MECHANICAL STRENGTH OF TUNGSTEN MICROCRYSTALS

PHYSICS

1967

SovietRxiv

Abstract

Full Text

UDC 539.4.01 + 620.17

PHYSICS

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MECHANICAL STRENGTH OF TUNGSTEN MICROCRYSTALS

(Presented by Academician I. V. Obreimov, 27 VII 1966)

A substantial increase in the strength of solid bodies as their dimensions decrease is one of the most interesting problems in crystal physics. The observed increase in the strength of filamentary crystals is most often explained by their defectlessness. The experimental data are characterized by a large scatter in the results of individual measurements. The highest strength values of whiskers approach $\tau = 0.1G$ (G is the shear modulus). For example, the tensile strength of filamentary iron crystals in one experiment reached $\sigma = 1340$ kg/mm^2 ([1]), which corresponds to $2\sigma/\sigma_T = 12$ (if the shear stress $\tau = {}^1/_2\sigma$). The highest value, $\sigma = 1500$ kg/mm^2, was obtained for filamentary aluminum oxide crystals ([2]).

For filamentary tungsten crystals the largest value of σ has hitherto been considered to be 1320 kg/mm^2 ([3]). The diameter of the whiskers possessing the greatest strength was 1.6μ ([1]), 1.0μ ([2]), and 11μ ([3]). With increasing whisker diameter their strength in all cases decreased sharply, so that the dependence

$$\sigma = a + b/d, \tag{1}$$

is regarded as acceptable, where a and b are constants, and d is the whisker diameter. (For filamentary iron crystals $a = -50$ kg/mm^2, $b = 1690$ kg$\cdot\mu$/mm^2, d in microns; for copper filamentary crystals $a = 36$ kg/mm^2, $b = 410$ kg$\cdot\mu$/mm^2 ([1]). The structure of expression (1) is connected with the assumption that there exists some minimum value $d_{\min}$, at which $\sigma = \sigma_T$, and in the region $d \leq d_{\min}$, $\sigma = \sigma_T = \text{const}$.

The influence of surface-tension forces becomes significant at $d \leq d_{\min}$, and therefore cannot be neglected. For calculating σ_T, several formulas have been proposed. The best known lead to

$$\sigma_T = 2\frac{G}{2\pi}\ ([4]), \qquad \sigma_T = 2\frac{G}{15}\ ([5]) \quad \text{and} \quad \sigma_T = 2\frac{G}{30}\ ([6]).$$

Figure 1 graph

Figure 1: Figure 1 graph

The choice between these expressions is made difficult by the absence of sufficiently reliable data on d_{min}. All investigations published so far have led to plots of the dependence $\sigma(d)$ corresponding to (1) for $d > d_{\mathrm{min}}$. It was therefore of interest to investigate the strength of crystals whose diameter is considerably less than 1μ, and to clarify the nature of the dependence $\sigma(d)$ in the region which apparently corresponds to the condition $d < d_{\mathrm{min}}$, where σ should change little with changing d.

It is known that experiments with micron-sized whiskers are very difficult, since the preparation of such whiskers and measurement of their strength characteristics require great skill. As a result, until now data on the strength of whiskers with diameter $< 1\mu$ have not appeared in the literature.

In autoelectron and autoion studies of microcrystals, it is possible, from the magnitude of the ponderomotive forces arising on the surface of a conductor in an electric field, to determine the stresses in the material of specimens with transverse dimensions of the order of 100–1000 Å. E. Müller ([7]) made use of the known expression for the ponderomotive–

forces for determining the stresses arising in microcrystals during field-ion-microscopic investigations:

$$\sigma = E^2/8\pi, \tag{2}$$

where E is the electric-field strength near the surface of the specimen. This same relation was used by Gomer [8] to determine the strength of mercury whiskers and by A. P. Komar [9] to determine the field strength from the strength of molecular threads.

In the present work, relation (2) was applied for the purpose of systematically studying the dependence of the strength of tungsten microcrystals on their dimensions at 77° K. The strength was determined as the stress σ corresponding to the maximum value of E before destruction of the specimen.

Specimens were prepared from tungsten wire of 99.9% purity, 0.05–0.15 mm in diameter, which was polished electrochemically in a layer of electrolyte 1–2 mm thick. The needle obtained by electrochemical etching in the layer has at its end a cylindrical part with a diameter of $100 \div 1000$ Å, about 1 mm long, i.e., 10^4 times greater than the diameter. In most cases the end part of the needle was a single crystal about ~ 10 microns long, i.e., 10^2 diameters; in other cases the end of the needle was a bicrystal of the same dimensions.

Fig. 1. Dependence of the strength of tungsten microcrystals on diameter (at a temperature of 77° K). The strength value marked by a cross corresponds to

Figure 2 micrographs

Figure 2: Figure 2 micrographs

Fig. 3. Microphotograph of the same specimen as in Fig. 2, after fracture; the surface relief is strongly dissected, small-angle boundaries are observed (their direction is indicated by arrows), and depressions in the form of dark regions are visible.

Figure 3: Fig. 3. Microphotograph of the same specimen as in Fig. 2, after fracture; the surface relief is strongly dissected, small-angle boundaries are observed (their direction is indicated by arrows), and depressions in the form of dark regions are visible.

a crystal with a defect (see Figs. 2a and 2b)

Fig. 2. *a*—field-ion-microscopic image of a defective region of a tungsten microcrystal (the image was obtained in helium ions at a temperature of 77° K): near the (211) pole the emergence of a screw dislocation is observed; *b*—the same, after evaporation by the electric field from the surface of the specimen of 10 atomic layers (211); the distortions did not disappear, which proves the presence of a linear defect oriented at a small angle to [211]

The diameter of the specimens was determined in the field-ion microscope from the curvature of the end of the needle polished by the electric field. It was assumed that the diameter of the needle is equal to twice the radius of curvature of the end surface, multiplied by the sine of half the aperture angle of the ion beam. Since

strength was determined independently from (2), the possible error in determining the needle diameter did not affect the results obtained.

To determine the stress from (2), the electric-field strength E was measured from the potential difference V between the needle and the screen. As reference points in calibrating $E(V)$ the following were used: E_1—the field strength for the best image in helium ions of the surface, and E_2—the electric-field strength at which the evaporation rate was 1-2 atomic layers of the (110) face per minute. Since E_1 and E_2 depend on the curvature of the surface [10], the data contained in [10] were used to calculate them. In those cases where $E > E_2$, the electric field was applied for a short time, not more than 1 sec, in order to avoid roughening of the specimen due to intensive evaporation.

Fig. 3. Microphotograph of the same specimen as in Fig. 2, after fracture; the surface relief is strongly dissected, small-angle boundaries are observed (their direction is indicated by arrows), and depressions in the form of dark regions are visible.

Figure 1 gives the results of measurements of the strength of the microcrystals described. It follows from the data of Fig. 1 that it was possible to obtain strength values for the metal of 2100 ± 100 kg/mm^2. It is very important to note that in the range of values d from 200 to 1200 Å the strength changes hardly at all. It may therefore be assumed that σ_{min} for tungsten lies somewhere near the indicated interval. Then the value obtained, 2100 ± 100 kg/mm^2, should correspond to σ_{T}. In this case $2G/\sigma_{\text{T}} \approx 12.4 \div 17.5$, where G was taken equal to $13\,000 \div 18\,400$ kg/mm^2, according to Smithells' data for drawn tungsten wires with diameters from 1 to 0.03 (11). For massive tungsten single crystals Wright (12) and Bridgman (13) obtained $G = 15\,350$ kg/mm^2, which gives $2G/\sigma_{\text{T}} = 14.6$. Wright also established that the difference in the elastic properties of crystals of different orientation is less than 1/500 of the absolute value of the measured quantity G (11). Thus, the results of the present work agree better with the assumptions of Hirsch (5) than with those of Frenkel (4) and Bragg and Lomer (6).

The points in the figure corresponding to lower strength values refer to experiments with microspecimens in which defects of a certain type could be detected. Thus, for example, Fig. 2a gives the image of a defective region of a specimen whose strength corresponded to the cross in Fig. 1. From Fig. 2a it is seen that near the (211) pole there is a distortion. Figure 2b shows the image of the same pole after removal of 10 layers (211). The distortion, as can be seen, remained; apparently, a linear defect emerges at the surface. From the nature of the arrangement of the atomic planes it may be concluded that this is the emergence of a screw dislocation 1/2[111].

Figure 3 shows the end face of the same specimen after fracture and additional polishing of the fracture surface by an electric field. As can be seen from Fig. 3, the crystal was strongly distorted after part of the specimen was torn off by the electric field; new low-angle boundaries, marked by arrows, appeared; the curvature of the surface changed little.

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Received
22 VII 1966

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Note: Figure translations are in progress. See original paper for figures.