ELECTROTHERMAL TREATMENT OF MOLYBDENUM

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To remove strain hardening of plates and tubing 0.35-1.0 mm thick of molybdenum alloys VM1 and TsM2A and to ensure conditions for further cold deformation, annealing by means of direct electric heating was used. Annealing was conducted in vertical vacuum furnaces designed by the Central Scientific-Research Institute of Technology and Mechanical Engineering (TsNIITMASh) (Fig. 1). To determine the optimal annealing conditions, the heating rate was varied from 50 to 300 deg/sec, the temperature from 1100 to 2300°C, and the vacuum from 1·10⁻¹ to 2·10⁻⁸ mm Hg. Upon reaching the given temperature, the metal was cooled either directly after heating or after holding (maximum holding time 30 min).

For even heating, the ends of the piece were wedge-shaped. This increased the current density in sections adjoining the water-cooled clamps (terminals) and thus compensated the high heat removal.

The effect of annealing was determined from tensile tests at 300 and 1000°C, from the microstructure, and from specimens.

In the original cold worked condition the molybdenum alloys have a relatively low ductility (δ = 5-7%). The variation of δ with annealing temperature for alloy TsM2A has a distinct peak at 1800°C. At higher temperatures the value of δ decreases sharply (Fig. 2).

Increasing the holding time to 30 min reduces the strength and ductility. In this case the annealing temperature corresponding to the maximum value of δ also decreases from 1800 to 1200-1400°C. A reduction of δ with some increase of σ₅ occurs after an increase of the heating rate from 50 to 300 deg/sec and an increase of pressure from 2·10⁻⁵ to 1·10⁻¹ mm Hg (Fig. 3). However, with a high heating rate (300 deg/sec) a change in the pressure has a negligible effect on the mechanical properties within the limits given.

In tests at 1000°C the ductile characteristics are highest for the alloy subjected to electrothermal treatment at 1600-2000°C in vacuum of 1·10⁻³ to 2·10⁻⁵ mm Hg. Heating was conducted at the rate of 50 deg/sec, without holding.

The capacity of molybdenum alloys for plastic deformation was determined by means of specimens. Plates 1.0 mm thick of alloy VM1 were heated and rolled in the DUO mill in one pass. After the first pass (ε = 40-55%) cracks were observed in the plates subjected to electrothermal treatment at 2300°C. After the second pass (ε = 42%), tears occurred in plates not subjected to electrothermal treatment. After a third pass (ε = 47%) tears were observed in plates heated to 1300°C. No defects were observed in plates subjected to electrothermal treatment with heating to 1800-2000°C before rolling (heating rate 50-100 deg/sec, vacuum of 1·10⁻³ to 2·10⁻⁵ mm Hg).

On another specimen it was found that the flattenability of VM1 tubing with a diameter of 6.5 mm and wall thickness of 0.3 mm was nearly zero after electrothermal treatment at 2100-2200°C (heating rate 50-100 deg/sec, vacuum of 1·10⁻³ to 2·10⁻⁵ mm Hg), which indicates considerable brittleness. After electrothermal treatment under the same conditions but at 1800°C the flattenability ranged from 0 to 100%. In this case 60% of the values were in the range of 40-100% flattenability and 25% of them were 100%.

Comparison of the mechanical properties with the results of the microstructural examination showed that high ductility corresponds to a fine-grained structure at the stage of the final recrystallization treatment. The disappearance of fibrousness and the formation of fine equiaxed grains along with an increase...
of ductility was observed after holding 20 sec at 1600°C. Similar changes in the structure and properties occurred directly in the process of heating at a rate of 50 deg/sec to 1800°C. However, with heating to 1800°C at the rate of 300 deg/sec recrystallization was not completed and the ductility proved to be lower. Increasing the holding time at 1800°C to 30 min caused grain growth. However, considerable grain growth was observed with heating to 2000°C even without holding.

After heating to 1600°C in vacuum of $1 \times 10^{-1}$ at the rate of 50 deg/sec and holding for 30 min, and also with heating to 2000°C without holding, an unrecrystallized layer 0.01-0.02 mm thick was observed on the surface. Raising the heating rate and lowering the residual pressure (from $1 \times 10^{-3}$ to $2 \times 10^{-5}$ mm Hg) eliminated this layer. The unrecrystallized surface layer is evidently due to a change in the chemical composition of the material resulting from absorption of gases from the atmosphere at higher residual pressures.

The minimal change in weight of the pieces was observed after annealing at 1800°C in vacuum of $2 \times 10^{-5}$ mm Hg without holding. With heating to 2000°C the weight decreased sharply, evidently due to evaporation of the base metal. The decrease in weight with heating at lower residual pressures is probably due to evaporation of molybdenum oxide, since the larger amount of oxygen in the atmosphere of the low vacuum ($1 \times 10^{-1}$ mm Hg) facilitates its formation. The gradual reduction of the weight loss with increasing holding times at 1800°C in vacuum of $1 \times 10^{-5}$ mm Hg indicates that oxidation of the metal predominates over evaporation of the oxide.

The advantage of accelerated heating and short holding times is evident from the appearance of the metal. After brief annealing at 1800°C in vacuum of $1 \times 10^{-3}$ to $2 \times 10^{-5}$ mm Hg the pieces have a light matte surface. Higher vacuum ($2 \times 10^{-5}$ mm Hg) is necessary to retain the same surface with longer holding times (30 min). Thus, fairly high deformability of molybdenum alloys VM1 and TsM2A can be achieved by rapid heating under optimal conditions. Treatment under optimal conditions with brief holding prevents substantial grain growth and saturation of the surface with gases from the atmosphere, ensures fairly complete recrystallization, and inhibits evaporation of the metal.