INVESTIGATION OF THE TEMPERATURE DEPENDENCE OF THE HARDNESS OF MOLYBDENUM IN THE RANGE OF 20-2500°C

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Material of Specimens and Experimental Method

The investigations were carried out on specimens of forged rods of molybdenum mark MRN, produced by the powder metallurgy method at the Moscow Electric Lamp Factory. The experimental data were obtained with the use of the UVT apparatus for the investigation of high-temperature hardness [1] in an atmosphere of purified inert gas, either argon or helium.

In the temperature range of 20-1750°C, the method used was that of static indentation by a sapphire indentor of standard, regular, four-sided pyramid type having an angle of 136° between opposite faces (according to GOST 2999-59). The hardness data at the higher temperatures of 1750-2500°C were obtained on the basis of the method of one-sided flattening of conical specimens having an apex angle of 120°.

In the determination of hardness by the method of static indentation, the specimen used has the form of a cylinder 8 mm in diameter and 5-7 mm in height, and for testing by the method of one-sided flattening, one of the plane faces of said cylinder was, in addition, machined to a cone.

The method of investigating hardness by one-sided flattening [2] gives good agreement with the results obtained by the method of static indentation, and enables hardness data of high-melting materials to be obtained at a high temperature level (1750-3000°C).

The load applied to the specimen for producing an indentation was 1 kg in the determination of hardness by the method of static indentation and 5 kg by the method of one-sided flattening. The duration of application of the load on the specimen was 1 min.

The temperature of the specimen in the range of 20-2000°C was measured by means of the thermocouples: platino-platinrhodium, tungsten-molybdenum (W-Mo + Al), type TeNIChM-1, and tungsten-tungsten-rhenium VR 5/20. The temperature of specimen, indentor, table, and heater was checked by means of a type OPPR-09 optical pyrometer.

The temperature of the specimen, plunger, and heater above 2000°C was measured only by means of a type OPPR-017 optical pyrometer, the readings of which were calibrated according to the melting point of pure molybdenum. In the calibration, the molybdenum was melted on the working table in the chamber of the UVT apparatus.

Temperature Dependence of the Hardness of Molybdenum

Figure 1 shows the temperature dependence of strain-hardened (cold-worked) and annealed molybdenum in the temperature range of 20-2500°C. The hardness data of the annealed molybdenum were obtained during test in the process of cooling the specimens from a temperature of 1750°C to room temperature.

The curves for the temperature dependence of hardness show a sharp drop in the hardness of molybdenum when the latter is heated from 20 to 300°C. Above the latter temperature, up to a temperature of 1000°C, the hardness diminishes insignificantly, particularly for the annealed metal. The hardness drops when the temperature is increased further to 1400°C.

The form of the curves of the temperature dependence of the hardness of strain-hardened and annealed molybdenum in the temperature range of 20-1000°C shows that molybdenum is hardened considerably in the process of plastic deformation. Thus, the hardness of strain-hardened molybdenum, for example at temperatures of 450-650°C, is double the hardness of annealed molybdenum.

At a temperature somewhat above 1000°C, recrystallization of the strain-hardened molybdenum commences.
Fig. 1. Temperature dependence of the hardness of molybdenum.

In agreement with the rule of A. A. Bochvar, according to which $T_{\text{comm. recryst.}} = (0.3-0.4)T_{\text{m.p.}}$, where $T_{\text{m.p.}}$ is the absolute melting point [3,4]. At a temperature of 1400°C, the curves of the strain-hardened and annealed molybdenum merge completely at a hardness value of 24.5 kg/mm². With further increase in temperature, the hardness diminishes smoothly, attaining values of 6.7 kg/mm² at 2000°C and 2.3 kg/mm² at 2500°C.

Equation of the Temperature Dependence of the Hardness of a Metal

The work of N. S. Kurnakov has shown that the temperature dependence of any mechanical properties determining the resistance of metallic materials to deformation is determined quantitatively by the following equation [5]:

$$M_2 = M_1 e^{-\alpha(T_2 - T_1)},$$

where $M_1$ is the given mechanical property at the temperature $T_1$; $M_2$ is the given mechanical property at the temperature $T_2$; and $\alpha$ is the temperature coefficient of the property.

In [6], in an investigation of duralumin, it was found that the temperature coefficient depends on:
1. The character of the stressed state (flow, hardness, or linear elongation) and, consequently, on the relationship of the values of the principal stresses;
2. the degree of deformation;
3. the rate of deformation: the higher the rate of deformation, the lower the temperature coefficient (absolute value);
4. the coefficient of external friction, since, in flow experiments the temperature coefficient has a different numerical value with or without lubrication;
5. the physicochemical state of the substance (solid solution, mechanical mixture, etc.) [5,6].

It is pointed out in [5] that an exponential law evidently describes fairly accurately many phenomena and processes in which the atoms pass from an unstable condition to a more stable condition, and fresh nuclei are formed and grow (recrystallization, crystallization, relaxation, diffusion, etc.).

In [7] a detailed examination is made of the numerous data of hardness as a function of temperature and of the functional expressions for the temperature dependence of hardness, and it is concluded that the most satisfactory expression, arrived at independently in [8] and [9], is

$$H = A e^{-\alpha T},$$

where $T$ is the temperature, °K; $A$ is the value of the hardness extrapolated to 0°C; and $\alpha$ is the thermal coefficient of hardness.

Expression (2) predicts a limited hardness at absolute zero, and zero hardness at an infinitely high temperature. Expressed logarithmically, we get the relationship

$$\ln H = \ln A - \alpha T,$$

representing a straight-line equation.

Thus, when $\ln H$ is plotted as a function of the test temperature for pure metals, a linear relationship is obtained. In reality, the relationship is more complicated and has a number of discontinuities. It should be noted that for metals subjected to strain aging, the temperature dependence of hardness is not described by Eq. (2).

The discontinuities in the curve of $\ln H - T$ are of two types: those with a sharp vertical break, and those with a sudden change in slope without break. A discontinuity of the first type with break is observed for those metals which undergo allotropic modification at the given temperature, for example, for cobalt, titanium, zirconium, and others. A discontinuity of the second type with variation in slope occurs at temperatures close to 0.5 $T_{\text{m.p.}}$, absolute