EFFECT OF COBALT ON THE STRUCTURE AND PROPERTIES
OF HIGH-SPEED STEELS

A. P. Gulyaev and I. K. Kupalova

The favorable effect of cobalt on the cutting properties of high-speed steels was first observed in 1912.* At the present time we have numerous data concerning the effect of cobalt on the cutting, physico-mechanical, and technological properties of various high-speed steels [1-9].

The cutting properties of steel R18 increase in proportion to the cobalt concentration. The durability of R18K12 cutters is 8.5-5.10 times that of R18 cutters [1]. Cobalt steels based on R9 and R18F2 have almost identical cutting properties at the same cobalt concentration, although steels based on R9 are less brittle [3].

Thus, the improvement in the cutting properties of high-speed steels with the addition of cobalt is indisputable [8]. The more difficult the material is to machine, the more effective the addition of cobalt to the tool steel (Fig.1). The durability of cobalt steels is higher in tools of simple shape (cutters) in a rigid lathe−tool−workpiece system.
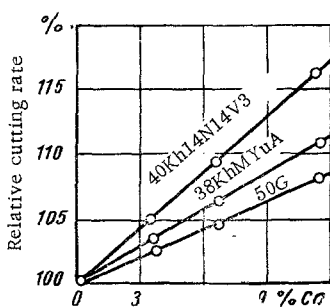

Fig.1. Effect of cobalt on the cutting properties steel R18F2 [9]. The steel numbers on the curves refer to the steels being machined.

Cobalt has the following effects on other properties of high-speed steels [3,5,7,8]. After annealing, cobalt increases the hardness HB, the coercive force H_c, the saturation magnetization $4\pi I_s$, and the electrical resistivity ρ; it reduces the remanence B_r and the maximum permeability μ_{max}; it slightly reduces the lattice constants of α phase and M_6C and MC carbides (Fig.2a). Cobalt also raises Ac_1 and Ac_3 [1] and the thermal conductivity [3,8].

After quenching, cobalt increases the coercive force, the amount of residual austenite A_{res}, and the resistivity; it slightly reduces the maximum permeability, the remanence, and the lattice constants of α phase and M_6C (Fig.2b). At austenitizing temperature cobalt increases the susceptibility of the steel to decarburizing [8] and slightly inhibits the grain growth of austenite [1,3].

After annealing and quenching, cobalt has no effect on the amount of carbide phase, the ratio of MC and M_6C in the carbides, or the

* German patent No.281,386, March 10, 1912.

TABLE 1

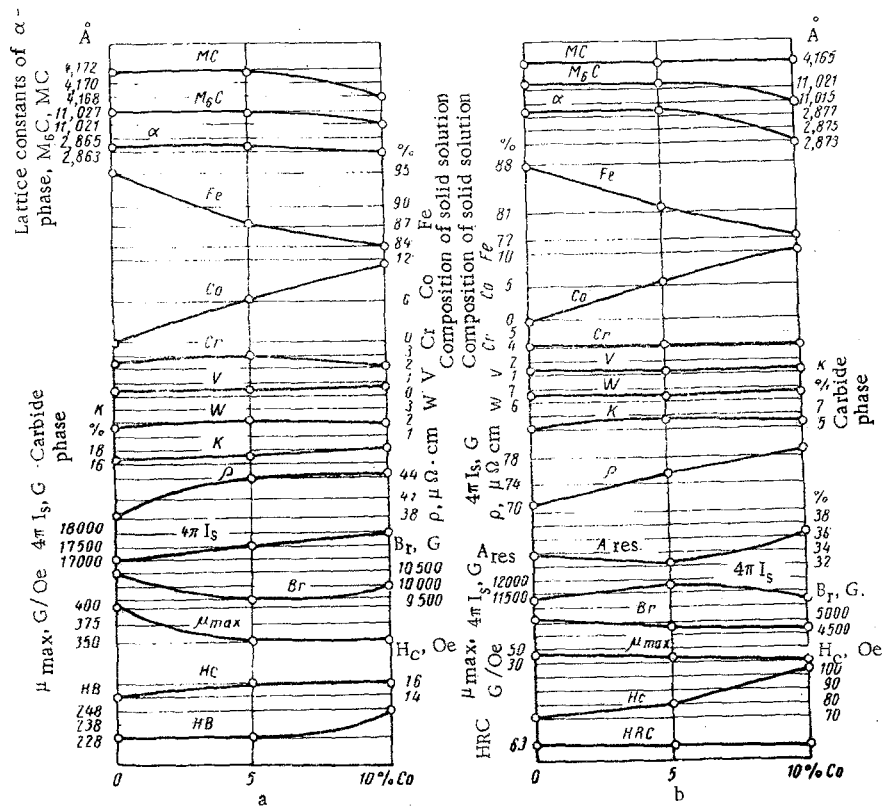| Steel	Composition, %					Time (h) to appearance of:	
	C	W	Cr	V	Co	W_2C	M_6C
9—3—0—0	0,33	8,15	2,95	0,16	—	5	200
9—3—0—3	0,36	8,83	3,04	0,20	3,2	10	400
18—4—1—0	0,78	18,4	4,32	1,22	—	10	—
18—4—1—5	0,80	18,2	4,42	1,50	5,12	100	—
18—4—1—10	0,86	18,8	4,10	1,83	9,87	200	—

Fig. 2. Effect of cobalt on the properties of steel R9 [8]: a) After annealing; b) after quenching from 1240°C.

TABLE 2

Steel	Tempering	Av. diam. carbide particles, d_{av}, μ	Total number carbide particles, $N_{tot} \times 10^8$, per mm³
R9m, R9K10m	600°C 1 h	0,17 0,08	100 300
R9m, R9K10m	700° 0,5 h	0,145 0,13	290 325

concentration of tungsten, vanadium, and chromium in the solid solution. Cobalt goes almost completely into solution (97-98%) in high-speed steels, and during heat treatment there is no redistribution of cobalt betwen the solid solution and the carbides [10].

The effect of cobalt is most evident after tempering. It increases the secondary hardness, inhibits reduction of the coercive force and resistivity, and substantially accelerates the transformation of residual austenite [1-8]. Cobalt increases the thermal conductivity [3], raises M_s, and lowers the strength and ductility [8]. Secondary hardening begins at lower tempering temperatures [3, 7]. The red hardness of high-speed steel, Kp_{58} (the temperature at which the hardness declines to HRC 58 after heating 4 h), increases in proportion to the cobalt content. The larger the tungsten content of the steel, the stronger this effect of cobalt.

The red hardness of high-speed steels [3-7] is as follows:

Steel, Kp_{58} (°C)
R9, R18 620
R9K5 630
R9K10 640

Steel, Kp_{58} (°C)
R18K10 650
R9K30 670
R20K30 700

Several hypotheses have been proposed to explain the effect of cobalt on the red hardness of high-speed steels.

In [1] the increase in the red hardness of cobalt steels was explained by the greater alloying of martensite with tungsten due to solution of a larger amount of carbides during heating. Such an effect of cobalt has not been found in any subsequent investigation [2-7, 10] (Fig. 2b, curves K and W).
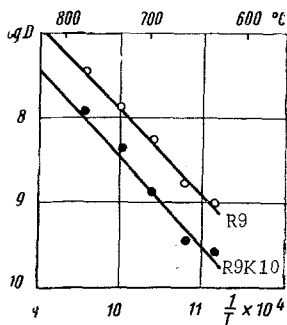
667

Fig.3. Temperature dependence of diffusion coefficient of carbon in α phase [36].
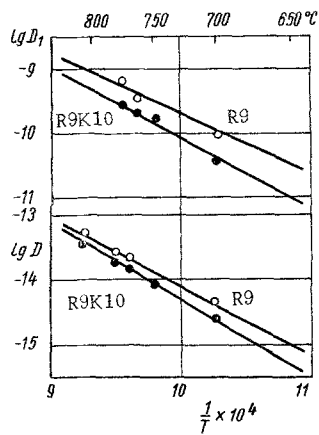
Fig.4. Temperature dependence of the coefficients of bulk diffusion D and boundary diffusion D_1 of tungsten in α phase [38].
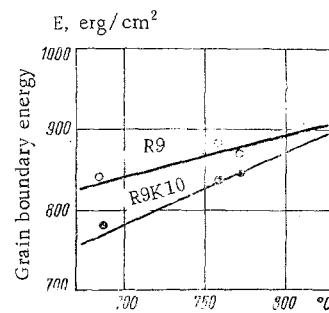
Fig.5. Temperature dependence of α grain boundary energy [38].

On the basis of experimental data and analysis of the Fe—Co—W phase diagram, it was proposed in [2,6] that the increase in the red hardness and brittleness of cobalt high-speed steels is due to the highly dispersed intermetallic compound Co_7W_6 formed in tempering, which has a high stability in comparison with carbides, and therefore coalesces more slowly than carbides. Intermetallic compounds were observed [2,6] in cast steel by x-ray diffraction from the presence of only two lines. No intermetallic compounds in cobalt high-speed steels were found in [1,3–5,7].

Intermetallic compounds enriched in tungsten and cobalt that go into solution during heating and precipitate during tempering should affect the concentration of tungsten and cobalt in the solid solution. The data in [10] indicate that all the cobalt is in the solid solution after annealing, quenching, and tempering, i.e., neither the dispersed phase or solid solution is enriched in cobalt during heat treatment and there is no redistribution of cobalt between them.

It was shown in [11] that in high-speed steel R18 and a heat-resisting steel with a composition close to that of martensite in R18 after quenching the cobalt inhibits the precipitation of M_6C and W_2C during tempering at 600°C (see Table 1). These data were explained by the strengthening of interatomic bonds in the α solid solution under the influence of cobalt, which also inhibits decomposition of martensite.

There are numerous experimental data in the literature concerning the effect of cobalt in slowing down the rate of softening of carbon and alloy steels, iron—cobalt alloys, and heat-resisting steels and alloys. An increase of the hardness of tempered carbon tool steel containing cobalt was reported in [12]. In an investigation of the influence of cobalt on the decomposition of martensite in carbon steel during tempering by means of measuring the tetragonality of martensite [13] it was shown that 6% Co inhibits reduction of the tetragonality of martensite by 150°C as compared with the carbon steel.

In structural steels [14] the addition of cobalt increases the strength of ferrite, which is retained at elevated temperatures. The effect of cobalt is stronger in the presence of carbide-forming elements. In heat-resisting steels [15] and maraging steels cobalt inhibits the softening process during tempering, with substantial hardening resulting from combined alloying with cobalt and molybdenum. In heat-resisting alloys [16,17] cobalt increases the time or temperature of softening, particularly in the presence of strong carbide-forming elements (tantalum, for example). Cobalt increases the stability of the supersaturated solid solution in many heat-resisting alloys and increases the time to the beginning of decomposition of the solid solution and precipitation of σ phase or $M_{23}C_6$.

The data presented concerning the inhibiting effect of cobalt on softening during tempering of carbon and alloy steels and various alloys are explained by most investigators as due to the increase in the binding strength of metal atoms in the solid solution, which is also indicated by the change in the temperature and rate of recrystallization when cobalt is added. The data in [18–20] indicate that
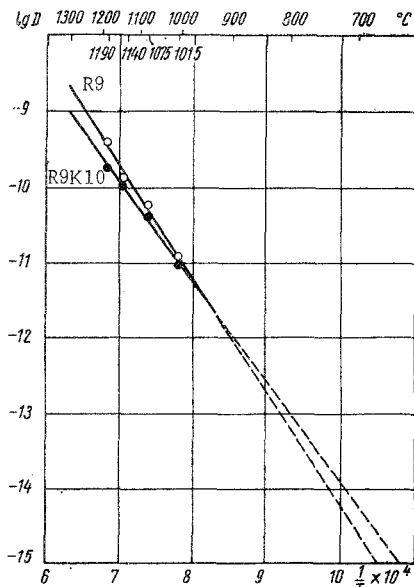
Fig.6. Variation of bulk diffusion coefficient of tungsten in γ phase with temperature [37].

cobalt raises the recrystallization temperature and increases the activation energy of the process. In the presence of tungsten, vanadium, and molybdenum the influence of cobalt appears to be stronger. In an experimental investigation of the characteristic temperature and dynamic and static distortions of the lattice of iron and iron alloys with molybdenum, cobalt, niobium, and manganese [21] it was found that all these elements increase the strength of the bonds in the ferrite lattice.

The red hardness, i.e., the ability of the hardened steel to retain its hardness at 600-700°C, is one of the most important properties of high-speed steels, since the cutting ability of the tool depends greatly on this characteristic. It was shown in [22] that there is a direct connection between the red hardness and cutting properties. The first general idea [23] that "red hardness depends on the composition of martensite and the nature and amount of carbide phase dissolved and precipitated" has been developed and defined more concretely.

The high hardness of quenched high-speed steels [24] is created by submicroscopic and microscopic structural heterogeneities preventing dislocation movements and increasing the resistance to dislocation movements in martensite crystals due to the strengthening of interatomic bonds. During hardening treatments the alloying elements are redistributed within the solid solution, the boundary areas being enriched in these elements, with formation of zones and finely dispersed precipitates coherently bound with the lattice of the solid solution.

The high hardness of tempered high-speed steel is due to the dispersity of coherent blocks of martensite crystals (120-180 A), the high dislocation density of the solid solution $(2 \cdot 10^{13}$ cm$^{-2})$, high coherent second-order microstresses $(4.5 \cdot 10^{-3})$, and the dispersity of evenly distributed MC and M_6C carbides [25].

The red hardness of high-speed steels depends on the rate of change in these factors in the process of secondary heating and also on the transformations occurring in the carbide phase in the conversion of one carbide into another [26-28]. Thus, the red hardness is determined by the rate of coalescence and reduction of the misorientation of mosaic blocks, reduction of second-order distortion, disruption of coherency and coalescence of particles of special carbides, leading to reduction of the dislocation density. The rate of all these processes depends on the strength of interatomic bonds in the lattice of the solid solution and the carbides.

The strength of the interatomic bonds in the solid solution and the carbides depends on their composition.

All the alloying elements except vanadium increase the binding energy of the atoms in the ferrite lattice. The increase of the binding strength is largest with complex alloying [21]. The composition of the martensite in various high-speed steels differing in their tungsten content (R9, R12, R18) is approximately the same [10] after quenching from optimal temperatures: 6.5-8.0% W, ~4.0% Cr, ~1.5% V. The identical alloying of martensite may explain the approximately equal red hardness of these steels (Kp_{58} = 620°C for the steels listed).

The decisive factor in the increase of the resistance of high-speed steels to softening at elevated temperatures is the coalescence of the special carbides, which controls the growth of blocks and the relief of second-order stresses in the α phase. A great deal of research has been done on the effect of alloying elements on the diffusion rate of carbon in ferrite and the rate of coalescence of carbides [29-35]. Quantitative relationships between the rate of coalescence of carbides in alloy steels and the diffusion parameters of carbon in ferrite were established in [31-33]. On the basis of the data in [31-33] it can be assumed that carbide-forming elements inhibit the coalescence of carbides and reduce the diffusion coefficient of carbon in ferrite.

Cobalt goes into solution almost completely in high-speed steels [10], not combining with carbides and not being redistributed between the carbides and the solid solution during heat treatment, and therefore the effect of cobalt on the rate of coalescence during tempering can be due only to slowing down the diffusion of carbon and alloying elements and the strengthening of interatomic bonds in the solid solution.

Data in [36-38] (Figs. 3-6) indicate that cobalt substantially reduces the diffusion mobility of carbon and tungsten in the ferrite of steel R9 — with 10% Co at 560°C the diffusion coefficient of carbon is reduced by a factor of approximately 4.5 and the bulk diffusion coefficient of carbon and the boundary diffusion coefficient of tungsten are reduced by a factor of 3. Cobalt also reduces the grain boundary energy of ferrite in steel R9. In high-speed steel cobalt affects the formation rate of carbides precipitating from the solid solution during tempering and also the coalescence of carbides. Reducing the grain boundary energy, cobalt reduces the work of formation of nuclei and increases the number of nuclei [39]. Cobalt is adsorbed on the surface of the precipitating carbides and inhibits their precipitation from the matrix [40]. With an increase of the temperature and time of tempering up to the beginning of growth of the precipitating carbides, cobalt inhibits the coalescence of these carbides due to the reduction of the diffusion mobility of carbon and tungsten. This is confirmed by electron-microscopic data on the size and number of carbide particles in steels $R9_m$ and $R9K10_m$, the chemical composition of which is the same as that of the solid solution corresponding to the steels after quenching from the optimal temperature (see Table 2).

Electron-microscopic studies have shown [41,42] that with tempering of alloy and maraging steels containing cobalt the number of carbides increases and the size decreases. From these data and the data obtained in [43] concerning the effect of cobalt on the increase in the activity of carbon in ferrite, it was shown in [41] that the diffusion flow $p = -DRT/a \cdot \partial a/\partial x$ on the surface of the growing carbide can be reduced substantially in the presence of cobalt due to the higher activity of carbon a and the smaller activity gradient $\partial a/\partial x$. An increase of the activity of carbon in the presence of cobalt favors an increase in the absolute value of the free energy of nucleation of carbides, resulting in a larger number of nuclei. Data on the diffusion of carbon in ferrite in high-speed steel [36] indicate that the diffusion flow $p = -DRT/a \cdot \partial a/\partial x$ on the surface of the growing carbide in the presence of cobalt may also be reduced as the result of the diffusion coefficient of carbon in ferrite. Thus, according to [41] cobalt should slow down the coalescence of carbides and increase the resistance to tempering of high-speed steel, which has also been confirmed by experimental data. The rapid transformation of residual austenite during tempering of high-speed steels with cobalt can be explained by the effect of cobalt on the diffusion mobility of tungsten in γ phase.

Extrapolation of the diffusion coefficients of tungsten in austenite to temperatures corresponding to supercooled austenite [37] (Fig. 6) indicates that in steel with cobalt the diffusion mobility of tungsten in residual austenite is higher than in steel R9 — at 560°C $D_W = 2.4 \cdot 10^{-19}$ cm^2/sec for steel R9 and $1.9 \cdot 10^{-18}$ cm^2/sec for steel R9K10. As the result of accelerated diffusion of tungsten in the process of tempering, the residual austenite is rapidly depleted of alloying elements, which raises M_S in subsequent cooling.

CONCLUSIONS

The main reason for the increase in the red hardness and cutting properties of cobalt high-speed steel is that cobalt, in the α solid solution, changes the properties of the solid solution — increases the binding strength, reduces the grain boundary energy and the diffusion mobility of tungsten and carbon — and as the result the rate of softening of martensite is slowed down (the red hardness increases).

Cobalt has no effect on the diffusion of carbon in austenite, but at temperatures below 950°C it increases the diffusion coefficient of tungsten, and therefore during tempering cobalt promotes acceleration of the transformation of residual austenite.

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