This work concerns the aging process in an alloy of molybdenum with 45% Re, 0.06% C, and a carbide-forming element — zirconium (0.4%). For comparison, a molybdenum alloy with 0.08% C and 0.4% Zr was also tested — alloy TsM-5.

As was shown in [1], the solubility of carbon in Mo—Re alloy MR-47VP is larger than in molybdenum, and this must also affect the properties of the Mo—Re alloy after heat treatment.

The original materials from which the alloys were prepared were commercial molybdenum (99.97%), electrolytic rhenium (99.99%) remelted in an arc furnace for additional purification, and iodide zirconium. Carbon was added in the form of Mo2C and spectrally pure graphite. Ingots of the alloys weighing 250 g (150 mm long and 8-10 mm in diameter) were melted in a furnace with a nonconsumable tungsten electrode and water-cooled copper hearth in an atmosphere of helium at a pressure of 300 mm Hg.

The heat treatment of the alloys consisted of quenching from 2100° and tempering at 1100-1800° C for 1 h. Heating was conducted in the TVV-4 vacuum furnace (1·10⁻⁴ to 1·10⁻⁵ mm Hg) for 3 h, with cooling in the furnace after shutting off the current, resulting in a cooling rate of 900 deg/min in the first minute.

The investigation was conducted on flat samples 45 × 5 × 1 mm. The samples were prepared from sheet 1 mm thick obtained from the forged ingots.

The susceptibility of the alloys to aging was determined from the change in the electrical resistivity, hardness, and microstructure. The nature of the precipitating phase was determined by examination in light and electron microscopes and also by limited-area x-ray analysis.

The resistivity was measured by means of the low-resistance PMS-48 potentiometer.

Microsections were polished first mechanically with a diamond paste of the ASM type on cloth dampened with a thin suspension of chromium oxide in water and then polished electrolytically in a mixture of concentrated sulfuric acid and methanol (95 ml H₂SO₄ + 5 ml methanol) at a current density of 20–25 A/cm² for 5-10 sec. The structure of the alloys was revealed by electrolytic etching in a reagent of 95 ml methanol + 5 ml H₂SO₄ at a current density of 0.05-0.1 A/cm² for 8-10 sec.

The electron microscopic examination was conducted with the TESLA VS-513A microscope with an accelerating potential of 80 kV on carbon extraction replicas. The carbon replicas were separated by electrolytic etching for 30-45 min in a mixture of 175 ml methanol + 25 ml H₂SO₄ at a current density of 0.05-0.1 A/cm². The extracted particles were identified by limited-area diffraction analysis.

The variation of the electrical resistivity and hardness of the alloys with tempering temperature is shown in Fig. 1.

After tempering at 1100-1300°C the resistivity of the alloys and the hardness remain almost unchanged. Further increase of the tempering temperature reduces the resistivity of both alloys. For the Mo—Re alloy Δρ decreases most (approximately 2%) after tempering at 1600°C, and then increases, approaching the original value at 1700°C. For the molybdenum alloy Δρ decreases most (approximately 7%)
Fig. 1. Variation of electrical resistivity and hardness with tempering temperature for alloys Mo 45Re 0.06C 0.4Zr (1) and Mo 0.08C 0.4Zr (2).

After tempering at 1800°C, which indicates the large effect of aging on this alloy as compared with the Mo-Re alloy. This is also confirmed by the substantial increase in the hardness of the Mo 0.08C 0.4Zr alloy after tempering at 1400-1600°C. The reduction of the hardness after tempering above 1600°C is probably explained by secondary recrystallization and coalescence of the carbide phase. The hardness of the Mo 45 Re 0.06C 0.4Zr alloy changes negligibly.

Examination of the microstructure showed that in the quenched condition the molybdenum alloy is characterized by hexahedral and lamellar carbides (see Fig. 2). Limited-area diffraction analysis showed that they consists of Mo2C (excess phase).

In the structure of the quenched Mo-Re alloy inclusions of Mo2C were also observed within the grains and particularly in the boundaries. However, the size and number of inclusions were substantially smaller than in the molybdenum alloy. This is due to the higher solubility of carbon in molybdenum in the presence of rhenium [1]. Along with Mo2C inclusions, the Mo-Re alloy also contained a large number of acicular particles (Fig. 2, IIb). On the electron micrographs these inclusions appear to be thin films. It was impossible to identify them by limited-area diffraction analysis. The matching of two to three interplanar distances of the particles with the interplanar distances of Mo2C leads to the assumption that these inclusions consist of a solid solution of rhenium in Mo2C [2].

After tempering of the quenched alloys at 1500°C the structure changes. The grain boundaries become thinner and the Mo2C inclusions are deposited intermittently (Fig. 2c, d).

Within the grains of the molybdenum alloy there is a finely dispersed and evenly distributed phase (Fig. 2, Ic, e) around partially dissolved Mo2C inclusions (Fig. 2, Id). There are no inclusions of this phase in the grain boundaries. The lamellar particles are oriented in relation to the grains of the matrix and, according to electron diffraction analysis, are ZrC (Fig. 2, Ie).

In the tempered Mo-Re alloy there are also separate particles of Mo2C that are finer than in the quenched condition and are distributed within the grains and in the boundaries (Fig. 2, IIc, d). Also within the grains there are lamellar inclusions larger in size and fewer in number than in the Mo 0.08C 0.4Zr alloy (Fig. 2, IIe). It can be assumed that these are particles of zirconium carbide precipitated from the solid solution of Mo-Re-C-Zr, which is less saturated than Mo-C-Zr.

After tempering at 1800°C one observes clusters of large coalesced particles of ZrC and Mo2C (Fig. 2, I, III).

The investigation indicates that during heat treatment the following phase transformations occur in alloys Mo 0.08C 0.4Zr and Mo 45Re 0.06C 0.4Zr.

In the Mo 0.08C 0.4Zr alloy quenched from 2100°C tempering results in precipitation hardening due to precipitation of finely dispersed ZrC distributed evenly through the body of the grains. At the same time, Mo2C is dissolved, which in the quenched condition is distributed as an excess phase in the form of large inclusions in the grain boundaries. The most intensive aging occurs at 1400-1800°C.