ELECTRICAL RESISTIVITY AND THERMAL CONDUCTIVITY OF TOOL STEELS AT OPERATING TEMPERATURES

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For the development of the optimal compositions of tool steels and the techniques of manufacturing cutting tools one needs to know the physical characteristics of these materials at elevated temperatures. The most important characteristics are the thermal conductivity and heat capacity, which determine the temperature and durability of the cutting edge, and the electrical resistivity, which is needed to calculate electrical heating. In addition, these data allow one to determine the transformations occurring during heat treatment of the steel.

We investigated the variation of the electrical conductivity of the principal tool steels, 45, U12, R9, and R18, and also the new tool steels R9K10 and R6M3. The physical properties of the annealed, quenched, and tempered steels were measured at 20-1000°C.

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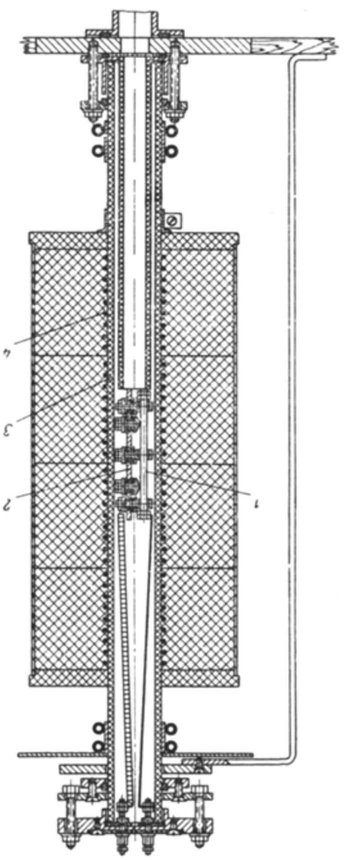

Fig. 1. Diagram of the apparatus for measuring the specific electrical resistivity of metals in vacuum during heating. 1) Sample; 2) sample holder; 3) porcelain tube; 4) furnace.

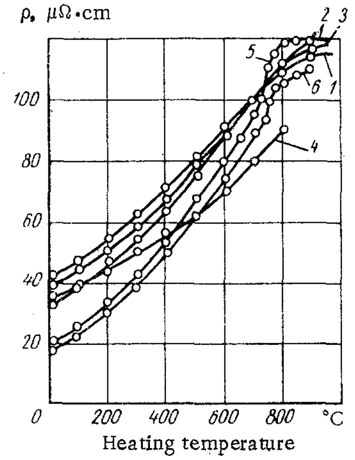

Fig. 2. Variation of electrical resistivity with heating temperature for annealed steels. 1) R18; 2) R9; 3) R6M3; 4) R9-K10; 5) U12; 6) 45.

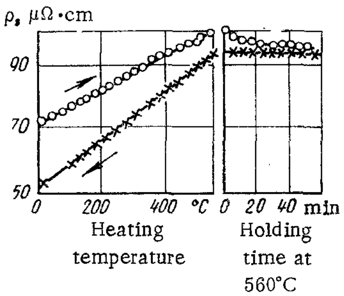

Fig. 3. Variation of electrical resistivity of quenched steel R18 during heating, holding 1 h at 560 °C, and cooling.

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TABLE 1

Steel	Equation for calculating electrical resistivity, ρ, μΩ·cm	Value of coefficient K
45	$\frac{20+Kt}{102+K(t-730)}$	$\frac{0{,}074}{0{,}05}$
U12	$\frac{20+Kt}{110+K(t-730)}$ $\frac{32+Kt}{-}$	$\frac{0{,}085}{0{,}06}$ $\frac{0{,}065\ (20-200°C)}{-}$
R9	$\frac{38+Kt}{115+K(t-800)}$ $\frac{46+Kt}{-}$	$\frac{0{,}081}{0{,}035}$ $\frac{0{,}070\ (20-550°C)}{-}$
R18	$\frac{41+Kt}{113+K(t-800)}$ $\frac{52+Kt}{-}$	$\frac{0{,}072}{0{,}015}$ $\frac{0{,}070\ (20-550°C)}{-}$
R6M3	$\frac{32{,}5+Kt}{112+K(t-800)}$ $\frac{41+Kt}{-}$	$\frac{0{,}095}{0{,}045}$ $\frac{0{,}075\ (20-550°C)}{-}$
R9K10	$\frac{34+Kt}{-}$	$\frac{0{,}05}{-}$ $\frac{0{,}048\ (20-660°C)}{-}$

Note: Data in the numerators for the ferritic region and in the denominators for the austenitic region.

The specific electrical resistivity during heating was measured in a special apparatus, a diagram of which is shown in Fig. 1. The sample 1, 120 mm long and 5 mm in diam., which was threaded on the ends for fastening the electric leads, was placed in the holder 2. The potential contacts were two blades against which the sample was held by three stays. The holder with the sample was installed in the porcelain tube 3 evacuated to 10^{-4} mm Hg. The sealing system permitted the introduction of the required number of electrodes into the working area for measuring the electrical resistivity (with a double Thomson bridge) and the temperature of the sample.

The apparatus makes it possible to measure the electrical resistivity with an error of 0.25% in vacuum of 10^{-4} mm Hg at temperatures up to 1000°C (±2.5°C).

Figure 2 shows the variation of the resistivity for steels 45, U12, R9, R18, R6M3, and R9K10. The approximately linear dependence of the resistivity on the temperature is given in Table 1.

The samples of steel U12 were quenched from 800°C (holding 3 min) in water and tempered 1 h at 170°C. Samples of the other steels were held 4 min at 850°C and then heated to quenching temperature in 2 min (1240°C for R9 and R9K10, 1280°C for R18, and 1220°C for R3M3). They were quenched in oil and then triple tempered (1 h) at 560°C.

Figure 3 shows the variation of electrical resistivity for steel R18 quenched and tempered. The steel was heated to quenching temperature at the rate of 10 deg/min. During holding the electrical resistivity decreases sharply, which is confirmed by data from high-temperature x-ray metallography [1] on the

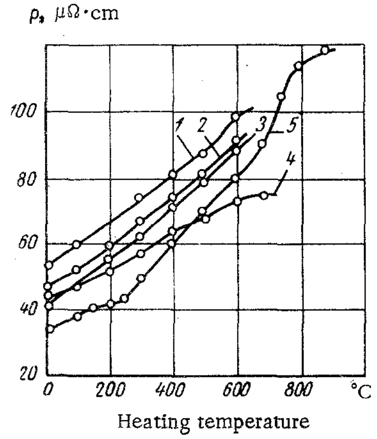

Fig. 4. Variation of electrical resistivity with heating temperature of heat treated tool steels. 1) R18; 2) R9; 3) R6M3; 4) R9K10; 5) U12.

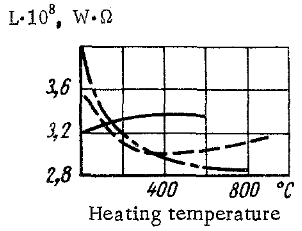

Fig. 5. Variation of Lorenz function with heating temperature. ——) Carbon steels; ----) high-speed steels; —.—.—.) austenitic steels.

reduction of the alloying components in austenite of quenched steel during tempering. This impoverishment leads to higher M_S temperatures during cooling after tempering.

The variation of electrical resistivity with the heating temperature following the heat treatment (quenching and tempering) is shown in Fig. 4. The linear relationships for these data in the operating temperature range can be expressed by the equations given in Table 1.

Thus, the more alloyed the steel, the higher the electrical resistivity of high-speed steels without changing the temperature coefficient of the electrical resistivity. Cobalt substantially reduces the temperature coefficient of the electrical resistivity, and thus above 500°C steel R9K10 has the lowest electrical resistivity of all the steels investigated.

The thermal conductivity coefficients were calculated by the method described in [2, 3], consisting of determining the variation of the Lorenz function L with temperature. Calculations with the use of literature data on the thermal conductivity of some tool steels [4-7] made it possible to obtain the following variation of the Lorenz function with temperature for high-speed steels:

Temperature, °C	$L, W\times\Omega/deg^2\cdot 10^8$
20	3.50
100	3.30
200	3.10
300	3.03
400	3.00
500	3.00
550	3.00
600	3.05
700	3.10
800	3.15

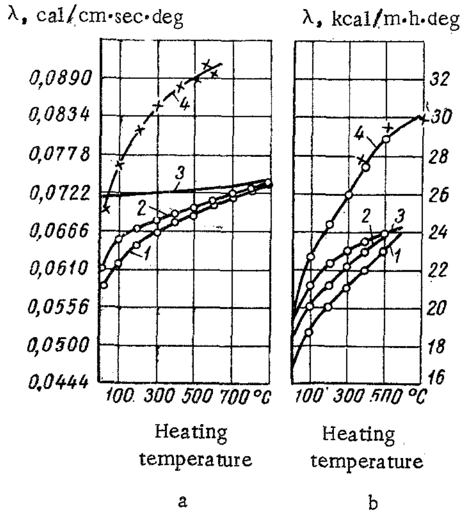

Fig. 6. Variation of thermal conductivity coefficients of high-speed steels with heating temperature. 1) R18; 2) R9; 3) R6M3; 4) R9K10; a) annealed; b) quenched and tempered.

This variation depends little on changes in the composition and heat treatment of the basic high-speed steels, including those investigated here, and is very similar to the data for austenitic steels, where the thermal conductivity also increases with temperature (Fig. 5).

The thermal conductivity coefficients of annealed and heat treated high-speed steels are shown in Fig. 6.

CONCLUSIONS

1. In the annealed and heat treated condition steel R18 has the lowest thermal conductivity.

2. Reduction of the tungsten content (R9) increases the thermal conductivity at low temperatures.

3. Replacing part of the tungsten with molybdenum substantially increases the thermal conductivity at low temperatures.

4. The lower the thermal conductivity at low temperatures, the higher the temperature coefficient of thermal conductivity, which holds true for austenitic, highly alloyed, and carbon steels (in the latter the temperature coefficient of thermal conductivity is negative).

5. During heating the thermal conductivity of the high-speed steels investigated (except for those with cobalt) becomes almost identical. At 800-900°C, i.e., near the critical points, steels R18, R9, and R6M3 have approximately the same thermal conductivity. In the heat treated condition the thermal conductivity of these steels is already approximately the same at 550-600°C.

6. The addition of cobalt to high-speed steels slightly increases the thermal conductivity at room temperature and strongly increases the temperature coefficient of thermal conductivity. At operating temperatures of 500-600°C the thermal conductivity of heat treated steel R9K10 is 30% above that of R18 at the same temperatures, which is responsible (along with the higher red hardness) for the higher cutting properties of cobalt high-speed steels.

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