Silchromes are widely used for parts operating at high temperatures with high dynamic loads. The heat treatment (quenching and high-temperature tempering) of valves in automobile engines made of Silchrome steel provides the necessary strength only up to temperatures of 600-650°C.

The heat resistance of these steels can be improved by increasing the alloying, although this impairs the technological properties (lower ductility and higher resistance to deformation).

It is known [1] that high-temperature thermomechanical treatment (HTMT) improves the mechanical properties of some heat-resistant steels and also improves the thermal stability of the structure. It was shown in [2] that utilizing the forging heat for subsequent heat treatment of Silchrome forgings lowers production costs, increases productivity, and shortens the heat treatment cycle.

Thermomechanical hardening with high-temperature heating depends mainly on the parameters of the technological process, and thus the purpose of this work was to determine the optimal HTMT for Silchrome steels.

We investigated steels 4Kh9S2 and 4Khl0S2M of standard chemical composition.

HTMT was conducted with hot pressing with large deformations - 75, 100, 125, and 145% - corresponding to the conditions used in producing valves for internal combustion engines. The diameter of the rods after pressing was 12.5 mm. The rods were immediately quenched in oil after pressing.

Samples were prepared from the rods for tensile tests and impact bending tests. Some samples were subjected to standard heat treatment for comparison.

The effect of the temperature and degree of deformation on the mechanical properties of the Silchrome steels after high-temperature tempering was determined in preliminary tests. It was found that with the highest deformation (125 and 145%) the heating temperature should be lowered to 1060-1020° in order to avoid intensive development of recrystallization processes. Recrystallization develops intensively due to the heat evolved in pressing with over 100% deformation.

After HTMT and tempering at 650° the strength of steel 4Kh9S2 at 550° is higher than after the standard heat treatment (Fig. 1a). The highest values of $\sigma_b$ (95 kg/mm²) and $\sigma_{0.2}$ (87 kg/mm²) are obtained with 100% deformation; the average increase of the strength is 11%. The reduction in section and elongation increase to 65 and 26%, respectively.

The highest values of the strength are also obtained for steel 4Kh10S2M with 100% deformation (Fig. 1b). After tempering at 550°, the ultimate tensile strength and yield strength at 550° are 185 and 163 kg/mm², respectively, which are 27 and 30% higher than after standard heat treatment. The reduction in section increases from 32 to 39%, the hardness increasing by 5-10 units HRC.

The increase in ductility, although small, and the simultaneous increase in hardness indicate that plastic deformation induces precipitation of additional fine carbides during tempering after HTMT. However, in contrast to precipitation hardening during tempering of quenched steel, the carbides remain coherent with the matrix. Therefore these dispersed carbides are semi-impervious to dislocation movements, leading to some increase of the ductility.

Electron microscopic analysis showed that rounded dispersed carbides are precipitated during tempering after HTMT (Fig. 2). Raising the tempering temperature from 550 to 650° leads to almost no increase in the size of the carbides (Fig. 2a, b), indicating the resistance of the carbide phase to coalescence at high temperatures. Carbides are precipitated not only in the boundaries of former martensite needles but also within them, and therefore retain their given orientation and even distribution (Fig. 2c), even with tempering at high temperatures - 750°.

Even though the strength decreases when the testing temperature is raised from 400 to 650°, the effect of thermomechanical hardening is completely retained, amounting to 16% for $\sigma_b$ and 12% for $\sigma_{0.2}$ at 650°. The ductility of the thermomechanically hardened and heat-treated samples is practically the same (Fig. 3).

When the testing temperature of the steel quenched and tempered at 650° is raised from 400 to 650° the fracture toughness decreases (Fig. 3). HTMT eliminates this temperature brittleness and reduces the scattering of the fracture toughness values. The largest increase of the fracture toughness for thermomechanically hardened samples of steel 4Kh9S2 is obtained after testing at 550-650° ($\delta_{k} = 12.6-14.0$ kg·m/cm²), amounting to 16%.

The high-temperature resistance of thermomechanically hardened steel 4Kh10S2M was determined after tempering at 550° for 1 and 3 h.

Fig. 2. Carbide phase in steel 4Kh10S2M after HTMT and tempering at 550° (a), 650° (b), and 750° (c).

Fig. 3. Mechanical properties of steel 4Kh9S2 at elevated temperatures after HTMT with 100% deformation (dashed lines) and after standard heat treatment (solid lines); tempering at 650°.