Study of the parameters of the pure iron structure after surface plastic deformation treatment with a complex-profile tool

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Abstract. The structure of pure iron after surface plastic deformation (SPD) by a multiradius roller (MR-roller) was studied using optical microscopy (OM) and atomic force microscopy (AFM). An optical microscope of reflected light is used to study the size and uniformity of grains and subgrains (Neophot-21). The fine structure of the sample surface was studied using an atomic force microscope (Solver PH47-PRO) contact method. The paper shows changes in the deformation relief of the material after processing with an MR-roller.

1. Introduction
Currently, a number of studies have proved the possibility of grinding the structure using surface plastic deformation (SPD) methods [1-7].

Thus, in the study [8], the possibility of grinding the structure was first discovered bearing steel $100Cr6$ after diamondburnishing. Klassen N. V., Kobelev N. P. and co-authors [9] showed the possibility of creating a gradient nanostructure using ball rolling ($\Omega 3$ mm). At the same time, as the depth increases even by 2-3 micrometers, the grain size increases several times. A team of authors [10] investigated the mechanical properties of alloy samples $PbTe$ under torsion conditions with high hydrostatic pressure. A decrease in the grain size to 300 nm was found, which led to significant strain hardening without failure; this is evidenced by the results of nano- and microhardness tests.

Previously, metal studies were conducted after processing SPD with a multiradius roller (MR-roller) [11-13] and a number of effects that positively affect the mechanical characteristics are established: increasing microhardness; reducing roughness; implementing a loading scheme, according to which an intense hydrostatic pressure is created in the surface layer of the material, and others. However, the characteristics of the structure were not sufficiently studied.

One of the informative methods for studying the structure of materials on submicron spatial scales after various processing methods is atomic force microscopy (AFM) [14-22].

In this regard, the aim of the work is to study the elements of the material structure after processing the SPD with an MR-roller.

2. Materials and methods
Experimental studies consisted in processing a sample of pure iron with an MR-roller $\Omega 60$ mm (fig.1, a) in the next mode: running-in force $P=2700$ H; traverse feeding $s=0,07$ mm/ rpm; speed $n=630$ rpm/min. The multiradius roller has the shape of a working surface profile in the form of a combination of sequentially arranged deforming elements (DE) with radii of constant value located relative to each other with some displacement in the radial and axial directions: $Rpr1 = 1$ mm with interference.
\[ h_{d1} = 0.05 \text{ mm}; R_{pr2} = 1 \text{ mm with interference} \]
\[ h_{d2} = 0.072 \text{ mm}; R_{pr3} = 1 \text{ mm with interference} \]
\[ h_{d3} = 0.076 \text{ mm}; R_{pr4} = 0.3 \text{ mm with interference} \]
\[ h_{d4} = 0.099 \text{ mm} \] (fig. 1, b) [23].

**Figure 1.** Scheme SPD by MR-roller: a) Scheme of the machining process on a numerical control lathe (NCL), 1 – MR-roller, 2 – work piece, 3 – pressure center; b) General view of the working part MR-roller

After rolling the MR-roller, the metallographic section was prepared for optical (OM) and atomic force microscopy (AFM). Any defects were not allowed on the surface of metallographic sections.

The parameters of the structure of the studied sections, namely, grain and subgrain sizes and their homogeneity, were determined using a reflected light optical microscope "Neophot-21" at magnifications of 200 and 500 microns. The thin structure of the surface of the sections was studied using an atomic force microscope Solver PH47-PRO. To study the deformation relief of the surface, the "Contact Mismatch Method" mode was used (DFL). The contact method is intended for more accurate detection of the deformation relief of cross-sections of sections by AFM method. The combination of contact mode with DFL allowed us to get additional information about the surface topography. The essence of the method is that during the scanning process, the current value of the signal associated with the cantilever bend is a signal of mismatch in the feedback circuit and contains additional information about the surface relief. This signal is used for a more accurate reproduction of the relief. During the scanning process, the adjusted speed of processing the mismatch signal was set so that the system worked out relatively smooth terrain features quickly enough and at the same time was slow enough to work out steeper sections. As a result, the mismatch signal weakly displays smooth terrain features (grains) and displays sharp roughness (inclusions and grain boundaries) with high contrast.

It should be noted that the working area of the cantilever of the device has dimensions of \( \sim 10 \text{ nm} \), and the characteristic distance between the probe and the sample surface in an atomic force microscope is \( 0.1-10 \text{ nm} \) in order of magnitude. Thus, the use of V-shaped NSG10 (NT-DMT) cantilevers with a resonant frequency of 240 kHz and pyramidal probes, which have a ratio of the probe height to the base width of 3:1, the radius of the rounded end is less than 10 nm, the ratio of the probe height to the base width of 1:1, and the radius of the rounded end is less than 50 nm, allowed us to obtain a surface topography with a fairly high resolution.

The size of the scanning area during the study of the deformation relief varied from 25 to 50 microns, depending on the size of the object under study. The image of the surface within one scan was built line by line along 255 lines and remained constant for all subsequent images.
3. Results and discussion

Metallographic analysis showed that from the edge of the free surface (0.01-0.02 mm), an intensely deformed layer with a depth of 150 microns was detected (fig. 2-3). The average grain size in this area was ~ 20-25 microns: horizontally 2 ±1.5 microns, vertically ~ 20 ± 5 microns.

![Figure 2](image1)

**Figure 2.** The structure of sample No. 1 after the SPD MR-roller (force of 2700 H): a – on an optical microscope, magnification of 200 times; b) on an optical microscope, magnification of 500 times, with sections: 1-intensely deformed layer (150 microns); 2-deformed layer (50 microns); 3-transition layer between the deformed and initial state (250 microns); 4-undeformed layer (initial state of pure iron); c, d – 2Dscan image of the deformed surface (AFM).

![Figure 3](image2)

**Figure 3.** The structure of sample No. 1 after the SPD MR-roller, OM- images, zoom x200 microns. Areas of OM and AFM studies: 1 – hardened layer (left edge), 2-3 – hardened layer (center), 4 – hardened layer (right edge), 5 – non-hardened layer (middle of the sample).

Figures (2 in and 4) show that the grains are thin, but strongly elongated along the direction of metal flow, and in some places repeat the undulating contour of the working part of the MR-roller.

At a depth of 150 microns from the free edge of the surface, you can observe a deformed layer (50 microns deep), in which the grains are slightly less elongated in the direction of the metal flow and slightly enlarged. The average grain size was ~ 23-25 microns: horizontally 4 ±1.1 microns, vertically ~ 23 ± 1.8 microns.
At a depth of 200 microns from the free edge of the surface, a transition layer was found between the deformed and initial state (depth of 250 microns), in which the size of the deformed ferritic grain can be increased. The average grain size in this area was ~ 25-30 microns: horizontally 5 ±2.3 microns, vertically ~ 25 ± 3 microns.

The dimensions of the structure elements were taken from an atomic force microscope using the profilogram method (Fig. 4). the size of the studied area was 25 × 25 microns.

The height of the grain boundaries at point # 1 (Fig. 3) varies from 0.01 microns to 0.08 microns, and the width varies from 0.05 microns to 0.5 microns. The height of inclusions (chromium carbides) at point # 1 varies from 0.011 to 0.45 microns, and the width varies from 0.09 to 5 microns. The height of the grain boundaries at point 2-3 (fig. 3) varies from 0.01 to 0.015 microns, and the width varies from 0.5 to 1 microns.

The height of inclusions (chromium carbides) at point # 2-3 varies from 0.04 to 0.8 microns, the width varies from 0.4 to 1 microns. The height of the grain boundaries at point # 4 (fig. 3) varies from

Figure 4. Scan images of the structure and topography of the Armco-iron surface:

(a) 2D scan-image with a profilogram of the structure; (b) 2D scan-image of the surface of the structure; (c) 3D scan-image of the surface relief
0.012 to 0.08 microns, and the width—from 0.04 to 0.5 microns. The height of inclusions (chromium carbides) at point # 4 varies from 0.04 to 0.8 microns, and the width—from 0.2 to 1 microns.

OM and AFM studies showed that a deformed layer up to 250 microns deep was detected from the edge of the free surface (0.01-0.02 mm). Figure 5 shows a graph of grain size distribution.

![Graph of grain size distribution over the depth of the hardened layer](image)

**Figure 5.** Graph of grain size distribution over the depth of the hardened layer

4. Conclusion
The distinctive features of grains in the hardened region are their "elongated" shape in the direction of the MR-roller feed (the direction of the main deformation) and curved grain boundaries.

The authors believe that the identified effects will favorably affect the macromechanical characteristics of the hardened metal.

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