Change of deformation characteristics and dislocation substructure of nonferrous metals under influence of magnetic field

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Abstract. The objects of the study were polycrystalline copper of M00b grade and commercially pure titanium BT1-0. Microindentation was carried out on the samples of titanium BT1-0 in the initial state, immediately after magnetic field exposure of 0.4 T and after certain time intervals. The defect substructure of cooper samples M00b, subjected to loading to failure in the creep mode under the influence of magnetic field of 0.35 T and without it, was investigated by the methods of electron diffraction microscopy. It was revealed that the effect of magnetic field exposure on commercially pure titanium BT1-0 leads to the decrease in microhardness with the subsequent stabilization during the time that depends on the processing parameters. And the effect of the magnetic field exposure on copper during the process of creeping results in the redistribution of dislocation substructure types. Also, there are changes in quantitative characteristics of dislocation substructures.

1. Introduction
Development of production technologies at the present stage of technological progress forces to search for materials with high performance properties, thus, contributing to the development of new methods of energy impact on materials. Since the 1980s the question of influence of weak magnetic fields on the real structure and plasticity of “non-magnetic” materials [1-5], including the metal ones (Al, Cu, Zn, etc.), has been actively studied [6-11].

One of the factors responsible for the physical and mechanical properties of materials is their structure. Changes in the structure characteristics occur during the plastic deformation. In this connection it is necessary to have comprehensive information about the changes in the material structure close to the source that caused its complete fracture [12-15]. In that context the purpose of work was to investigate the magnetic field effect on the change in properties of non-ferrous metals undergoing plastic deformation. Commercially pure titanium was subjected to microindentation, and commercially pure copper was tested for creep.

2. Materials and methods
We used samples of titanium BT1-0 with dimensions of 0.4×1×1 cm³. Samples were prepared by annealing at 800 K during 2 hours followed by furnace cooling, mechanical polishing, chemical etching in the solution composed of hydrofluoric and nitric acids with the addition of water in the ratio...
of 1:1:6. The etching time was empirically adjusted. After etching the samples were thoroughly washed with running water and dried. The average grain size in the initial state was 79.1 µm.

Part of the research is carried out on polycrystalline copper of M00b grade. Flat samples with the dimensions of the working part 150×5×0.46 mm$^3$ were used. Before creep testing the material structure was equilibrated by recrystallization annealing during 2 hours at a temperature of 700 °C with the subsequent cooling in water. Tests in the creep mode under constant tensile stress $\sigma = 130$ MPa and a temperature of 25 °C were performed up to fracture. The first half of the samples was deformed under the conditions of external magnetic field with induction 0.35 T, the second half – under the normal conditions [16].

Microhardness measurements were performed with the help of microhardness tester HVS-1000A by the method of micro-Vickers for three variants: without the magnetic field influence, immediately after exposure to magnetic field, and after certain time intervals; magnetic field exposure time was constantly varied.

The microhardness value was expressed as an average of at least 30 measurements. Quantitatively the effect of the magnetic field was characterized by the relative change in microhardness:

$$Q = \frac{HV - HV_0}{HV_0} \times 100\%,$$

where $HV$ is the microhardness value of the sample exposed to magnetic field, $HV_0$ – the initial value of the microhardness.

For the creep tests like in [17, 18] the upgraded testing machine for studying processes of plastic deformation in metals was used. The permanent magnet was applied as a source of magnetic field. The field density was controlled by the milliteslameter TPU with a precision up to $1 \times 10^{-3}$ T.

The research of the dislocation substructure of samples (DSS) was performed by the transmission electron microscopy of foils with the help of electron microscope EM-125. The foils were prepared from the material adjacent to the fracture zone and at some distance from it. Images of the material fine structure were used for the classification of morphological features of the structure.

3. Results and discussion

3.1.1. Influence of magnetic field $B=0.4$ T on titanium microhardness

Dependences of the relative change in microhardness on the magnetic field exposure time 0.4 T in the interval from 0.75 hour to 2 hours, obtained from the experimental data, are presented in Figure 1.

It can be seen that at these processing parameters the decrease in microhardness with its subsequent stabilization for all processing times (except for 2 hours) takes place. Stabilization of microhardness occurs according to the same exponential law, regardless of the processing time. The processing time that equals to 2 hours is characterized by the residual influence, even after 24 hours, which is about 2 ± 1.3%. The dependence of the relative change in microhardness on the processing time, given in Figure 2, shows the initial effect of the magnetic field.

The analysis of this dependence shows that a linear decrease in microhardness takes place as the exposure time in the field increases. The presented dependence obeys a linear law $Q = -4 t + 2$. The magnetic field effect is not observed for the exposure times less than 0.5 hour, which indicates the existence of a certain time threshold below which the effect is not observed.

Since the initial effect of the magnetic field depends on the exposure time in it, it becomes relevant to analyze the stabilization dependencies of microhardness value on the magnetic field exposure time. This dependence is shown in Figure 3. It can be seen that it is of exponential character.
Figure 1. Dependence of the relative change in microhardness ($Q$) on the time elapsed after the treatment by magnetic field of 0.4 T during 0.75 h (a), 1 h (b), 1.25 h (c), 1.5 h (d), 1.75 h (e), 2 h (f).
3.2. Magnetic field effect $B = 0.35$ T on the change in dislocation sub-structure of commercially pure copper at creep

In the fractured areas of copper samples the structure in the form of fragments and dislocation chaos is found. Flexural extinction contours indicate the internal stresses arising during the creep (Fig. 4). The main dislocation sub-structure is a cellular one. Also the strip dislocation substructure is present in the material.

As the distance from the fracture surface increases (the foils prepared at a distance of 85, 325 and 635 μm are investigated), the strip and cellular dislocation substructures are observed in copper. In the strip substructure and in the cells the dislocation substructure in the form of randomly distributed dislocations is found.
The analysis of the density of flexural extinction contours from the distance to the fracture surface of copper is carried out. This characteristic is linearly related to the density of stress concentrators. It is found that the density of flexural extinction contours decreases exponentially as the distance from the copper fracture surface increases, ranging from 1200 cm\(^{-2}\) to 195 cm\(^{-2}\).

The magnetic field effect on copper leads to the redistribution of dislocation substructure types. In addition to the identified types of dislocation substructures the sub-grain structure is formed with the sub-grain sizes of a nanoscale interval.

The analysis of changes in the scalar dislocation density from the distance to the fracture surface of copper, tested for creep under the conditions of magnetic field exposure and without it, is carried out. It is found that the difference in the values of scalar density of dislocations in the copper, fractured without a magnetic field and exposed to the magnetic field, is most clearly revealed in the material adjacent to the fracture surface. The analysis of internal stress fields, formed during the creep of copper under the conditions of magnetic field exposure and without it, is performed. They are predominantly located at the intraphase interfaces: grain boundaries and grain boundary intersections; sub-grain boundaries and sub-grain boundary intersections; boundaries of a strip substructure. Besides, these contours are detected at the fragmented sub-boundaries. As a parameter characterizing the bending-torsion of the copper crystal lattice the density of flexural extinction contours is used.

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The similarity in the number of stress concentrators in cooper, deformed by the magnetic field and without it, is established. There is a pronounced maximum of stress concentrator density in the material, located at a distance of \(\sim 4\) mm from the fracture surface. At this depth the maximum of scalar density of dislocations is identified and the maximum of relative content of a strip sub-structure in copper is located [16]. Consequently, the main source of bending-torsion of the crystal lattice of copper during creep are the interfaces formed in the stripe dislocation substructure.

4. Conclusions
The magnetic field effect on commercially pure titanium BT1-0 leads to the decrease in microhardness with its subsequent stabilization over the time that depends on the processing parameters. The typical feature in determining the relative microhardness value immediately after the magnetic treatment is the increase of the exposure time resulting in the inevitable build-up effect. The initial effect is characterized by the linear dependence on the processing time for the value of field density of 0.4 Tesla. Stabilization time of microhardness is of exponential nature for the induction of 0.4 Tesla.

It was found that during the destruction of commercially pure copper without magnetic exposure on the creep process, regardless of the distance to the fracture surface, the main type of dislocation substructure is cellular. Along the grain boundaries the strip substructure is detected.

The differences in quantitative characteristics of dislocation substructures are revealed and the gradient nature of the change in the amount of stress concentrators as the distance from the fracture surface increases, regardless of the magnetic effect, is identified.

In the case of a magnetic field effect on the process of creeping the main type of dislocation substructure, regardless of the distance to the fracture surface, is a strip dislocation substructure. In some instances, the grains with the structure of dislocation chaos, cellular and mesh substructure are identified.

The reduction in the density of flexural extinction contours is established as the distance from the fracture surface increases during fracture in the magnetic field.

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