A. B. NAIZABEKOV, S. N. LEZHNEV, H. DYJA, T. BAJOR, K.TSAY, A. ARBUZ,
N. GUSSEYNOV, R. NEMKAEVA

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THE EFFECT OF CROSS ROLLING ON THE MICROSTRUCTURE OF FERROUS AND NON-FERROUS METALS AND ALLOYS

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The cross rolling is the one of most perspective method of refinement microstructure metals by severe plastic deformation method. This method gives ability to get the long length billets. However, deformation and trajectories of the metal is very heterogeneous across the section of the rolled piece. This paper presents the finite element method (FEM) simulation of hot cross rolling and experimental study of the effect of the cross rolling on a different three-roll mills on the microstructure of ordinary structural alloy steel, stainless steel and technical copper in different zones of the bar. Analysis showed significant structure refinement in all cases. The best result was achieved on the stainless steel, and shown the formation of equal-axis ultra-fine-grain structure on the bar periphery.

Key words: steel, cooper, cross rolling, severe plastic deformation, ultrafine grain structure

INTRODUCTION

Most of metal product making industrial processes are oriented to manufacturability of metal deformation, and mechanical properties are obtained by means of using appropriate steel grades. Generally, after traditional plastic processing metal products have granulated structure. In the meantime, it is known that 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].

Of 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) [3, 4].

Its difference from cross rolling [5] used, for example, in pipe piercing is that there is rolling of solid bar using three-high mill arrangement with large feed angles [4]. However, in order to avoid confusion, later the more common name – cross rolling – will be used.

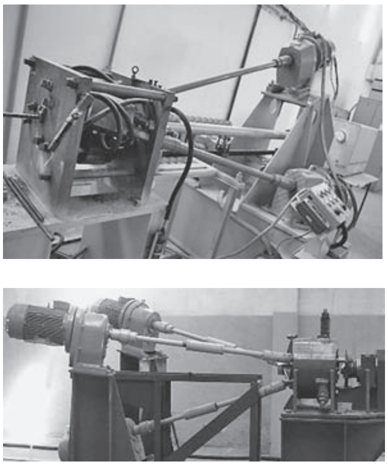
A.B. Naizabekov, S.N. Lezhnev, Rudny Industrial Institute, Rudny, Kazakhstan;
H. Dyja, T. Bajor, Czestochowa University of Technology, Czestochowa, Poland;
K. Tsay, Institute of Nuclear Physics of the National Nuclear Center of the Republic of Kazakhstan, Almaty, Kazakhstan;
A. Arbuz, N.Gusseynov, R. Nemkaeva Al-Farabi Kazakh National University, Almaty, Kazakhstan

PECULIARITIES OF CROSS ROLLING AND EQUIPMENT USED FOR IT

In process of cross rolling stressed state close to triaxial compression with big shear deformations appears in the deformation zone.

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 [3].

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 streaking [4]. These peculiarities are described and illustrated in details in the works of S. P. Galkin [3, 4, 6].



A)

B)

A) – RDR "10 - 30" mill (KSTU, Temirtau);
B) – RDR "14 - 40" mill (PCz, Czestohowa)
Figure 1 Using cross rolling mills

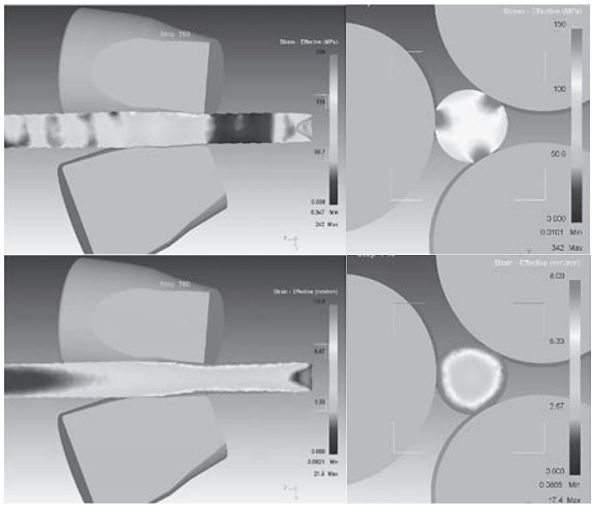


Figure 2 Strain-stress state of deformation zone at the last pass

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 (NUST «MISA»). These mills include RDR "10 - 30" mill [6] delivered to Karaganda State Industrial University (KSIU) in Temirtau, Kazakhstan and RDR "14 - 40" mill purchased in 2012 in Czestochowa University of Technology (CUT, PCz), Czestochowa, Poland. The exterior view of the both mills is shown at the Figure 1.

RDR "10 - 30" mill (Fig 1A) 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 × 5,5 kW [6].

RDR "14 - 40" mill (Fig 1B) is very similar with first mill and differs only in larger diameter of rolls, more powerful engines and other constructions of working stand. At the same time, the main process parameters such as angles of the rolls arrangement and it`s calibration – identical on the both mills. This mill allows to obtain rods with a diameter of 14 - 30 mm from the original billet diameter 16 - 40 mm.

This mills was selected for running experiments on looking into impact of cross rolling on ferrous and non-ferrous materials 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 alloyed construction steel grades worldwide. Rolling temperature was 800 °C as corresponding to low limit of rolling temperature for steel grades of this class. The result of last pass modeling are shown at the Figure 2.

At the cutaway section layering of strain distribution at the billet cross section can be seen. In this case degree of 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, which, according to R. Z. Valiev [1], should facilitate obtaining fine-grain structure in bar periphery after just two or three passes.

Strain-stress state received at models corresponds to theoretical outline given above, is appropriate for intensive structure refinement and complies well with data given in works [6 - 8] on cross rolling modeling.

EXPERIMENTAL PART

After receiving modeling results in a similar way the experiment was implemented on RDR "10 - 30" mill for the purpose of looking into steel microstructure changes and on RDR "14 - 40" for copper. Two experiments on ferrous materials have been done with two different steel grades was made on the RDR "10 - 30" mill. For the first experiment alloyed construction steel of 40X grade (analog of AISI-5140) was used. For the second one stainless heat-resistant steel of austenitic class AISI-321 grade was used. All experiment conditions were slightly different.

a) Rolling of 40X steel

For the first experiment a bar with 25 mm initial diameter was used. Chemical content of 40X steel - 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 RDR "10 - 30" rolling mill two consequent deformations during one heating were done – from 25 mm to 20 mm at 900 °C and from 20 mm to 15 mm at 700 °C with intensive water cooling of the bar. Similar temperature setting was used in works [8 - 9] for receiving ultra-fine grain structure of alloyed steel.

b) Rolling of AISI-321steel

For the first experiment a bar with 30 mm initial diameter was used. Chemical content of AISI-321 steel - 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).

Rolling temperature was chosen to be constant and equal to 700 °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 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.

c) Rolling of copper

Rolling temperature was chosen to be constant and equal to 500 °C. In several passes, the billet was rolled from 35 mm to 25 mm with intensive water-cooling of the bar. Similar temperature setting should provide intensive grinding of copper structure. After the rolling some slices were cut off the bar longways which were used to make samples for looking into the structure using optical microscope.

RESULTS AND ITS DISCUSSION

a) 40X steel

Photographs of distinctive microstructure views in the centre and edges of the bar from scanning electron microscope (SEM) are shown at the Figure 3.

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. 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 the Fugure 3 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. Microstructure of peripheral area has mostly equiaxial subultrafinegrain view with grain size about 5 micron. Central area of the bar has distinctive streaking «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.

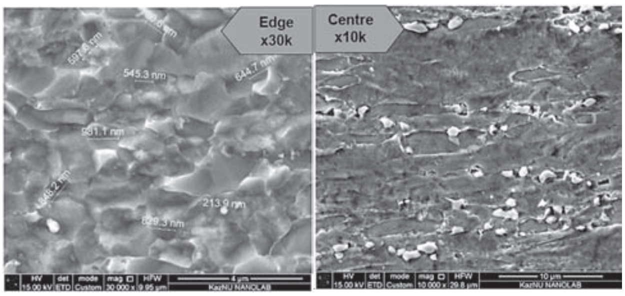
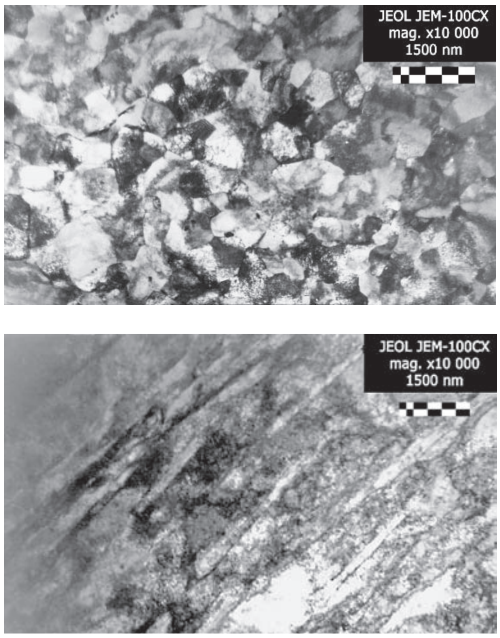


Figure 3 40X steel grade microstructure after cross rolling (scanning electron microscope image)

This way, after deformation with total stretching of 2,8 on reaching cumulative deformation of 6 - 8 in appropriate stressed state ultra-fine-grain microstructure providing 2,7 times hardness increasing was obtained.

b) AISI-321 steel

Photographs of distinctive microstructure views in the center and edges of the bar are shown at the Figure Original structure in regular shipping state has grain size about 40 – 60 micron. After deformation with total stretching of 4 on reaching cumulative deformation of (approximately) 11 - 13 in appropriate stressed state ultrafinegrain microstructure in the peripheral part of the bar with grain size 600 – 900 nm was used, which correlates with results of previous experiment. It also should be noted that comparing to the previous experiment peripheral area structure is significantly less ani-



A)

B)

Figure 4 Microstructure of peripheral (A) and axial (B) parts of the AISI-321 steel bar after cross rolling (transmission electron microscope image) somerous and has more equiaxial view. Central area structure includes long narrow grains stretched along the rolling direction similar to the first experiment.

c) Copper

The microstructure of the hot-rolled copper bar in the delivery condition is shown on first picture in Fig. 5. This coarse structure with grain sizes of 50-100 microns is typical for this material. The analysis micro-sections made after rolling showed a significant refinement of the microstructure at the periphery of the rod and less intensive grinding rod in the central zone. The border zone was 0,5 fine radius rod. Character ratio fine peripheral and central zones comparable to that in [6]. The grain size in the region of greatest deformation (periphery) is 5-10 microns. While in the central area of the grain size is 15-30 microns. Increasing the degree of deformation at a given temperature does not give greater penetration deeper grained areas rod and prevents crush grained microstructure finer than 5,3 micrometers. Pictures grains are characterized by a large number of compound crystals, which suggests strongly deformed metal state.

It can be concluded that the treatment carried out significantly rolled microstructure, but to obtain a more fine state should be processed at lower temperatures, even as the receiving accumulated strain about 6 - 8, does not allow to grind copper microstructure UFG state.

CONCLUSION

This way, by means on cross rolling with total stretching of 2,8 and 4 for two steel grades microstructure of two different kinds and cross rolling of copper was received. In the peripheral area of steel there is more or less equiaxial ultra-fine-grain structure, and in the central bar area there is longways oriented streaking texture. Peripheral area grain size was 600-900 nm for both materials. At this time, AISI-321 steel microstructure which had higher deformation was less anisomerous.

Received microstructure correlates well with research data [8 - 11]. 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 - 2, 7, 10] 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 UFG materials with the least time and energy consumption, which will make which will make commercial efficiency and cheapening of this materials production available.

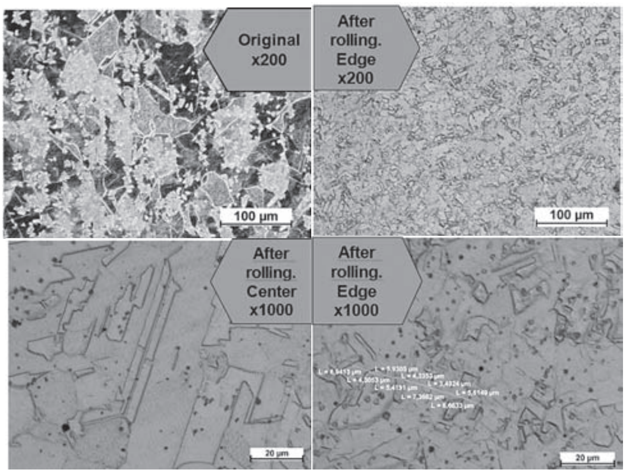


Figure 5 The microstructure of copper before and after cross rolling from 35 mm to 25 mm at 500 °C (optical microscope image)

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Note: Translator responsible for English language is G. Arbuz, Almaty, Kazakhstan