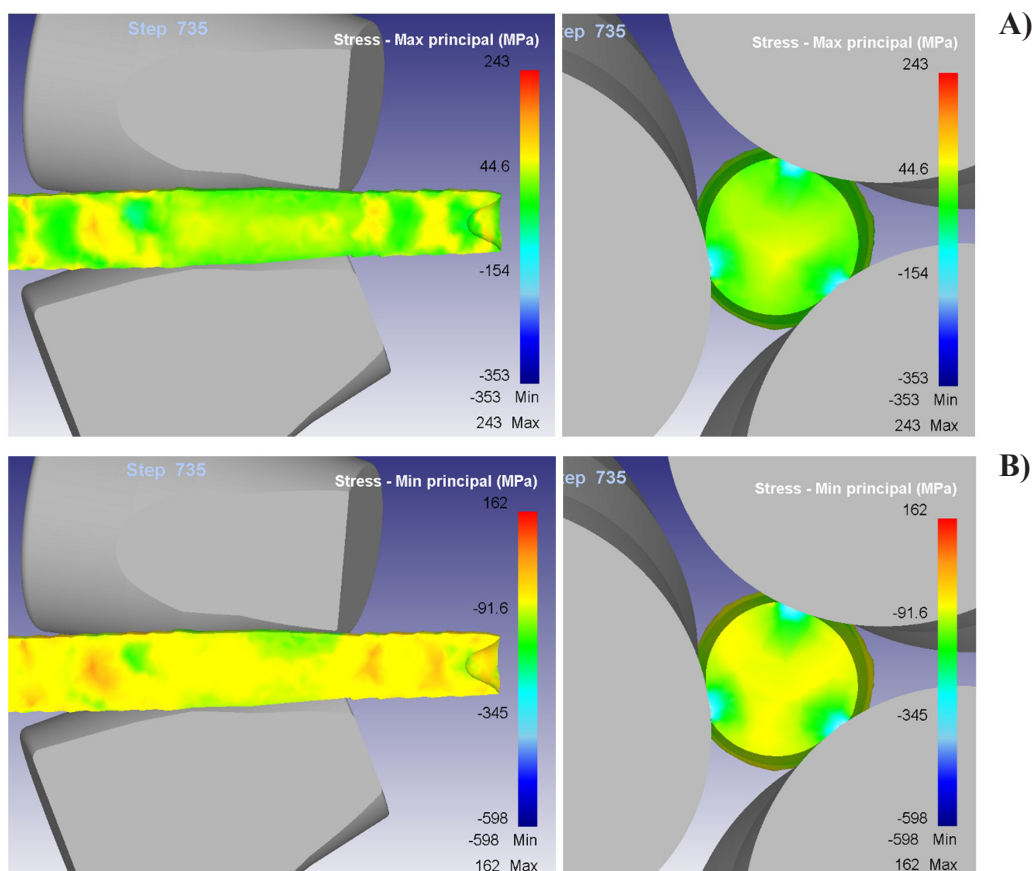
Fig. 3. Stress state of the deformation in the last pass (A - Principal (maximum tensile) strain σ_1; B - Principal (maximum compressive) strain σ_3).

run with different configurations of rolls (setting on the smaller diameter rolling). For this purpose, the finite element model of the rod after rolling with the diameter of 25 to 20 mm in diameter was re-imported into the model with the rolls, tuned to a diameter of 15 mm. The simulation results of the last pass are shown in Figs. 2 - 3.

At the cutaway section lamination of strain distribution at the billet cross section can be seen. In this case cumulative deformation in outer areas of the bar after the first pass (at the Fig. 2 – before deformation zone) reaches 3 - 4, after the second pass 6 - 8, with maximum values of up to 14.2, which, according to R.Z. Valiyev [1], should facilitate obtaining fine-grain structure in bar periphery after just two or three passes.

The stress value reaches maximum of 240 MPa, the average stress at the center of the deformation zone is about 100 - 120 MPa. The picture of stress distribution corresponds with the published data [14, 16, 17] on cross rolling modeling.

However, the values of equivalent stress only do not give full information on the stress state of the processed bar. To form the correct structure of the UFG, it is necessary to have a compressive stress in the deformation zone, for that we should analyze the parameters that allow to estimate proportion of tensile and compressive stresses in the deformation zone. These are the principal stresses σ_1 and σ_3, components of the stress tensor (σ_2 is the average between the two values), which distribution is shown in Fig. 3.

When considering the components σ_1 the compressive stress takes a minimum value, while the tensile stresses are maximized. This makes it possible to estimate the maximum level of tensile stress occurring in the workpiece, the growth of which can lead to the formation of defects. During the screw rolling the value of tensile stress reaches an average of about 100 MPa, which are directed along the tangent line on the workpiece. In the area of direct contact with the workpiece rolls normal compressive stresses are formed, reaching an average value of 400 MPa. This stress distribution can

be considered favorable, since the level of compressive stress in absolute value is several times higher than the maximum possible tensile stress. As a result, discharge of tensile stress occurs.

The stress state obtained in the models corresponds to the theoretical scheme above, favorable for intensive grinding of the structure and is consistent with the data presented in [14, 16, 17] modeling of the screw rolling.

EXPERIMENTAL

After receiving modeling results in a similar way the experiment was implemented on RSP "10-30" mill for the purpose of looking into steel microstructure changes. Two experiments have been done with two different steel grades. For the first experiment alloyed construction steel of GOST 40X grade (analog of AISI-5140) was used. For the second one stainless heat-resistant steel of austenitic class AISI-321 grade was used. The experiment conditions were slightly different.

Rolling of 40X (analog to AISI-5140) steel

For the first experiment a bar with 25 mm initial diameter was used. The chemical content of 40X steel is: 0,36 - 0,44 % C; 0,8 - 1,1% Cr; 0,5 - 0,8 % Mn. This steel is widely used in mechanical engineering for making high durability parts (shaft axles, spindles, gear wheels). At RSP «10-30» rolling mill two consequent deformations during one heating were done – from 25 mm to 20 mm at 900ºC and from 20 mm to 15 mm at 700ºC with intensive water cooling of the bar. Similar

temperature setting was used in works [7 - 8] for receiving ultra-fine grain structure of alloyed steel.

Rolling of AISI-321 steel

For the first experiment a bar with 30 mm initial diameter was used. The chemical content of AISI-321 steel is: 0,08 % C; 17 - 19 % Cr; 9 - 11 % Ni; 2 % Mn; 0,8 % Si; 0,5 - 0,7 % Ti. Equivalent of this steel is 08X18H10T grade. 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). The rolling temperature was chosen to be constant and equal to 700ºC. 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 work [10] for receiving ultra-fine grain structure of stainless steel. After the rolling some slices were cut off the bar longways which were used to make samples for looking into the structure using transmission electron microscope.

RESULTS AND DISCUSSION

40X (analog to AISI-5140) steel

Because of cross rolling metal flow peculiarities samples for research were cut only longways. From these samples longitudinal micro-sections were made, which were analyzed using Quanta 200i 3D scanning election microscope (FEI Company, USA). Photographs of distinctive microstructure views in the centre and
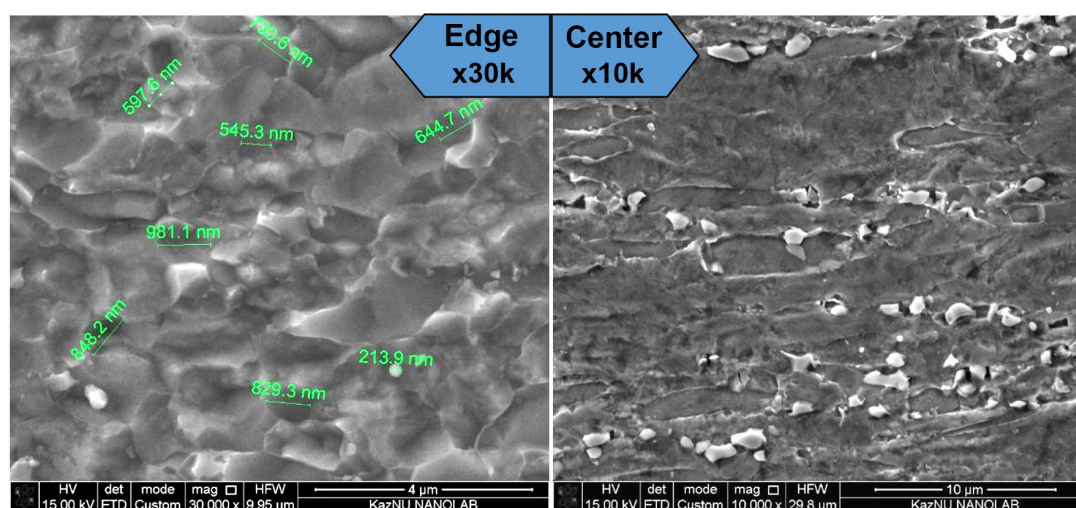

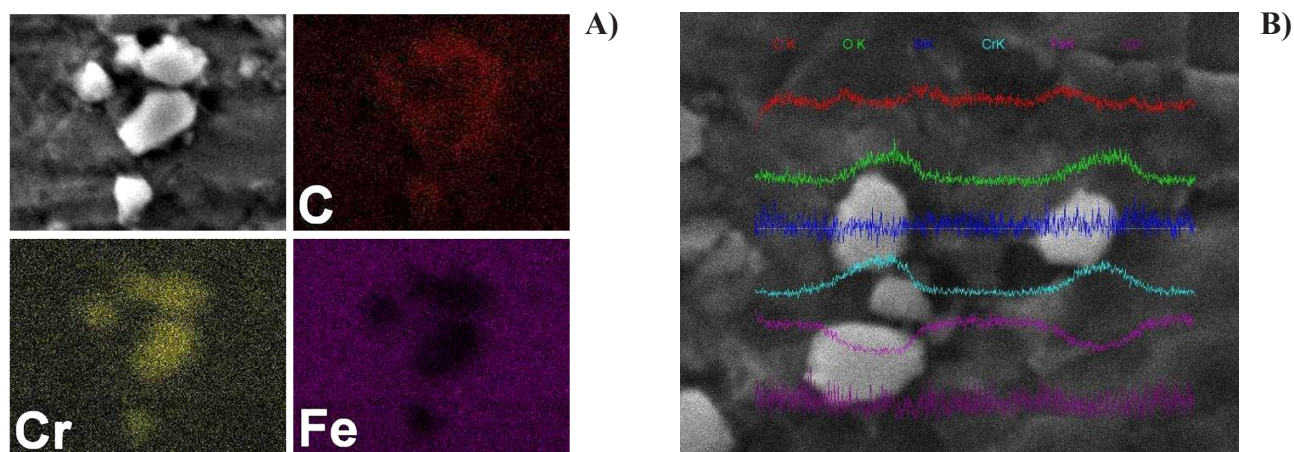Fig. 4. 40X steel grade microstructure after cross rolling.

Fig. 5. EDX-analysis of the chemical composition (A - on the surface of microsection; B - EDX-linear analysis).

edges of the bar are shown at Fig. 4.

The original structure in regular shipping state has typical for these kind of steel grades large grain ferrite-pearlite type with grain size 40 - 60 micron and microhardness 150-160 HV. The microhardness of the bar after the rolling was measured at FM-800 microhardness tester (FUTURE-TECH CORP., Japan) aid was on average 428 - 432 HV at the edge and 400 HV in the centre of the bar.

At Fig. 4 on the left and right there is structure of (accordingly) peripheral and central parts of the bar after after cross rolling from 25 to 15 mm diameter. The microstructure of peripheral area has mostly equiaxial subultrafinegrain view with grain size about 5 microns. The central area of the bar has distinctive streaky (like a ordinary «rolling») texture of long narrow grains stretched along the rolling direction with size of 5-10 x 0.9 - 1.5 micron and chains of chromium carbide crystals (white phase). Chromium carbide was identified by means of energy-dispersive analysis (EDX). The size of separate chromium carbide crystals is 200 nm or smaller. EDX-analysis results are shown in Fig. 5.

This way, after deformation with total stretching of 2.8 on reaching cumulative deformation of 6 - 8 in appropriate stressed state ultrafinegrain microstructure providing 2.7 times hardness increasing was obtained.

AISI-321 steel

The original structure was able to supply the grain size of about 40-60 microns. After the deformation with a total stretch 4 we achieved an equal degree of accumulated deformation (for rough estimates) 11 - 13 in a favorable state of stress of the finished rod, samples were cut in the longitudinal direction for TEM study. To prepare specimens in the precision cutting machine AccuTom (Struers, Switzerland) 0.3 mm thick plates were cut in longitudinal sectional rods. Then, 2 discs with a diameter of 3 mm were stamped by special punch in each of them in the central and peripheral zones on the. The etching was performed automatically on electropolishers machine TenuPol-5 of company Struers (Switzerland) in the electrolyte A2 (Struers) until the hole in the sample appeared, and the process stopped automatically. Then prepared TEM objects have been investigated with a transmission electron microscope JEM-100CX (JEOL, Japan) at an accelerating voltage of 100 kV. Photos of the typical kinds of microstructure in the center and on the periphery of the bar are shown in Fig. 6.

The studies have shown that the material really has the dominant sub-micron grain size. The structure of the TEM-object is homogenous from the center to the periphery of the workpiece. There is considerable scatter in the data size of grains and the level of texturing the area containing the "right" ultrafine microstructure of equiaxed polyhedral grains in the peripheral zone (Fig. 6A) and a microstructure characterized by elongated along the direction of deformation of small grains (Fig. 6B), which is typical for large uniaxial strain. Also there are fragmentation and characteristic mesostrips in the axial zone, sometimes combined into bundles.

The size of equiaxial grains of the peripheral area change in the average interval of 500 nm - 900 nm. The
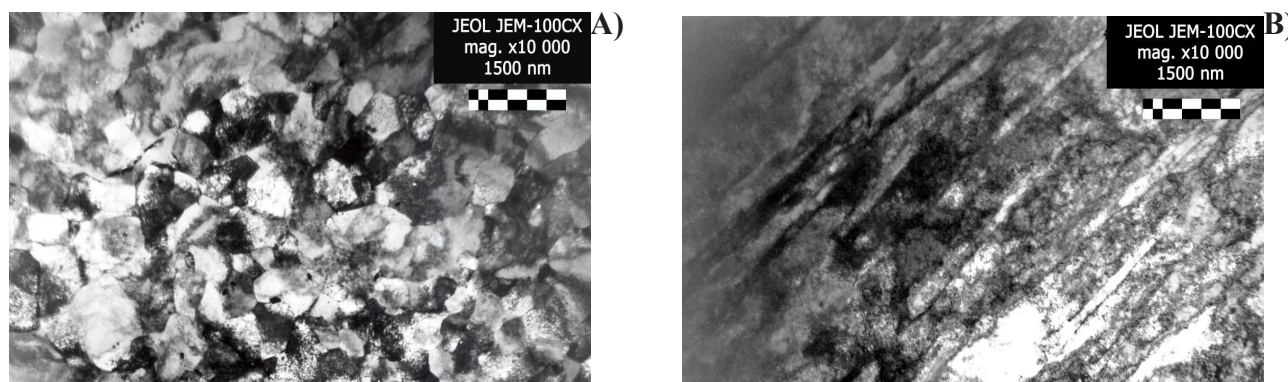
Fig. 6. Microstructure of peripheral (A) and axial (B) parts of the AISI-321 steel bar after cross rolling.

elongated grains are comparable in size with equiaxed grains, but their length is several times the size of the latter.

Dislocation structure in grains belongs to reticulate-cellular type. The dislocation density varies within the range of $10^{10} - 10^{11}$ cm^{-2}.

Thus, it should be noted that in comparison to previous experience peripheral zone structure steel AISI-321 inequigranularity is significantly less and has more the character of equiaxed. The structure of the central zone of the bar is elongated in the rolling direction of the grain long and narrow, as in the first experiment.

CONCLUSIONS

By means on cross rolling with total stretching of 2.8 and 4 for two steel grades microstructure of two different kinds was received. In the peripheral area, there is more or less equiaxial ultrafinegrain structure, and in the central bar, zone there is longways oriented streaky texture. Peripheral area grain size was 600-900 nm for both materials. At this time, AISI-321 steel microstructure that had higher deformation was less anisomerous.

The microstructure received correlates well with the research data [17 - 19]. Receiving of this structure by means of one of the most common ways of severe plastic deformation – equal channel angular pressing requires not fewer than 6 - 8 pressing cycles [1, 3, 4] and is available only for small length billets, meanwhile at the cross rolling mill it can be obtained for 3 - 4 passes for billets of any length. The problem is inhomogeneity of structure in central and peripheral areas of the bar.

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 ultrafinegrain materials with least time and energy consumption, which will make commercial efficiency and cheapening of UFG materials production available.

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