Effect of Shock-Wave Loading on the Internal Microstructure and Mechanical Properties of Fine-Grained Copper

O. N. Ignatova, I. I. Kaganova, A. N. Malyshev,
A. M. Podurets, V. A. Raevskii, V. I. Skokov,
M. I. Tkachenko, G. A. Salishchev, and T. N. Kon'kova

UDC 539.411.5

It is shown that preloading of fine-grained copper with a the grain size of 0.5 m by a shock wave of intensity ≈25–50 GPa does not lead to changes in its internal microstructure and mechanical properties, and the dislocation density increases only slightly from $1.8 \cdot 10^{11}$ cm^{-2} in the initial state to $(3.1–3.6) \cdot 10^{11}$ cm^{-2} after shock-wave loading. An increase in shock wave intensity to pressures > 55 GPa leads to a decrease in the dislocation density to $2.5 \cdot 10^{9}$ cm^{-2}, an increase in the grain size to ≈19 μm, the occurrence of microtwins inside the grains, and a reduction in the mechanical properties of fine-grained copper to the level of coarse-crystalline copper.

Key words: shock wave, fine-grained metals, loading intensity, softening, conventional yield stress, dislocation density.

INTRODUCTION

Shock-wave loading is a unique method for creating high pressure and high strain rate conditions, and it can be used as a method for changing mechanical properties by changing structure [1–4].

At present, the loading of coarse-grained metals by a shock wave with a maximum pressure of ≈100 GPa has been studied most extensively. For example, in [3, 5] the mechanical properties and microstructure of coarse-crystalline copper were studied after loading by a pressure of up to 70 GPa at various strain rates and temperatures. Significant structural changes in the metal were observed. Thus, at shock pressures above a certain threshold (30 GPa), both homogeneous and heterogeneous deformation occur. This is manifested in the formation of parallel layers ≈1–2 μm wide with a period of 1–10 μm [5] in the grains. For aluminum, similar results were obtained for loading by a pressure of ≈10 GPa, [1]. Modeling of this process shows that the formation of heterogeneous structure in metals is accompanied by significant temperature increases in localized deformation bands and short-term strength reduction. This localized heating and strength reduction occur in a fairly short time ≈0.1–0.5 μsec, after which the temperature is equalized and the strength is restored. Moreover, preliminary shock-wave loading of coarse-grained copper leads to an increase in its conventional yield stress by a factor of 4–6, a ≈20% increase in the tensile resistance, and an increase in the dislocation density by a factor of 30, to ≈10^{11} cm^{-2} [6].

Maximum strength characteristics have been found in metals with ultrafine-crystalline structure. The question arises of whether it is possible, by shock-wave loading, to change the structure of fine-grained and nanostructured materials and improve their properties to an extent that is not observed under quasistatic deformation. In the present paper, we consider the effect of shock-wave loading on ultrafine-crystalline copper in comparison with coarse-crystalline copper (99.9% purity; grain size of 110 μm).

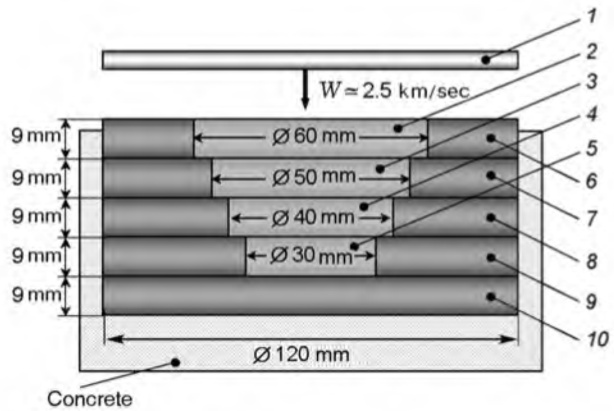

Fig. 1. Diagram of shock-wave loading experiments with varying intensity: steel impactor (12Kh18N10T steel; thickness $h = 1$ mm) (1), copper samples Nos. 1–4 (2–5), copper holders (6–9), and copper support (10).

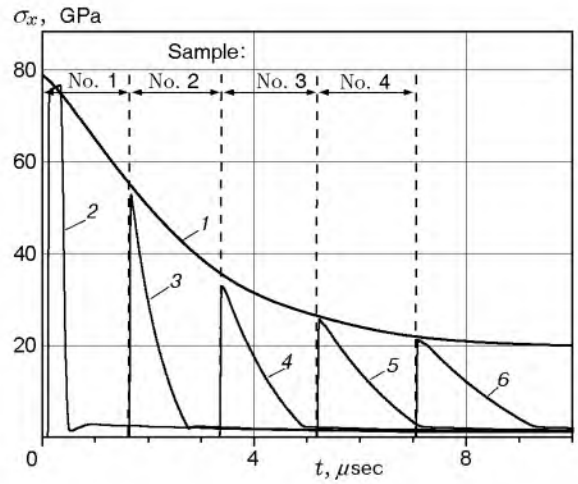

Fig. 2. Shock-wave amplitude versus time curves (1) and calculated stress profiles (2–5) in sample Nos. 1–4 and in the initial state (6).

1. EXPERIMENTAL TECHNIQUE

Samples of ultrafine-grained (UFG) copper with initial density $\rho_0 = 8.93$ g/cm^3 were exposed to high-intensity shock-wave loading. UFG copper was produced by all-round isothermal forging; the average size of its grains is $d_0 = 0.5$ μm [7], and the dislocation density is $\rho_{\rm d} = 1.8 \cdot 10^{11}$ cm^{-2}.

Loading was carried out by a steel impactor (steel12Kh18N10T) which was accelerated by explosion products to a velocity of ≈2.5 km/sec and decelerated by the copper samples (No. 1–4) arranged in a stack consisting of four disks. The samples were pressed into copper holders (M1 copper) which protect from tensile stresses due to side unloading. The lower solid copper disk prevents the samples from spalling. A diagram of the loading is shown in Fig. 1. Coarse-crystalline copper was also loaded in this assembly.

A one-dimensional computation procedure taking into account viscoelastoplastic properties [8] was used for numerical modeling of the wave processes occurring in the assembly. Figures 2 and 3 show curves of shock-wave amplitude versus time and stress and temperature profiles (at the shock-wave front and in the unloading wave) obtained for sample Nos. 1–4. In the text below, samples are denoted by number Nos. 1–4 according to their location in the assembly — from maximum loading to minimum one. Note that in sample No. 1, the stresses $\sigma_x = 75$–55 GPa and temperatures $T = 1000$–550°C occurring at the shock-wave front exceed the annealing temperature in the microsecond range of time (1–1.55 μsec).

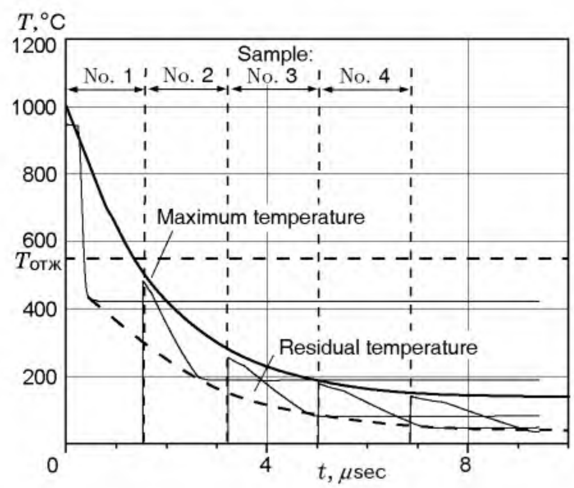

Fig. 3. Temperature versus time curves at the shock-wave front and in the unloading wave in sample Nos. 1–4.

2. RESULTS

2.1. Internal Microstructure of the UFG Copper after Loading

The microstructure of UFG copper samples was investigated with a Quanta 200 3D scanning electron microscope. A previously prepared sample tilted at an angle of 70° to the horizontal was scanned by an electron beam with an accelerating voltage of 30 kV. The crystallographic orientation at each point of the scanned area was determined from backscattered electron diffraction patterns using theTSL OIM Analysis 5

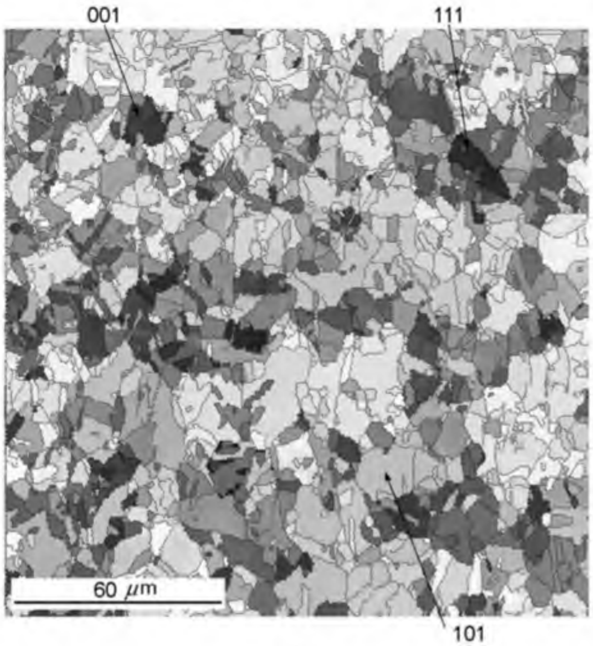

Fig. 4. Microstructure of UFG copper sample No. 1 after exposure to a pressure of $p \approx 55$–75 GPa.

software. Data processing by the TSL OIM Analysis 5 software allows one to obtain an image of the material grain structure, grain size distribution and grain disorientation and to determine the presence of low-angle and high-angle boundaries and the presence of texture in the scanning area.

Figure 4 shows the microstructure of sample No. 1 after exposure to a pressure of 75–55 GPa. One can see that the microstructure of sample No. 1 is nonuniform in the grain size, which varies in the range $d = 1$–$19\ \mu$m, mostly in $d = 6$–$12\ \mu$m. The grain boundaries are curved and have a predominantly high-angle disorientation. Twins formed during deformation were found in some large grains. The number of twins in the structure is small. High-angle boundaries are ≈95% of the total number of the recognized boundaries.

The microstructure of sample Nos. 2–4 is fine-grained and very uniform; the grain size is almost unchanged in comparison to the initial state. The grains have an equiaxed shape with slightly curved boundaries. The fraction of low-angle boundaries in the microstructures of sample Nos. 2–4 is much larger that in sample No. 1 and is 35–38%. Strain twins in the grains of the sample were not found. Meanwhile, in coarse-crystalline copper exposed to pressure 20–50 GPa, the volume fraction of twins is ≈10–15% [9].

The pressure threshold at which strain twins begin to occur in UFG copper equals ≈55 GPa.

TABLE 1
Dislocation Density in UFG Copper after Shock-Wave Loading of Varying Intensity

Sample number	ρ, 10^{10} cm^{-2}	p, GPa,	ε_i
1	0.25	75–55	0.38
2	31.0	55–35	0.32
3	32.6	35–30	0.24
4	22.8	30–25	0.20

2.2. Measurement of Dislocation Density

The change in the dislocation density as function of the pressure of the samples recovered after loading was determined by the profile of diffraction lines using an x-ray diffraction method [10]. The initial density of dislocations in UFG copper is $\rho_\mathrm{d} = 1.8 \cdot 10^{11}$ cm^{-2}, which is three orders of magnitude higher than the density in the initial coarse-crystalline state after annealing $\rho_\mathrm{d} \approx 10^8$ cm^{-2}. The measurement results are given in Table 1 and in Fig. 5. The total strain for shock-wave loading is calculated from the compression of the metal: $\varepsilon_i = \dfrac{3}{4}\ln\delta = \dfrac{4}{3}\ln\dfrac{\rho}{\rho_0}$ ($\delta = \rho/\rho_0$, where ρ_0 and ρ are the initial density of copper and its density during shock-wave loading, respectively).

As can be seen from Fig. 5, in UFG copper with the highest initial dislocation density, exposure to a pressure of 30–50 GPa increases the dislocation density by a factor of ≈2. Then, it decreases to $\rho_\mathrm{d} \approx 2.5 \cdot 10^9$ cm^{-2}, which is most likely due to the annealing of defects during adiabatic heating because of the shock-wave loading.

Similar measurements were carried out for coarse-crystalline copper. In coarse-crystalline copper, shock-wave loading generates higher dislocation density than does quasistatic deformation. From Fig. 5, it is evident that loading of coarse-crystalline copper at a pressure of 75–55 GPa leads to annealing of dislocations to values $\rho_\mathrm{d} \approx 5 \cdot 10^{10}$ cm^{-2}, which are an order of magnitude higher than in UFG copper. This may be due to differences in the dynamics of dislocation growth and temperature annealing during loading.

2.3. Mechanical Properties of UFG copper before and after Shock-Wave Exposur

UFG copper samples in the initial state and after shock-wave loading were studied under both static and dynamic compression.

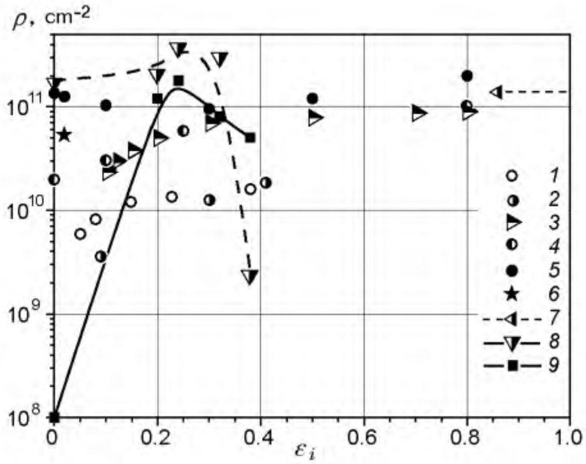

Fig. 5. Dislocation density in copper with various grain sizes versus degree of deformation (experiment and comparison with literature data): 1) $d_0 =$ 150 μm [2]; 2) $d_0 = 20$ μm [2]; 3) single crystal [11]; 4) OFHC copper ($d_0 = 500$–2000 μm [12]); 5) UFG copper ($d_0 = 200$ nm [13]); 6) UFG copper ($d_0 = 100$–200 nm [14]); 7) UFG copper [15]; 8) UFG copper (this work); 9) coarse-grained copper (this work).

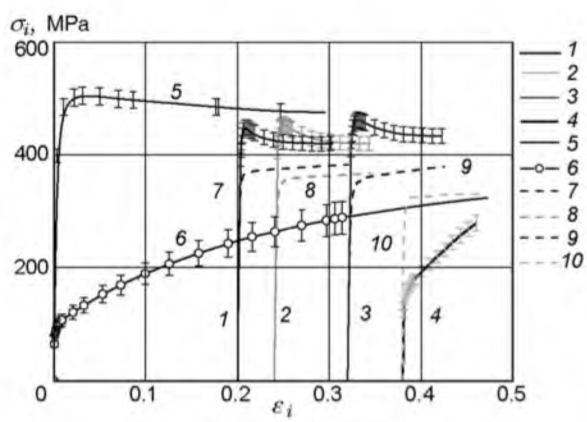

Fig. 6. σ–ε Diagrams for static compression of UFG copper and coarse-crystalline copper at normal temperature before and after shock-wave loading of varying intensity: UFG copper after loading: 1) $\sigma_x \approx 30$–25 GPa; 2) $\sigma x \approx 38$–30 GPa; 3) $\sigma_x \approx$ 55–38 GPa; 4) $\sigma_x \approx 75$–55 GPa; 5) UFG copper in the initial state; 6) coarse-crystalline copper in the initial state; 7–10) coarse-crystalline copper after shock-wave loading at a pressure of 75–25 GPa.

Static tests of the samples at room temperature were performed on a INSTRON-1185 test setup using an A0706-P798 compression device at a machine traverse speed of 0.4 mm/min, which corresponds to a strain rate of $1.3 \cdot 10^3$ sec^{-1}. For each type of samples, 4–6 experiments were performed. Figure 6 shows the average true σ–ε diagrams for static compression at normal temperature for UFG copper in the initial state and after shock-wave loading of varying intensity. The diagrams were plotted taking into account the total strain accumulated during loading. For comparison, the figure shows σ–ε diagrams for static compression of coarse-crystalline annealed copper M1 in the initial state and after shock-wave loading of varying intensity. The conventional yield stresses ($\sigma_{-0.2}$) of UFG copper before and after loading obtained from the diagrams in Fig. 6 are, respectively, $\sigma_{-0.2} = 416$ MPa in the initial state and $\sigma_{-0.2} = 430$–400 MPa after exposure to a shock wave of intensity $\approx$25–55 GPa. As the intensity increased to 55–75 GPa, the yield stress decreased to $\sigma_{-0.2} \approx 190$ MPa, which is probably due to the annealing of the metal under such loading conditions.

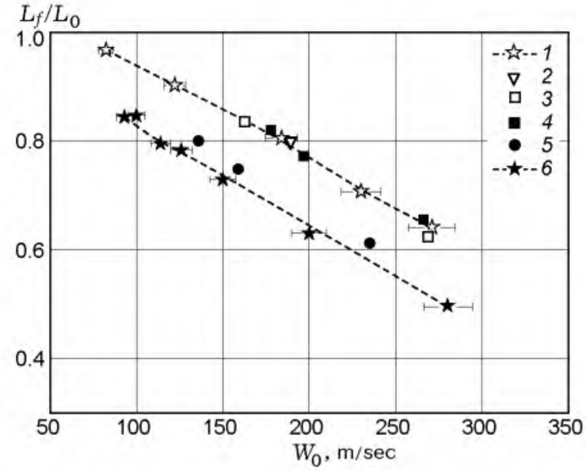

Fig. 7. Relative change in the length of UFG copper cylinders and cylinders of coarse-crystalline M1 copper versus velocity of their impact on a rigid target before and after shock-wave loading: UFG copper in the initial state (1) and after loading for $\sigma_x \approx 30$–25 (2), 38–30 (3), $\approx$ 55–38 (4), and $\approx$ 75–55 GPa (5); coarse-crystalline copper in the initial state (6).

Mechanical properties under dynamic compression were studied by the method of Taylor cylinders [16]. Taylor proposed a simple method for determining the dynamic yield stress (Y) in which the finite length of a cylinder L_f after impact on a rigid target at a velocity W_0 is used to determine the dynamic yield stress of the material. Taylor's method provides strain rates in the range of $\approx 10^3$–10^5 sec^{-1}. Figure 7 shows the relative change in the finite length of cylinders (L_f/L_0) versus impact velocity (W_0). The initial dimensions of the cylinders: length $L_0 = 25$ mm and diameter $D_0 = 5$ mm. It is evident in Fig. 7 that for $W_0 =$

100–300 m/sec, the values of L_f/L_0 for UFG copper are 20% higher than those for coarse-crystalline copper. The dynamic yield stress can be estimated by using the well-known formula $\frac{L_f}{L_0} = \exp\left(-\frac{\rho_0 W_0^2}{2Y}\right)$. However, more precise estimates of the dynamic yield stress from experimental data of Taylor's method can be obtained if the cylinder geometry is adequately described using numerical modeling methods by solving the two-dimensional problem and specifying the realistic strength properties of the rod material.

The values of L_f/L_0 UFG copper after loading to pressures of $\approx$ 25–55 GPa are close within the experimental error to L_f/L_0 of initial unloaded UFG copper. As the shock-wave intensity increases to $\approx$ 55–75 GPa, the values of L_f/L_0 decrease to values characteristic of coarse copper.

CONCLUSION

• Loading of UFG copper by shock waves with intensity $\approx$ 25–50 GPa does not change its internal microstructure and mechanical properties.

• Loading of UFG copper by shock waves with intensity >55 GPa leads to a factor of 20 decrease in the dislocation density, an increase in the grain size to $\approx$19 μm, the occurrence of microtwins in the grains, and a reduction in the mechanical properties, which are close to the same characteristics of annealed coarse-crystalline copper.

• Shock-wave exposure of annealed coarse-crystalline copper increases its yield stress by a factor of 4–5 and increases the dislocation density from 10^8 to $5 \cdot 10^{10}$ cm^{-2}.

This work was supported by the Russian Foundation for Basic Research (Project No. 08-02-0087a, 09-02-97036_povolzh'e).

REFERENCES

1. M. A. Meyers and L. E. Murr, (ed.) *Shock Waves and High-Strain Rate Phenomena in Metals,* Plenum Press, New York–London (1980).
2. G. H. Epstein, *Structure of Metals Deformed by Explosion* [in Russian], Metallurgiya, Moscow (1988).
3. G. A. Salishew, V. A. Raevskii, O. N. Ignatova, et al., "Influence of intensive plastic strain and shock-wave loading on copper strength," in: *New Models and Hydrocodes for Shock Wave Processes in Condensed Matter*, Int. Conf., Dijon, France, April 9–14 (2006), p. 17.
4. J. Petit and J.-L. Dequiedt, "Constitutive relations for copper with two mechanisms including twinning for a use under shock wave loading," *J. Phys. IV, France*, **110** (2003).
5. V. A. Raevsky, "Heterogeneous deformation of copper in shock waves at subgrain scale level," in: *14th APS Total Conf. on Shock Compression of Condensed Matter*, Vol. 50, No. 5 (2005).
6. V. A. Raevskii, A. M. Podurets, O. N. Ignatova, et al., "Effect of high-velocity loading on the microstructure and dynamic properties of copper," in: *IX Kharitonov Scientific Readings*, Proc. Conf., Inst. of Exp. Phys., Russian Federal Nuclear Center, Sarov (2007).
7. S. V. Zherebtsov, R. M. Galeev, O. R. Valiakhmetov, et al., "Formation of submicrocrystalline structure in titanium alloys by intense plastic deformation and their mechanical properties," *Kuzn.-Shtamp. Proizv.*, No. 7, 17–22 (1999).
8. N. F. Gavrilov, G. G. Ivanova, V. I. Selin, and V. N. Sofronov, "UP-OK Program for solving one-dimensional problems of continuum mechanics in a one-dimensional complex," *Vopr. Atom. Nauki Tekh.*,, **3** (11), 11–14 (1982).
9. V. A. Raevskii, A. M. Podurets, and V. G. Khanzhin, "Twin structures in copper after impact and nonimpact high-velocity loading," in: *IX Kharitonov Scientific Readings*, Proc. Conf., Inst. of Exp. Phys., Russian Federal Nuclear Center, Sarov (2007).
10. Ya. S. Umanskii, Y. A. Skakov, A. N. Ivanov, and L. N. Rastorguev, *Crystallography, X-Ray Diffraction and Electron Microscopy* [in Russian], Moscow (1982).
11. M. Haberjahn, P. Klimanek, and M. Motylenko, "Substructure development in cold rolled copper single crystals," *Mater. Sci. Eng., A*, **324**, 196–199 (2002).
12. M. Zehetbauer, T. Ungar, et al., "Scanning X-ray diffraction peak profile analysis in deformed Cu-polycrystals by synchrotron radiation," *Acta Mater.*, **47**, 1053–1061 (1999).
13. N. A. Koneva, E. V. Kozlov, et al., "Substructural and phase transformations during plastic deformations of materials obtained by intensive deformation," *Mater. Sci. Eng. A*, **410**, **411**, 341–344 (2005).
14. R. Z. Valiev and I. V. Aleksandrov, *Nanostructured Materials Obtained by Intense Plastic Deformation* [in Russian], Logos, Moscow (2000).
15. E. Schafler, G. Steiner, et al., "Lattice defect investigation of ECAP-Cu by means of X-ray line profile analysis, calorimetry and electrical resistometry," *Mater. Sci. Eng. A*, **410**, **411**, 169–173 (2005).
16. J. Taylor, "The testing of materials at high rates of loading," *J. Inst. Civil. Eng.* (1946).