Influence of free torsion deformation modes on the microstructure and mechanical properties of commercially pure copper

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Abstract. The paper investigates the effect of the free torsion rate of cylindrical specimens of commercially pure copper (grade M1) on their deformed state, microstructure, and mechanical properties. The study of the microstructure was carried out by means of transmission electron microscopy and X-ray diffraction analysis in the central region and at the periphery of the deformed rod. The mechanical properties were evaluated by measuring the microhardness. It was found that an increase of the torsion rate, other things being equal, promotes more intensive strengthening and refinement of the microstructure.

1. Introduction
Recently, it has become more and more obvious that traditional methods of thermomechanical treatment have been developed so completely that it is impossible to expect a significant improvement in the properties of the resulting bars [1-3]. The use of new methods of plastic deformation is one of the most promising ways in the creation of materials with an improved set of mechanical properties. With various combined processing schemes, processes are implemented that make it possible to improve the operational properties of materials by purposefully changing their microstructure [1-4].

Studies [4-14] have shown that the use of a simple shear in various deformation schemes allows realizing a special state of intensified motion of defects, which, in turn, leads to the formation of equiaxed fine grains with a small number of defects in its body. One of the promising methods of deformation for obtaining such a state in metal workpieces is the free torsion method. This method provides a significant non-monotonicity and, at the same time, a high value of the accumulated degree of shear strain in the metal, which leads to the evolution of the dislocation structure, activation of new slip systems, misorientation of microvolumes inside the grain and rearrangement of the formed fragments into ultrafine grains with nonequilibrium high-angle boundaries [1,6, 15,16].

The aim of this work was to study the effect of the rate of deformation processing by the method of free torsion on the microstructure and mechanical properties of commercially pure copper (grade M1).

2. Experimental
The studies were carried out on rods with a length of 250 mm and a diameter of 10 mm. The deformation was carried out at rates of rotation of the gripper - 12.5, 20 and 40 rpm until the failure of the rods (16,
12 and 9 revolutions, respectively. The accumulated shear strain before failure was determined by the expression [15]:

\[
e = \frac{\pi d N}{h},
\]

where \(d\) is the sample diameter, \(N\) is the number of revolutions before failure, \(h\) is the sample length.

After deformation processing, the specimens were cut at an angle of 15° to the axis of the rod. The mechanical properties were evaluated by the microhardness measurement method (Buehler Micromet 5101) at a load of 100 g during 10 s. Microstructural studies were carried out in the center and periphery of the beveled samples by transmission electron microscopy (JEM JEOL 2100; accelerating voltage 200 kV) and X-ray diffraction analysis (Rigaku Ultima IV) using CuKα radiation. The X-ray diffraction patterns were calculated using the full-profile Rietveld analysis in the MAUD software [17]. The dislocation density was calculated using the expression given in [18, 19]:

\[
\rho = \frac{2\sqrt{3}\sqrt{\langle \varepsilon^2 \rangle}}{d \cdot b},
\]

where \(b\) is the value of the Burgers vector for FCC copper alloys, \(d\) is the size of the coherent scattering domains (CSD) and \(\varepsilon\) is the value of the microstrain.

3. Results and discussion

The calculation of the accumulated strain at rotation rates of 12.5, 20, and 40 rpm showed that the workpieces accumulate shear strain \(e = 2.5, 1.9, \text{ and } 1.4\), respectively, before failure. Fig. 1 demonstrates the effect of deformation processing at different rates on the microhardness value. It can be concluded that, in general, an increase in the rotation rate of the lathe gripper leads to an increase in the microhardness value. In the initial state, the average microhardness was (102 ± 7) HV. The deformation leads to an increase in this parameter up to (109 ± 9 HV), (120 ± 6 HV) and (123 ± 9 HV) at gripper rotation speeds of 12.5, 20 and 40 rpm, respectively.

![Figure 1](image_url)  
**Figure 1.** Microhardness distribution on the cross section of the samples in the initial state and after processing at different strain rates.

TEM studies have shown that in the central zone of the sample after processing at a speed of 12.5 rpm, the dislocation substructure is a weakly oriented cellular structure with a fragment thickness of about 300 nm. An increase in the deformation rate to 40 rpm (Fig. 4) led to a thinning of the fragments.
to 200 nm and to a further set of misorientations between them, which is noticeable by the blurring of reflections in the electron diffraction patterns (Fig. 2 and Fig. 4). In the peripheral region, after free torsion at 12.5 rpm (Fig. 3), the dislocation substructure has the form of a disoriented cellular structure with partial fragmentation with a cell size of 300-600 nm and a fragment thickness of 200 nm. An increase in the deformation rate to 40 rpm (Fig. 5) led to a further refinement of the structural elements — cells to 250 nm and the thickness of fragments to 150 nm.

The XRD study (table 1) showed that the intensity of the peaks in the peripheral region of the samples decreases relative to the center and their broadening occurs, which indicates an increase in the defectiveness of the structure. The calculation of diffraction patterns showed that the dislocation density at the periphery of the studied samples was higher than at the center, the CSD was lower, and the microstrain value was non-monotonic, which is associated with the rearrangement of the dislocation structure and relaxation of internal stresses.
Figure 4. Microstructure after processing: a - bright field, b - electron diffraction pattern from the corresponding area (zone axis 310). 40 rpm, center

Figure 5. Microstructure after processing: a - bright field, b - electron diffraction pattern from the corresponding area (zone axis 310). 40 rpm, periphery

Figure 6. Diffraction patterns of deformed samples.
### Table 1. XRD analysis results

| State          | Lattice parameter, Å | CSD size, nm | Microstrain, % | Dislocation Density, m$^{-2}$ |
|----------------|----------------------|--------------|----------------|-----------------------------|
| 13 rpm center  | 3.6168               | 83           | 0.13           | 2.1E+14                    |
| 13 rpm periphery | 3.6167              | 62           | 0.11           | 2.3E+14                    |
| 20 rpm center  | 3.6172               | 96           | 0.10           | 1.5E+14                    |
| 20 rpm periphery | 3.6160              | 68           | 0.12           | 2.4E+14                    |
| 40 rpm center  | 3.6160               | 87           | 0.12           | 1.9E+14                    |
| 40 rpm periphery | 3.6169              | 71           | 0.12           | 2.3E+14                    |

4. **Summary**

It was found that the deformation by the method of free torsion leads to the hardening of the workpiece practically without changing the initial geometric parameters, and more intensively in its peripheral layers. Thus, an increase in the rotation rate provides a more intense hardening, but leads to a decrease in the plasticity resource at the moment of failure, therefore, at a speed of $\omega = 12.5$ rpm, the accumulated deformation before fracture was 2.5, and at $\omega = 40$ rpm - 1.4. Despite the decrease in the accumulated strain to fracture with an increase in the rate, the average value of the microhardness continues to increase and reaches 123 HV at 40 rpm, which is 20% higher than the initial value.

An increase of the gripper rotation rate leads to the refinement of structural elements at the periphery (from 600 nm to 250 nm) and in the central region (from 300 to 200 nm) of the metal. There is also a rearrangement of the dislocation substructure from a weakly misoriented cellular to a misoriented cellular one.

The CSD size and dislocation density reflect the distribution pattern of the accumulated strain during free torsion, since the most deformed peripheral layers have a higher dislocation density and, accordingly, a smaller CSD parameter.

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