Investigation of defect copper substructure disrupted in creep condition under the action of magnetic field

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Abstract. The defect substructure of M00b copper samples loaded up to disruption in creep condition both under and without the action of 0.35 T magnetic field is investigated in the paper. Material near the disrupted surface and at certain distances from it received the serious study. It has been ascertained that when copper disrupting without magnetic action on creep process the main type of dislocation substructure is the cellular one irrespectively of the distance to disruption surface. As the result of magnetic field influence on creep process the main type of dislocation substructure is replaced by the stripe-like one. The distinctive quantitative characteristics of dislocation substructures are observed. Moreover, a gradient behavior of the number of stress raisers has been revealed when moving away from disruption surface both in deformation conditions with and without a magnetic field.

1. Introduction
The progress in engineering and technologies facilitates development of high-power electric power plants forming magnetic and electric fields, which constantly effect on the materials around them. On the other hand, the most of essential products, components of the machines and structures are maintained in conditions of constant stress (creep), so strict requirements are specified for them in terms of operational characteristics. However, such factors as external power effects and mechanical stress acting simultaneously can significantly reduce an operational time of essential products and units causing their premature failure [1-6]. Extended operational time of metals and alloys determines the advances in improvement of metal products reliability. One of the factors responsible for physical and mechanical properties of materials is considered to be their structure evolving in conditions of stress. Therefore, one needs exact information on material structure near the point which caused its complete disruption. For the fore-going reasons the work focuses on investigation of magnetic field effect on the gradient of copper defect substructure subject to creep tests near the zone of disruption.
2. Materials and research methods

Polycrystalline M00b copper was used as material of research. Flat samples with $150 \times 5 \times 0.46$ mm$^3$ working sections were applied in experiments. Before creep tests material structure was balanced via recrystallization annealing for two hours at the temperature $700\ ^\circ\text{C}$ succeeded by chilling in water necessary for removal of annealing cinder. The tests in conditions of creep were carried out under constant tension stress $\sigma = 130$ MPa and the temperature $25\ ^\circ\text{C}$ up to disruption. The first half of samples was deformed in conditions of external magnetic field with induction $0.35$ T, the second half – in normal conditions.

To record the deformation of creep a modernized testing machine for research into the processes of metal plastic deformation was used. The testing machine operates in coordination with the software intended for recording the data on sample elongation in regard to the time of experiment with a possibility to analyze creep phases and approximate creep curves [7].

As the source of a magnetic field we used a permanent electromagnet which can adjust magnetic field induction. Magnetic field induction was monitored by milli-teslameter TPU with the accuracy up to $10^{-3}$ T.

Dislocation substructure of samples was researched via transmission electron diffraction microscopy (TEM) of thin foils by electron microscope EM-125. The foils were made of material taken near the zone of disruption. Images of thin structure of material were used for classification of morphological characteristics of structure [8, 9].

![Figure 1](image1.png)

**Figure 1.** General view (b) and sub-surface part (a) of ion thinned foil (the sample is disrupted by creep in the magnetic field). As ovals TEM analyzed foil zones are marked; (a) – 1 – disruption surface; 2 – the layer over the distance ~20 µm from the disruption surface; (b) – layers, located at the depths 3 – ~265 µm; 4 – ~325 µm; 5 – ~610 µm.

3. Results and their discussions

3.1. Layer by layer analysis of dislocation substructures emerging in copper in conditions of creep

The experiments demonstrated that in the layer bordering with disruption surface a stripe-like substructure is forming, the azimuthal component of full disorientation angle in a stripe-like
substructure is up to $\Delta \alpha = 5.7$ degrees. In stripes a dislocation substructure occurs in the form of chaotically distributed dislocations with scalar density $\sim 3.5 \times 10^{10} \text{ cm}^{-2}$. Moreover, a lot of bend contours were revealed.

The experiments ascertained that irrespectively of the distance to disruption surface a cellular dislocation substructure prevails – is the main one (Fig. 2b). On grain boundaries a stripe-like substructure occurs (Fig. 2a).

![Image](image1.png)

**Figure 2.** Electron microscopical image of dislocation substructure of the layer $\sim 85$ µm away from copper disruption surface

In the layer $\sim 85$ µm away from disruption surface the scalar density of dislocations in the stripe-like substructure is $\sim 2.2 \times 10^{10}$ cm$^{-2}$; in the cellular one - $\sim 2.6 \times 10^{10}$ cm$^{-2}$. In the layer $\sim 325$ µm away from disruption surface the scalar density of dislocations in the stripe-like substructure is $\sim 2.7 \times 10^{10}$ cm$^{-2}$; in the cellular one - $\sim 2.9 \times 10^{10}$ cm$^{-2}$. In the layer $\sim 495$ µm away from disruption surface the scalar density of dislocations in the cellular substructure is $\sim 2.5 \times 10^{10}$ cm$^{-2}$; in the stripe-like one - $\sim 2.3 \times 10^{10}$ cm$^{-2}$. In the layer $\sim 635$ µm away from disruption surface the main type of dislocation substructure is the cellular one (Fig. 3a). On grain boundaries the stripe-like substructure occurs (Fig. 3b).

![Image](image2.png)

**Figure 3.** Electron microscopical image of dislocation substructure of the layer $\sim 635$ µm away from disruption surface of copper

Moreover, grains with dislocation substructure in form of a grid and chaotically distributed dislocations are found. In cells and stripes there is a dislocation substructure in form of chaotically distributed dislocations. The scalar density of dislocations in cells is $\sim 2.7 \times 10^{10}$ cm$^{-2}$; the scalar density
of dislocations in stripes is $\sim 2.5 \times 10^{10} \, \text{cm}^{-2}$; the scalar density of grid-like dislocations in grains is $\sim 6.0 \times 10^{10} \, \text{cm}^{-2}$.

Copper structure analyzed in terms of quantity demonstrated changes in contours density relatively to the distance to disruption surface. The analysis of results shown in Fig. 4 demonstrates the gradient character of changing number of stress concentrators in copper. The layer bordering with the surface of disruption is in the most stressed condition.

![Figure 4. The dependence of bend contours density of extinction (density of stress concentrators) on the distance to copper disruption surface](image)

3.2. Layer-by-layer analysis of dislocation substructures emerging in copper in conditions of magnetic field creep

A lot of bend extinction contours characterize electron-microscopical images of copper structure in disruption zone (the density of contours $\sim 2.9 \times 10^{3} \, \text{cm}^{-2}$), it confirms curvature and torsion of material crystal lattice.

The analysis of electron-microscopical images of a substructure forming in $\sim 2 \, \mu m$ layer of copper after its disruption in condition of magnetic creep demonstrates that stripe-like and sub-grain substructures are forming in this layer in conditions of creep (the sphere of sub-grains is marked with a circle). Quasi circular arrangement of reflexes is typical for micro-electron diffraction patterns of this structure (Fig. 5 b), it indicates a nano-crystal condition of the substructure, and secondly, a high level of disorientation in these crystals. Taken measurements, indeed, showed that sub-grain dimensions vary from 35 to 85 nm. A dislocation substructure in form of chaotically distributed dislocations with the scalar density $\sim 3.85 \times 10^{10} \, \text{cm}^{-2}$ is observed in stripes.

The experiments stated that irrespectively of the distance to disruption surface a stripe-like substructure is the main type of dislocation substructure.

For copper structure of the layer, which is $\sim 6 \, \mu m$ away from disruption surface a dislocation substructure in form of chaotically distributed dislocations is typical. The scalar density of dislocations in stripe-like substructure is $\sim 4.1 \times 10^{10} \, \text{cm}^{-2}$; in grains $\sim 2.4 \times 10^{10} \, \text{cm}^{-2}$. The density of bend extinction contours in this material is $\sim 0.67 \times 10^{3} \, \text{cm}^{-2}$.

In stripe-like copper substructure in the layer, which is $\sim 20 \, \mu m$ away from disruption surface there is a dislocation substructure in form of chaotically distributed dislocations, grids are infrequent. The scalar density of dislocations is $\sim 3.3 \times 10^{10} \, \text{cm}^{-2}$. The density of bend extinction contours in this material is $\sim 0.54 \times 10^{3} \, \text{cm}^{-2}$.

In stripe-like copper substructure in the layer, which is $\sim 20 \, \mu m$ away from disruption surface there is a dislocation substructure in form of chaotically distributed dislocations, grids are infrequent. The scalar density of dislocations is $\sim 3.3 \times 10^{10} \, \text{cm}^{-2}$. The density of bend extinction contours in this material is $\sim 0.54 \times 10^{3} \, \text{cm}^{-2}$. 
Figure 5. Electron-microscopical image of copper surface layer disrupted in conditions of creep in magnetic field; a – light-colored fields; b – micro-electron diffraction pattern. The arrows show disruption surface.

In the layer ~265 µm away from disruption surface in stripe-like substructure there is a dislocation substructure in form of chaotically distributed dislocations, and grids are less frequent; the scalar density of dislocations is ~2.8x10^{10} cm^{-2}. The scalar density of dislocations in grains without stripe-like substructure is ~3.3x10^{10} cm^{-2}. The density of bend extinction contours in this material is ~0.62x10^3 cm^{-2}.

Figure 6. Electron-microscopical image of the layer structure, which is ~325 µm away from disrupted copper surface in conditions of magnetic creep.
Figure 7. The dependence of scalar density of dislocations $\langle \rho \rangle$ in the stripe-like substructure (curve 1) and in grains (curve 2), densities of bend contours of extinction (curve 3) on the distance to copper disruption surface (creep in conditions of magnetic field).

For the layer of material $\sim 325 \, \mu m$ away from disruption surface the same two types of dislocation substructure as in the above mentioned layers are typical, however, in grains with chaotic dislocation structure broken sub-grain boundaries are often observed (Fig. 6). In stripe-like substructure there is a dislocation substructure as chaotically distributed dislocations, grids are less frequent (Figure 7); the scalar density of dislocations is $\sim 2.1 \times 10^{10} \, cm^{-2}$. The scalar density of dislocations in grains without a stripe-like substructure is $\sim 3.6 \times 10^{10} \, cm^{-2}$. The density of bend extinction contours in this material is $\sim 0.28 \times 10^3 \, cm^{-2}$.

In a stripe-like copper substructure in the layer $\sim 610 \, \mu m$ away from disruption surface the scalar density of dislocations is $\sim 2.5 \times 10^{10} \, cm^{-2}$. The scalar density of dislocations in grains without stripe-like substructure is $\sim 3.1 \times 10^{10} \, cm^{-2}$. The density of bend extinction contours in this material is $\sim 0.42 \times 10^3 \, cm^{-2}$.

It has been stated that in the layer bordering with disruption surface a stripe-like dislocation substructure is mainly forming. It has been revealed that the scalar density of dislocations naturally decreases as it is moved away from disruption surface (Fig. 7, curve 1). The second type of copper structure includes grains with chaotically distributed dislocations or grid dislocation substructure. In this case the scalar density of dislocation slightly increases (within measurement errors) as moving away from disruption surface (Fig. 7, curve 2). In copper disruption zone there are internal stress fields, indicated by bend extinction contours seen on electron-microscopical images of thin foil structure. The density of bend extinction contours reduces as moving away from disruption surface (Fig. 7, curve 3).

4. Conclusion

It has been determined that when copper disrupting without magnetic action on creep process the main type of dislocation substructure is a cellular one irrespectively of the distance to disruption surface. On grain boundaries a stripe-like substructure is revealed.

The distinctive quantitative characteristics of dislocation substructures have been revealed, as well as a gradient nature of changing number of stress concentrators when moving away from disruption surface irrespectively of magnetic action.

Under magnetic action on creep the main type of dislocation substructure is a stripe-like one, irrespectively of the distance to disruption surface. In some cases grains with dislocation chaos structure, as well cellular and grid substructures are revealed.
The reducing character of extinction bend contours density has been determined when moving away from disruption surface in conditions of magnetic creep.

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