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Optimization of properties of carburized high-chromium steels

B. M. KHUSID
A.V. Luikov Heat and Mass Transfer Institute, Byelorussian Academy of Sciences, 15, P. Brovka St., Minsk 220072, Republic of Belarus
E. M. KHUSID, B. B. KHINA
Byelorussian State Polytechnic Academy, 65, F. Skorina Ave., Minsk 220027, Republic of Belarus

The influence of the pack carburization regime on the bulk strength and wear properties of hypoeutectoid (0.3 wt% C, 3–17 wt% Cr) and hypereutectoid (0.8 wt% C, 4–16 wt% Cr) high-chromium steels was examined (950–1050 °C, and duration, 4–8 h). The results obtained enable an optimum combination of bulk (tensile, bending and impact strength) and surface properties (abrasive and unlubricated sliding wear resistance) of a carburized high-chromium steel to be obtained.

1. Introduction

High-strength chromium steels do not possess the required level of wear resistance for specific applications. Numerous papers on wear of high-alloy steels, Cr–Mo white cast irons, ledeburitic steels, high-chromium cast irons, etc. [1] have shown that wear resistance may be significantly improved by increasing the carbide volume. For optimum wear characteristics, a material should contain a moderate volume fraction (20%–40%) of fine-grained carbides of the type M_7C_3; a higher carbide volume may induce microcracking.

Carburization has been applied to form a subsurface carbide layer in high-alloy steels since the early 1970s [2, 3]. Until then it was traditionally used to harden plain carbon and low-alloy steels. The advantages, namely the process simplicity, a large thickness (about 1 mm) of carburized case, and a gradual change in the carbon content and carbide volume fraction from the surface to the bulk, which result in gradual alteration in mechanical properties, are combined with substantial disadvantages: (a) typical carburizing media promote intensive oxidation of chromium, thus lowering the surface properties; and (b) the formation of a carbide zone increases the article brittleness due to local stress concentration in the subsurface layer [2, 3].

Pack carburization is proved to be more admissible for high-alloy steels [2–5]. Recently [4, 5], the effect of different substances used as energizers was examined, and a pack carburizator containing 2 wt % γ-Fe_2O_3 was produced. The case produced by this carburizator in high-chromium steels is practically disposed of both an oxidized zone and a zone of coarse-grained carbides, and contains a wide layer of fine-grained carbide particles. The effects of the post-carburization heat treatment on the carbide zone morphology and structure, the surface hardness and the bulk strength were examined [5]. It was shown that the carburization of high-chromium steels in charcoal–2 wt % γ-Fe_2O_3 significantly increases wear resistance under both abrasion and unlubricated sliding wear [6].

In studying the characteristics of surface-hardened materials, the primary attention is paid to surface properties [2]. However, the factors enhancing them have a negative impact on the bulk strength. For carburized high-alloy steels, these effects are associated with an increase in the carbide content of the subsurface layer. The strength of a carburized steel depends on the case and core structures as well as on the ratio of the case thickness to the specimen half-width [2, 3]. The structure and thickness of a case depend on the carburization temperature and duration. Therefore, producing an optimum combination of wear resistance and bulk strength necessitates the examination of the influence of a case-hardening regime on both properties. The purpose of the present work was to optimize the regime of the carburization of high-chromium steels.

2. Experimental procedure

2.1. Preparation of materials

For experiments, six high-chromium steels were smelted in an induction furnace: hypereutectoid, 80Cr7, 80Cr12, and 80Cr16; hypoeutectoid, 30Cr6, 25Cr13, and 25Cr17. The first number denotes the average carbon content of a steel (in 10^{-2} wt %) while the second one is the chromium concentration in weight per cent (Table I). The variations of carbon and chromium contents of these steels envelope the compositions of major high-strength tool and stamp steels [3, 7]. The commercial 40Cr13 steel (0.36%–0.45% C, 12%–14% Cr, 0.8% Mn, 0.8% Si (wt %)), was also used in tests for comparison.

For pack carburizing, charcoal (particle size 0.5–3 mm) was used as a carbonaceous base while 2 wt % γ-Fe_2O_3 [4–6] or 15 wt % $NaHCO_3$ [2] were used as energizers. Carburizing was carried out in a sealed container that was afterwards air-cooled to room temperature and unpacked. The post-carburization heat treatment consisted of reheating in a salt bath, oil quenching, and tempering at 180 °C for 2 h. After tempering, the samples were air cooled.

The following regimes [5] of the post-carburization heat treatment have been proved to produce a high value of the surface hardness of a carburized steel and a high level of tensile and impact strength of its core: quenching from 970 °C for 30Cr6, 80Cr7, and 80Cr12 steels and from 1000 °C for 25Cr13, 25Cr17, 80Cr16, and 40Cr13 steels; tempering at 180 °C for 2 h. A special test for tool and stamp steels is known [3, 7]: the room-temperature Rockwell C hardness, which a steel retains after it has been exposed to elevated temperature for 4 h, should exceed 45 HRC. The ultimate temperature determined by this test is an important property of such steels. The above-mentioned regimes of post-carburization heat treatment have been found to raise this ultimate temperature to 600–640 °C for all steels listed in Table I [5].

2.2. Testing procedures

Tensile and bending tests were carried out on a Universal testing machine, Instron-1195. The specimen shape and sizes were cylindrical (diameter 6 mm, length 50 mm) for the tensile test, and prismatic (10 mm × 5 mm × 55 mm) for the bending test. Impact strength was studied by Izod impact testing. For non-carburized heat-treated steels, 10 mm × 10 mm × 55 mm samples with a U-notch were used, the notch radius being 1 mm. For carburized steels with subsequent heat treatment, 10 mm × 10 mm × 55 mm samples without a notch were used. The impact strength value, *K*CU, was estimated from the absorbed energy in relation to the original cross-sectional area.

Unlubricated sliding wear tests were performed in a ring-on-disc apparatus with the use of an immovable disc made of WC–15 wt % Co sintered hard alloy as a counter-body. In order to reduce the running-in period, both a specimen and a counter-body were fitted-in on a lapping tool using a diamond 30 μm polishing paste before testing. The tests were run at a sliding speed of 0.3–0.7 m s^{-1} under a normal pressure of 1–3 MPa. The sliding surface temperature did not exceed 130–150 °C for carburized steels. Pin abrasion tests were carried out in a pin-on-disc machine with the use of the abrasive paper of 6–12 μm electrolytically produced corundum (93% α-Al_2O_3) fixed on a rotating steel disc. The tests were run under a normal pressure of 1 MPa. In both abrasion tests and sliding wear tests, the linear amount of wear and mass loss due to wear were measured. The details of the wear-testing procedures were described in a recent publication [6].

Each experimental point on the graphs is an average value measured on three to five samples.

TABLE I Chemical compositions of smelted steels

Material	Elements (wt %)				
	C	Cr	Mn	Si	S
Hypereutectoid steels					
80Cr7	0.82	7.0	0.3	0.4	0.01
80Cr12	0.78	12.3	0.7	0.4	0.03
80Cr16	0.82	16.0	0.7	0.4	0.03
Hypoeutectoid steels					
30Cr6	0.30	6.1	0.3	0.6	0.02
25Cr13	0.25	13.3	0.2	0.5	0.02
25Cr17	0.25	16.7	0.2	0.5	0.02

3. Results and discussion

Fig. 1 shows the influence of the quenching temperature and the chromium content on the ultimate tensile strength, σ_{UTS}, and impact strength, *K*CU, of the non-carburized heat-treated high-chromium steels. Maximum σ_{UTS} is observed at about 3–4 wt % Cr for hypoeutectoid steels and at about 10–12 wt % Cr for hypereutectoid steels. The σ_{UTS} and *K*CU values of the commercial 40Cr13 steel are somewhat greater than those of the smelted steels.

3.1. Optimization of strength and wear properties

To find the region of optimum combination of the wear and strength properties, carburizing temperature and duration were varied from 950–1050 °C and from 4–8 h, correspondingly. This region enveloped the carburizing regimes to provide high surface hardness and wear resistance of high-chromium steels [5, 6]. The charcoal–2 wt % γ-Fe_2O_3 carburizator was used.

For optimization, the factorial experiment design methods are widely used. A composite orthogonal

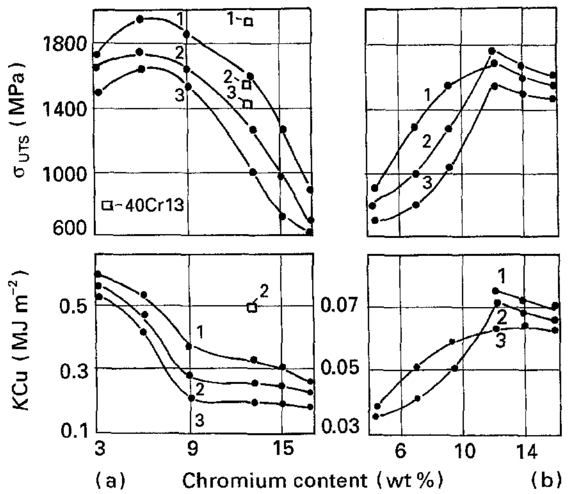

Figure 1 Effects of chromium content on the tensile and impact strength of heat-treated (a) hypoeutectoid, and (b) hypereutectoid steels. Quenching from: (1) 950 °C, (2) 1000 °C, (3) 1050 °C; tempering at 180 °C for 2 h. In addition to the steels listed in Table I, the properties of steels 80Cr4, 80Cr9, 80Cr14, 30Cr3, 30Cr9, and 25Cr15 are included. Their compositions are presented elsewhere [5].

design for two factors (temperature, T, and the carburization duration, τ) at three levels ($T = 950$, 1000, 1050 °C and $\tau = 4$, 6, 8 h) with a central point, was chosen (the 3^2 design) [8, 9]. To describe experimental results, the second-order regression model was used

$$y = b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{12}x_1x_2 + b_{22}x_2^2 \quad (1)$$

where y is the value of the property; $x_1 = (T - 1000)/50$; $x_2 = (\tau - 6)/2$. The matrix of the experimental design with nine points is shown in Table II; $+1$ denotes the upper level of a variable and -1 the lower level; ($x_1 = 0$, $x_2 = 0$) is the central point. The coefficients determined by a least-squares method have the form

$$b_1 = \frac{1}{6}\sum_{i=1}^{9} y_i x_{1i} \quad (2a)$$

$$b_2 = \frac{1}{6}\sum_{i=1}^{9} y_i x_{2i} \quad (2b)$$

$$b_{12} = \frac{1}{4}\sum_{i=1}^{9} y_i x_{1i} x_{2i} \quad (2c)$$

$$b_{11} = \frac{1}{2}\sum_{i=1}^{9} y_i (x_{1i}^2 - \tfrac{2}{3}) \quad (2d)$$

$$b_{22} = \frac{1}{2}\sum_{i=1}^{9} y_i (x_{2i}^2 - \tfrac{2}{3}) \quad (2e)$$

$$b_0 = \frac{1}{9}\sum_{i=1}^{9} y_i - \tfrac{2}{3}(b_{11} + b_{22}) \quad (2f)$$

It is seen that all coefficients (except b_0) are independent on each other, which is inherent in orthogonal designs [8, 9].

The standard deviation of the regression models was about 9%–13%. For the sake of comparison, the properties of steels carburized at 1000 °C for 6 h in charcoal–15 wt % $NaHCO_3$ were also measured.

3.2. Tensile and bending strength

The strength of a carburized steel depends on the case and core structures as well as on the ratio of the core thickness to the specimen half-width [2, 3]. The best results are obtained if this ratio equals 0.2–0.3. The strength of tool and stamp steels heat-treated to attain the Rockwell C hardness of 63–65 HRC is highly sensitive to varying shape, size and distribution of

TABLE II Matrix of the 3^2 composite orthogonal design of experiment with a central point [8, 9]

Number	x_1	x_2	Experimental data
1	+1	+1	y_1
2	+1	−1	y_2
3	−1	−1	y_3
4	−1	+1	y_4
5	+1	0	y_5
6	−1	0	y_6
7	0	+1	y_7
8	0	−1	y_8
9	0	0	y_9

TABLE III Strength properties of carburized steels

	Ultimate tensile strength (MPa)						
	30Cr6	25Cr13	25Cr17	80Cr7	80Cr12	80Cr16	40Cr13
Coefficients of Equation 1							
b_0	1180	851	569	914	988	767	941
b_1	−113	−53	−60	−80	−113	−190	−90
b_2	32	−37	−68	−129	−115	−52	−28
b_{11}	0	0	0	0	118	158	68
b_{12}	−57	0	−30	0	0	−57	0
b_{22}	−119	0	0	−42	−66	93	−41
Carburization at 1000 °C for 6 h							
2 wt % γ-Fe_2O_3	1140	910	540	930	900	840	870
15 wt % $NaHCO_3$	970	810	500	750	770	750	740

	Ultimate bending strength (MPa)					
	30Cr6	25Cr13	25Cr17	80Cr7	80Cr12	80Cr16
Coefficients of Equation 1						
b_0	1890	1230	1050	1500	1920	1750
b_1	−389	−239	−241	−475	−417	−304
b_2	−200	−199	−159	−161	−199	−180
b_{11}	0	112	0	67	−134	0
b_{12}	−63	−75	0	0	−71	−87
b_{22}	0	126	0	176	−129	0
Carburization at 1000 °C for 6 h						
2 wt % γ-Fe_2O_3	1840	1120	1020	1580	2030	1790
15 wt % $NaHCO_3$	1043	940	820	1080	1050	1030

	Impact strength (10^{-2} MJ m^{-2})						
	30Cr6	25Cr13	25Cr17	80Cr7	80Cr12	80Cr16	40Cr13
Coefficients of Equation 1							
b_0	9.8	10.4	8.8	21.5	6.5	3.5	5.4
b_1	−5.4	−2.0	−1.0	−9.7	−8.1	−4.4	−3.0
b_2	0.0	1.4	0.0	4.3	−5.9	0.0	−1.8
b_{11}	6.2	0.0	0.0	0.0	5.2	5.8	3.7
b_{12}	0.0	0.0	0.0	0.0	5.1	−3.7	−7.2
b_{22}	4.4	0.0	2.1	0.0	5.1	4.3	5.8
Carburization at 1000 °C for 6 h							
2 wt % γ-Fe_2O_3	9.2	9.7	8.9	20.3	7.7	4.2	7.9
15 wt % $NaHCO_3$	8.4	8.2	5.2	10.7	6.3	3.2	5.8

carbide particles [3, 7]. Tensile and bend tests were used to estimate the ultimate stress, σ_{UTS} and σ_{UBS}, respectively. These tests differ in the stress profiles and the tangential-to-normal stress ratio, α. In the former, the specimen is uniformly stressed and α is 0.5 while in the latter α varies from 0.5–2, and the carburized case is subjected to a greater stress than the core.

In both tensile and bend tests, the carburized samples demonstrated an elastic behaviour, the plastic part of the load–deformation graphs being small. The contraction of a cross-sectional area was not practically observed. Therefore, only the ultimate strength was measured. A carburized layer occupied 20%–40% of the total specimen half-thickness in all samples.

Table III summarizes the coefficients determined by Equations 2a–f for the tensile and bending strength. The isolines calculated using Equation 1 are shown in Figs 2 and 3. The tensile strength of carburized steels is 1.2–1.7 times less than that of non-carburized ones. This is caused by the subsurface layer weakening due to the formation of a carbide zone. The occurrence of carbide particles highly intensifies the local stresses. The values of the tensile and bending strength are lowered with increasing carburizing temperature for all of the tested steels. The prolongation of carburizing time exhibits similar effects on strength, which are more pronounced for the bending strength (Fig. 3). A carburizator with γ-Fe_2O_3 provides 7%–24% increase in σ_{UTS} and 20%–74% increase in σ_{UBS} in comparison with the corresponding values for the $NaHCO_3$-containing medium (Table III).

Varying the chromium content from 6–17 wt % steeply decreases the strength of hypoeutectoid steels, while σ_{UTS} and σ_{UBS} of hypereutectoid steels attain maximum values at about 12 wt % Cr. These results are similar to those demonstrated by non-carburized heat-treated steels (Fig. 1).

3.3. Impact strength

The value of the absorbed energy measured by impact testing heat-treated high-strength tool and stamp

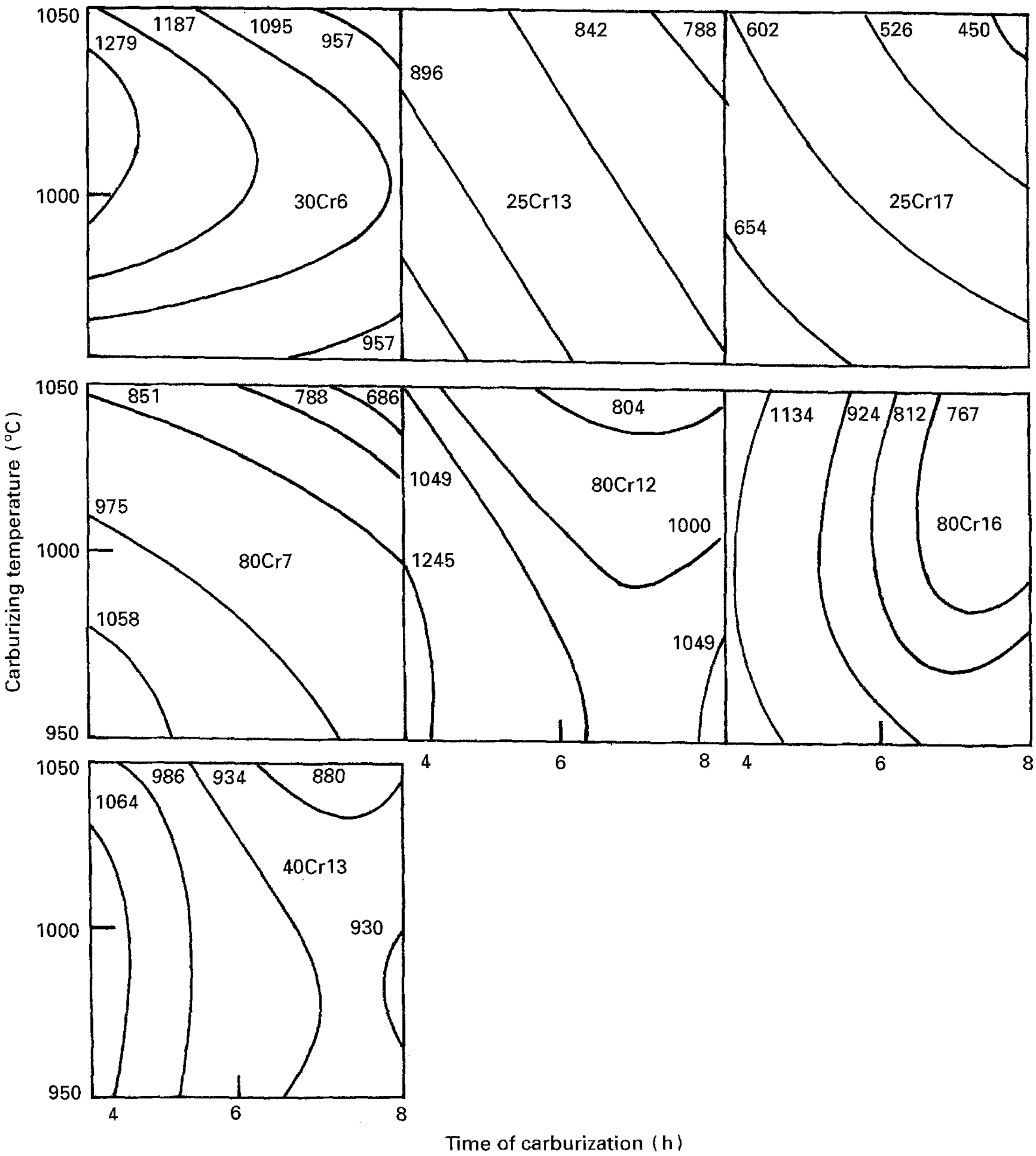

Figure 2 Isolines of ultimate tensile strength (MPa) under varying temperature and time of carburization in charcoal–2 wt % γ-Fe_2O_3.

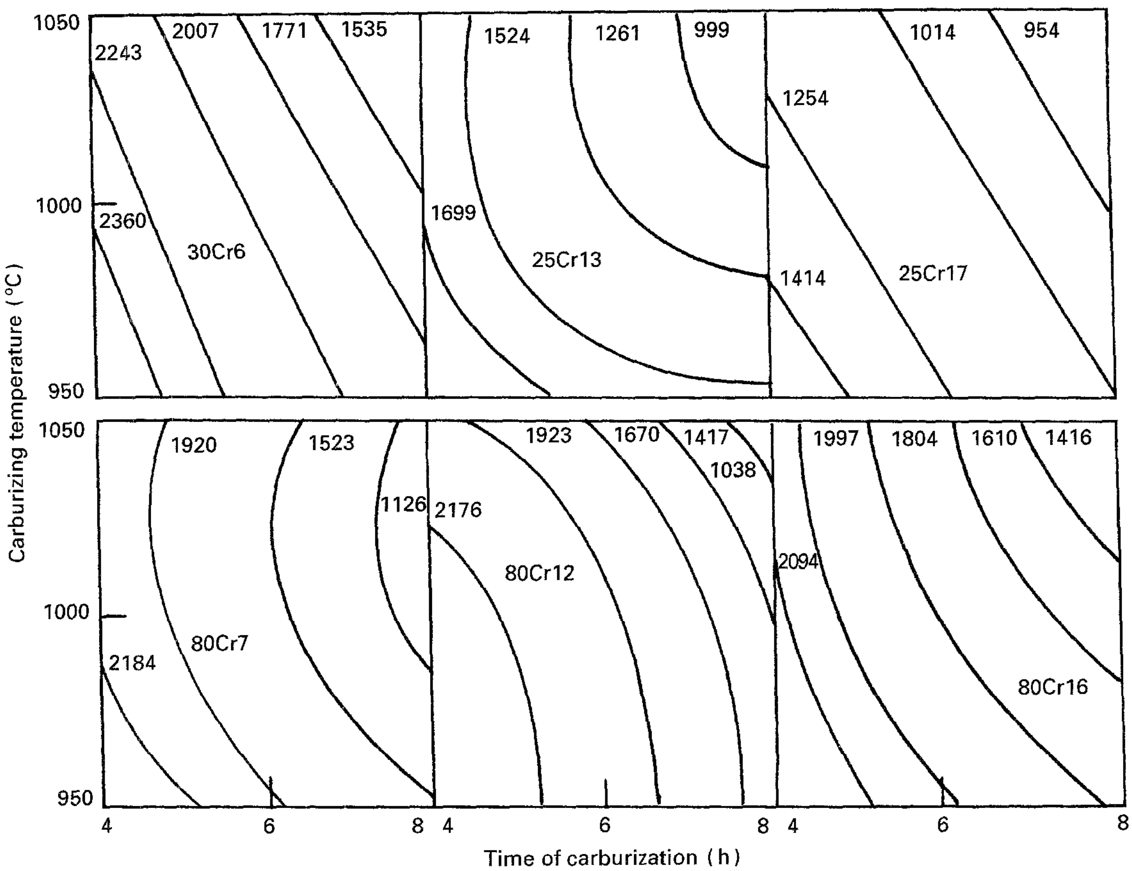

Figure 3 Isolines of ultimate bending strength (MPa) under varying temperature and time of carburization in charcoal–2 wt % γ-Fe_2O_3.

steels (with hardness above 50–55 HRC) is mainly determined by crack initiation because the crack propagation energy losses are rather small [3, 7]. Because the carburized zone raises the specimen brittleness, the samples to be tested were not notched.

The coefficients found from Equations 2a–f are listed in Table III while the isolines calculated using Equation 1 are shown in Fig. 4. The impact strength decreases with rising temperature. The carburizator with γ-Fe_2O_3 provides a 10%–90% increase in impact strength in comparison with the results given by the $NaHCO_3$-containing medium because of improving the case structure (Table III). The impact strength is highly sensitive to carburization parameters; its value may be varied by the factor of up to 10 under the examined conditions. Increasing the chromium content of a steel lowers the impact strength, its value being greater for hypereutectoid steels. The influence of the steel composition on the impact strength of carburized and non-carburized steels is different. For a carburized sample, most of the lost energy is connected with the crack initiation in the carbide layer, thus the effects of the bulk properties become weaker.

The fracture surfaces of heat-treated and surface-hardened steels were studied by SEM. Some micrographs are shown in Fig. 5. For both carburized and non-carburized samples, heavily dimpled surfaces are observed, the depressions being associated with carbide particles. The revealed structure is typical of the ductile fracture of high-strength carbide-containing steels [3, 7]. A rise in the carbide phase volume fraction causes the plastic deformation of the carburized layer to decrease.

3.4. Abrasive wear resistance

Abrasive wear tests have demonstrated that carburization followed by heat treatment raises wear resistance in comparison with that of heat-treated steels by a factor of 1.5. This is induced by an increase in the volume fraction of carbides in the subsurface layer. It has been shown that the wear loss is brought about by microploughing and microcutting [6]. The distance of running-in did not exceed 10 m; after that the wear rate became stable for all specimens. The deviations from a stable regime were observed at a wear distance over 45 m due to wear-out of the carburized case. For non-carburized heat-treated steels, the wear losses depend on the steel compositions: the maximum weight loss is observed for 25Cr13 and 25Cr17 steels while the minimum one is attained for 80Cr12 steel [6].

The coefficients of Equation 1 for a stable wear regime (wear distance 10–30 m) are summarized in Table IV. The wear loss isolines are shown in Fig. 6. Minimum wear losses for all of the steels correspond to the following carburizing parameters: $T = 1000$–$1030\,°C$, $\tau = 5$–7 h. Carburizing in a γ-Fe_2O_3-containing medium gives a 10%–70% better wear resistance in comparison with the results obtained in the $NaHCO_3$-containing carburizator. The difference in the wear loss values for all of the carburized steels does not exceed 15% despite different carbon and chromium contents. These data illustrate

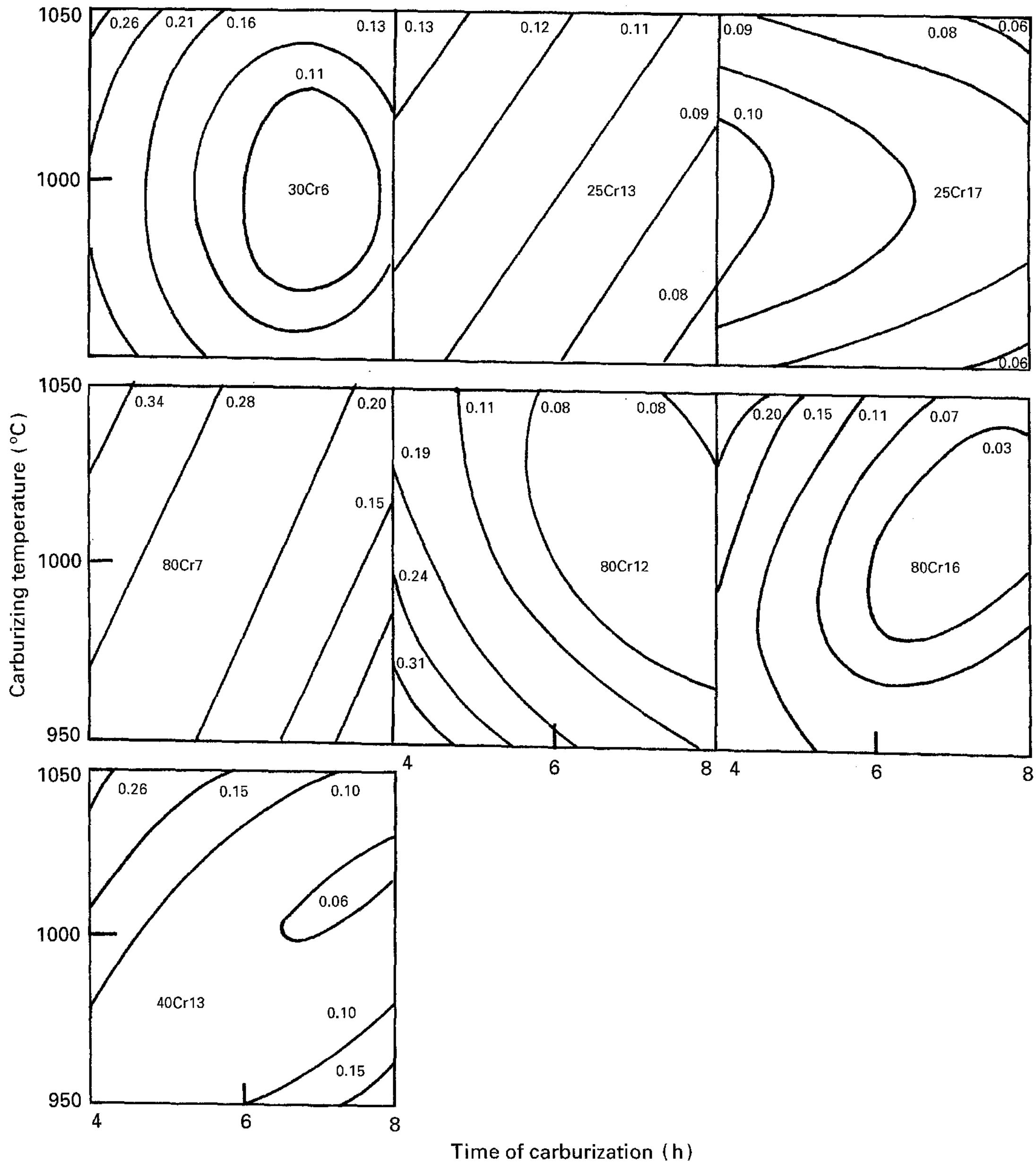

Figure 4 Isolines of impact strength (MJ m^{-2}) under varying temperature and time of carburization in charcoal–2 wt % γ-Fe_2O_3.

the major dependence of abrasive wear resistance upon the volume fraction, shape and size of carbide particles in the subsurface layers.

3.5. Sliding wear resistance

It has been revealed that the heat-treated steels without surface hardening could not be used under heavy testing conditions (0.5 m s^{-1}, 2 MPa) owing to intensive adhesive wear [6]. Carburization followed by a heat treatment significantly reduced adhesion and thus dry wear losses. For carburized steels, the weight-loss dependence on distance is nearly linear [6]. This is due to the previous fitting-in of both the specimen and the counter-body, which eliminated the running-in process.

The coefficients of Equation 1 calculated for wear loss at 1 km sliding distance at a speed of 0.5 m s^{-1} and a normal pressure of 2 MPa are listed in Table IV. The wear loss isolines are shown in Fig. 7. Minimum weight losses correspond to carburizing at 1000–1040 °C for 5.5–7.5 h. The use of γ-Fe_2O_3-containing carburizator instead of one-containing $NaHCO_3$ results in 2%–50% better wear resistance, the friction coefficient being 0.4–0.7 for the former and 0.6–0.8 for the latter within the range of the carburizing temperature variation. The dependence of friction coefficient on carburizing temperature is similar to that of wear loss. The composition of a steel does not markedly influence the weight loss; for all steels the difference in values is less than 11%. This is due to a similar structure of subsurface carbide zones in all tested steels.

The effect of a sliding regime on the wear loss of steels carburized in a γ-Fe_2O_3-containing medium was examined in the following range of parameters: pressure, p, 1–3 MPa, and sliding speed, v, 0.3–0.7 m s^{-1}. The 3^2 orthogonal design of the experiment was used: $p = 1$, 2, and 3 MPa, $v = 0.3$, 0.5, and 0.7 m s^{-1}. In our previous works [5, 6], the linear wear

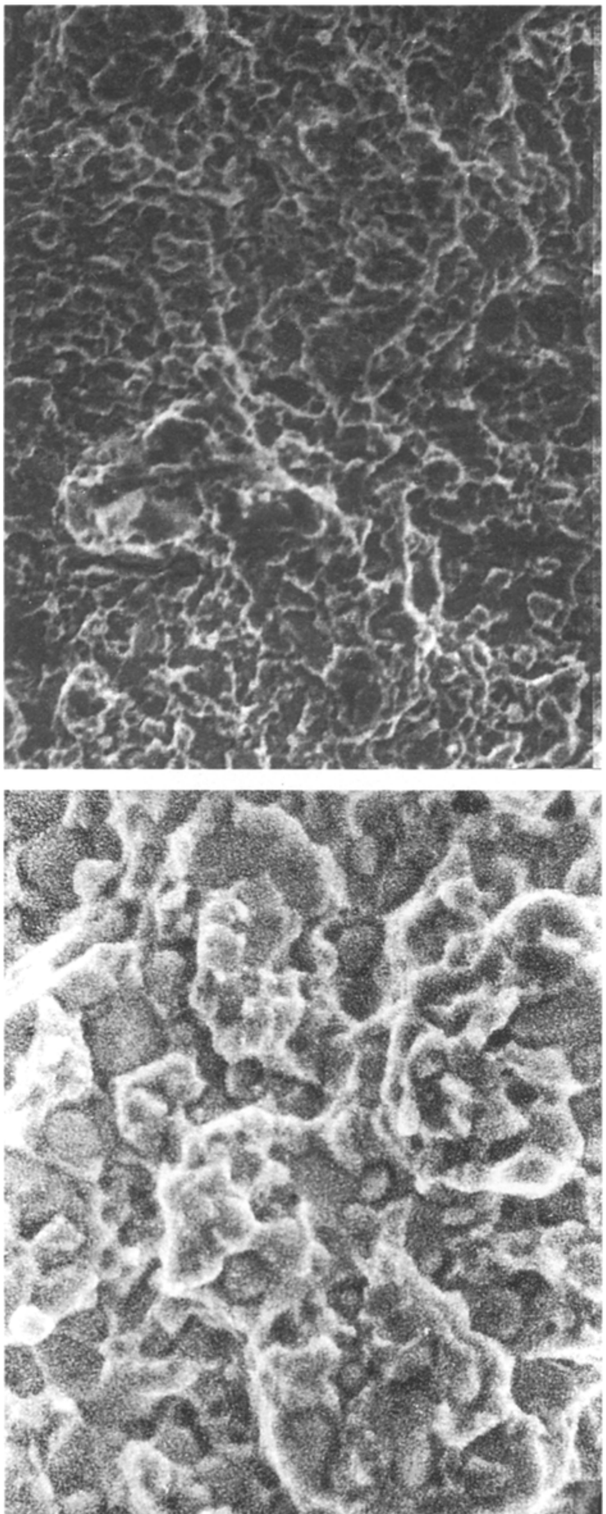

Figure 5 Scanning electron micrographs of ductile fracture of the heat-treated (quenched from 1000 °C, tempered at 180 °C for 2 h) (a) non-carburized and (b) carburized (charcoal–2 wt % γ-Fe_2O_3 at 1000 °C for 6 h) samples of 80Cr12 steel; 300 μm distance from the surface. (a) × 1000, (b) × 2000.

behaviour was observed within these ranges of parameters: the wear losses decreased almost linearly with rising speed at constant pressure and increased with rising pressure at constant speed. Thus to describe the experimental results we use the first-order regression

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 \qquad (3)$$

TABLE IV Wear losses of carburized steels

	Abrasive wear loss (10^{-2} kg m^{-2})							Sliding wear loss (10^{-3} kg m^{-2})						
	30Cr6	25Cr13	25Cr17	80Cr7	80Cr12	80Cr16	40Cr13	30Cr6	25Cr13	25Cr17	80Cr7	80Cr12	80Cr16	40Cr13
Coefficients of Equation 1														
b_0	70.6	79.5	67.3	75.1	71.3	65.7	75.5	180.0	165.0	155.0	113.0	137.0	138.0	121.0
b_1	− 9.3	0.0	− 10.6	− 4.7	0.0	− 3.4	− 3.1	− 5.9	− 3.0	− 15.1	− 34.0	− 37.1	− 32.7	− 26.2
b_2	0.0	0.0	− 9.6	− 4.0	4.4	− 5.3	− 3.9	− 7.5	0.0	18.2	− 36.6	− 44.7	0.0	0.0
b_{11}	11.0	8.0	10.9	3.5	9.0	5.5	4.5	7.6	15.1	18.7	52.7	23.3	30.3	36.0
b_{12}	0.0	1.9	− 2.2	0.0	0.0	4.3	0.0	0.0	0.0	0.0	− 22.3	14.2	0.0	− 7.1
b_{22}	12.5	7.7	10.1	5.6	8.6	6.9	3.6	5.0	14.6	25.4	53.2	48.4	38.8	36.6
Curburization at 1000 °C for 6 h														
2 wt %, γ-Fe_2O_3	79.0	83.0	71.0	79.0	74.0	67.0	80.0	1.9	1.7	1.5	1.1	1.4	1.4	1.1
15 wt % $NaHCO_3$	88.0	90.0	89.0	96.0	92.0	115.0	89.0	1.9	1.8	1.5	1.7	1.6	1.7	1.5

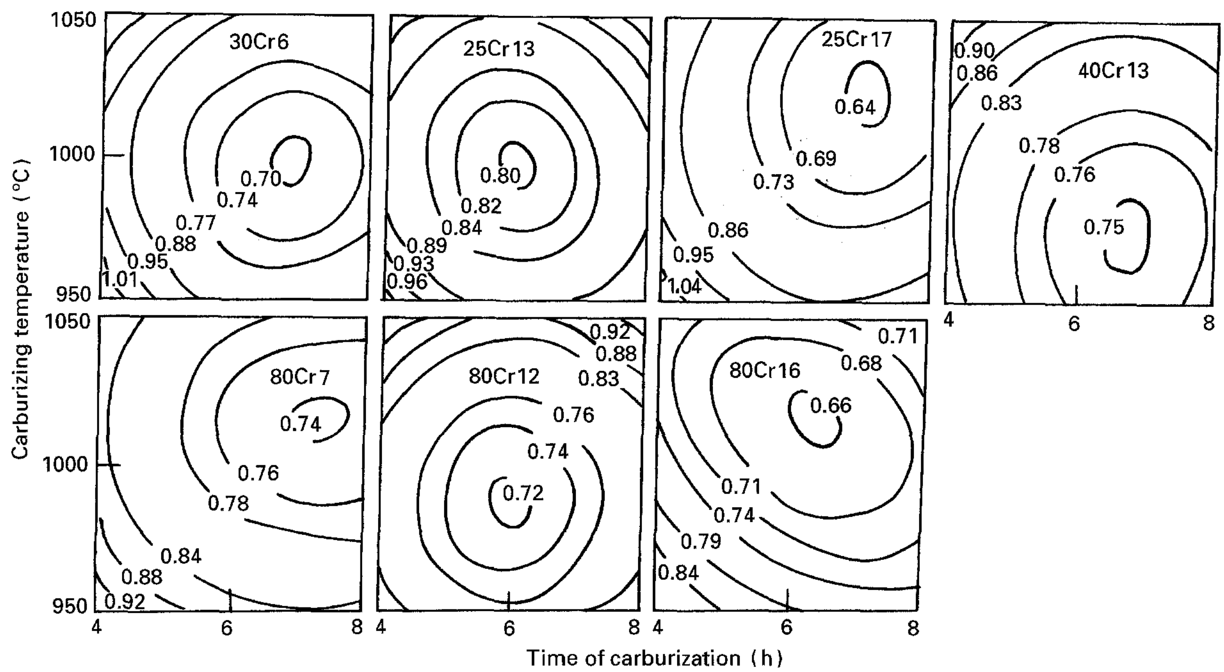

Figure 6 Isolines of abrasive wear loss ($kg\,m^{-2}$) under varying temperature and time of carburization in charcoal–2 wt % γ-Fe_2O_3.

TABLE V Sliding wear of steels carburized in charcoal–2 wt % γ-Fe_2O_3 at 1000 °C for 6 h

Steel	Coefficients ($10^{-2}\,kg\,m^{-2}$) of Equation 3			
	b_0	b_1	b_2	b_{12}
30Cr6	17.5	− 4.60	7.60	0
25Cr13	17.4	− 4.84	8.22	0
25Cr17	15.7	− 3.01	6.68	− 0.47
80Cr12	13.7	− 4.39	6.17	− 0.89
40Cr13	11.1	− 3.39	4.76	− 0.88

where y is the weight loss, $x_1 = (v - 0.5)/0.2$, $x_2 = p - 2$; b_{12} has been included in Equation 3 to estimate non-linear effects. Five experiments were performed (Table II): at points 1–4 to determine the coefficients, and in the central point ($x_1 = 0, x_2 = 0$) to verify the adequacy of the regression model. The coefficients are calculated by a least-squares method

$$b_1 = \frac{1}{4}\sum_{i=1}^{4} y_i x_{1i} \tag{4a}$$

$$b_2 = \frac{1}{4}\sum_{i=1}^{4} y_i x_{2i} \tag{4b}$$

$$b_{12} = \frac{1}{4}\sum_{i=1}^{4} y_i x_{1i} x_{2i} \tag{4c}$$

$$b_0 = \frac{1}{4}\sum_{i=1}^{4} y_i \tag{4d}$$

Table V presents the coefficients of Equation 3. The value of b_{12} is by an order of magnitude smaller than the others, thus confirming the model's suitability. The isolines of weight loss are shown in Fig. 8. The wear loss decreases with rising speed and lowering pressure. Such dependencies are typical of oxidation-dominated wear partially accompanied by adhesion [6, 10].

Under the test conditions, maximum-to-minimum weight loss ratio is about 6–7 for each steel, while the difference between the results obtained for different steels does not exceed 30%. This also demonstrates the weak dependence of the wear resistance for a carburized steel on the bulk steel composition.

4. Conclusions

1. The influence of carburizing temperature and duration on the values of tensile, bending, and impact strength of chromium steels was determined. Below 9%–10% Cr, the tensile and bending strength of carburized hypoeutectoid steels is greater than that of hypereutectoid ones, the relationship becoming inverse above 9%–10% Cr. The carburized hypereutectoid steels exhibit a higher value of impact strength.

2. Carburizing causes the abrasive wear resistance to increase by a factor of about 1.5. The variation of weight loss due to difference in the composition of steels does not exceed 15%. Abrasion is predominantly caused by a combination of microploughing and microcutting.

3. Heat treatment does not protect high-chromium steels from the catastrophic surface damage under heavy regimes of dry sliding because of intensive adhesion. Adhesive wear is significantly suppressed by carburization and subsequent heat treatment. The oxidation-dominated wear mechanism partially accompanied by adhesion operates under the testing conditions (0.3–0.7 $m\,s^{-1}$, 1–3 MPa). An increase in normal load and a decrease in sliding speed promote transition from mild wear to adhesive wear.

4. The results obtained enable estimation of the regime of carburization and subsequent heat treatment to produce the desired combination of the wear resistance and bulk strength of a high-chromium steel.

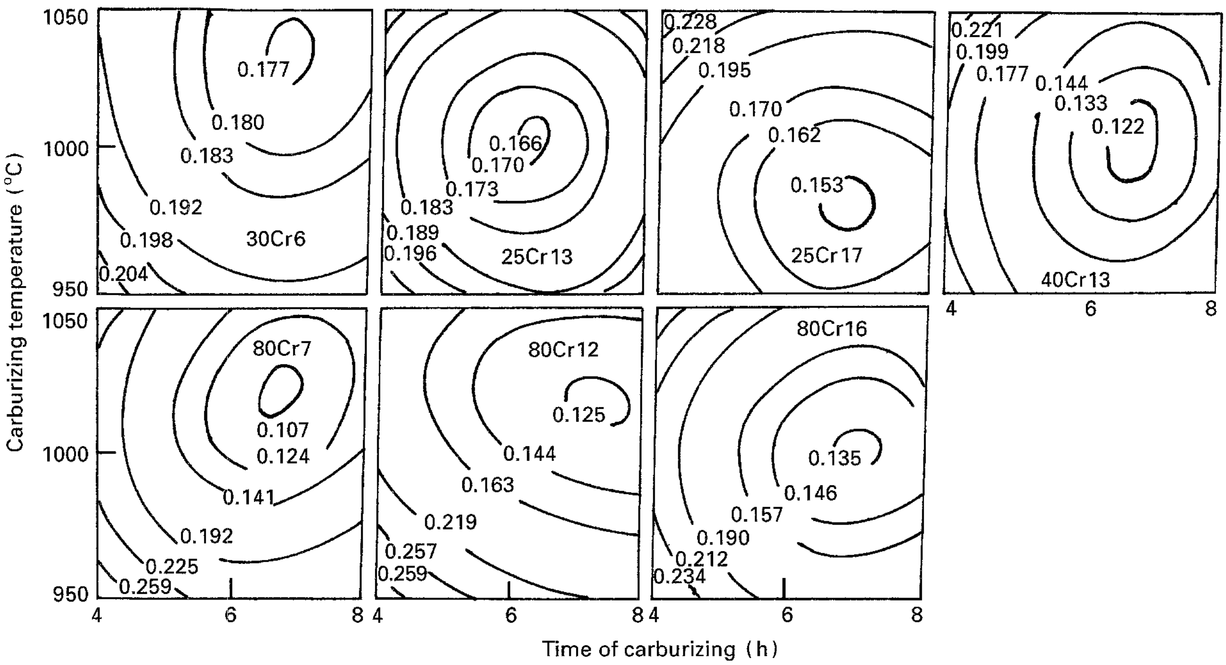

Figure 7 Isolines of wear loss (kg m^{-2}) at a sliding speed of 0.5 m s^{-1} and a normal pressure of 2 MPa under varying temperature and time of carburization in charcoal–2 wt % γ-Fe_2O_3.

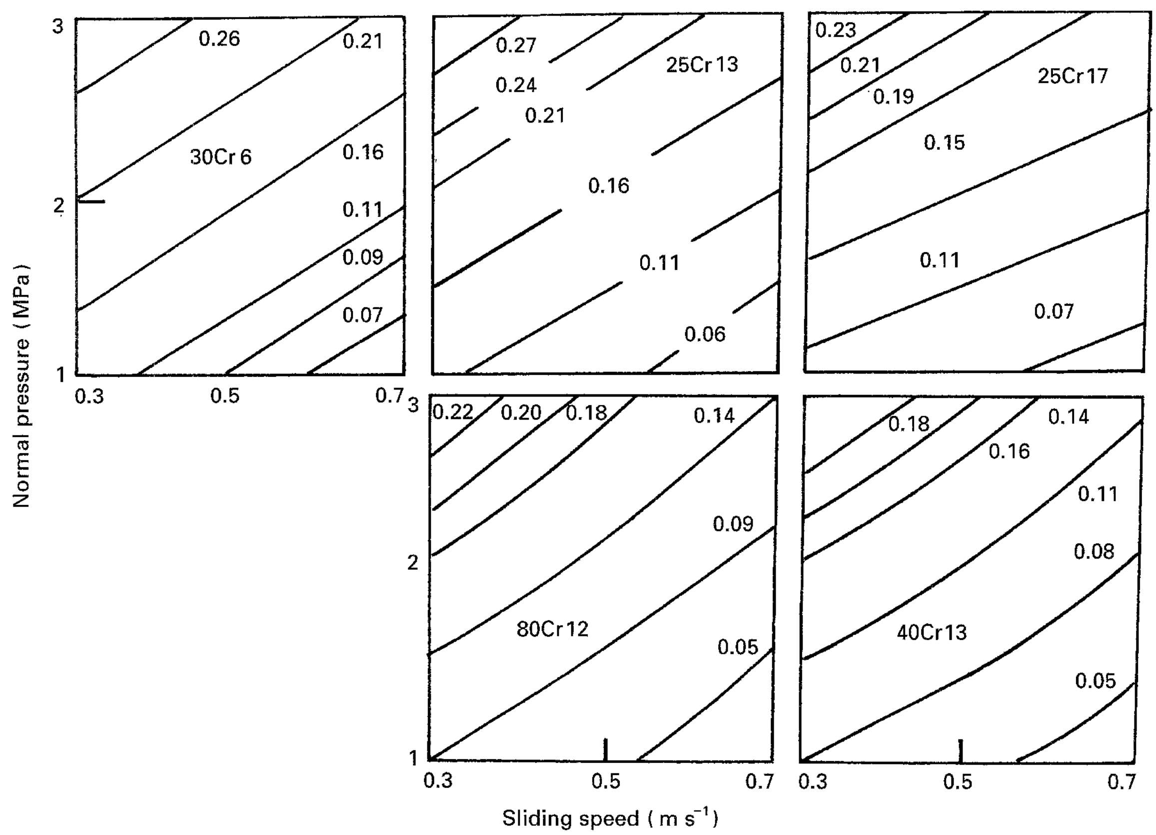

Figure 8 Isolines of wear loss (kg m^{-2}) of carburized (charcoal–2 wt % γ-Fe_2O_3 at 1000 °C for 6 h) steels under varying sliding speed and nomal load.

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