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THE EFFECT OF CARBON AND CHROMIUM ON WEAR RESISTANCE OF FERRITIC HIGH CHROMIUM CAST ALLOYS

Keywords

Erosion abrasive wear resistance, ferritic high chromium cast alloys, Bitter theory.

Summary

The studies of abrasion wear behaviour have as a target more profound knowledge of the wear mechanism and of the possibilities to improve the wear resistance. As regards an improvement of wear resistance, the results of the studies enable: simple comparison of the material properties, a description, by means of regression egratrans, of a space determined by the scope of variables used, as well as, an application of the selected theory in describing final output of the tests. Applying Bitter's theory, the wear of high-chromium ferritic alloys attacked by an abrasive material at 450°C was described. The theory enables the material wear rate to be analyzed as a function of the incidence angle of abrasive, with the material loss in volume ascribed separately to the two different wear mechanisms, i.e. microcutting and surface fatigue. Analysis leads to a conclusion that the characteristic curves can be divided into three groups. The division can be made adopting as a point of reference two curves for which the value of the product of Cr and C content is constant. For the first group the product does not exceed the value of 30. Group three includes the alloys for which the product of Cr and C content exceeds in this case the value of 60. For the second group of alloys, the product of chromium and carbon content is within the range of 30 to 60.

Introduction

The studies of abrasion wear behaviour have as a target more profound knowledge of the wear mechanism and of the possibilities to improve the wear resistance. The method of single scratches quoted by many research workers [1, 2] provides numerous valuable pieces of information on the behaviour of individual structural phases in the examined materials. As regards an improvement of wear resistance, the results of the studies enable: simple comparison of the material properties, a description by means of the equations of regression analysis of a space determined by the range of the used variables, and an application of the chosen theory in describing final output of the tests.

In the case of abrasive wear, numerous theories have been developed, and it is quite difficult to choose the best one, if own experience is not rich enough. Meng and Ludema [3] quoted 28 different theories regarding the possibility of determining by analytical technique the wear resistance of materials under the effect of abrasive stream.

One of the theories referred to in study [4] is Bitter's theory. It has been based on the research done previously by Finne [5] and enables material wear analysis as a function of the angle of incidence of the abrasive material, dividing the wear mechanism into relevant components, such as microcutting and surface fatige. Bitter's theory has been based on the theories of elasticity, plasticity and machining, and it enables describing the abrasive behaviour of material [4]. According to this theory, the wear rate Z (Fig. 1) depends on the incidence angle α of the abrasive and can be divided into individual components.

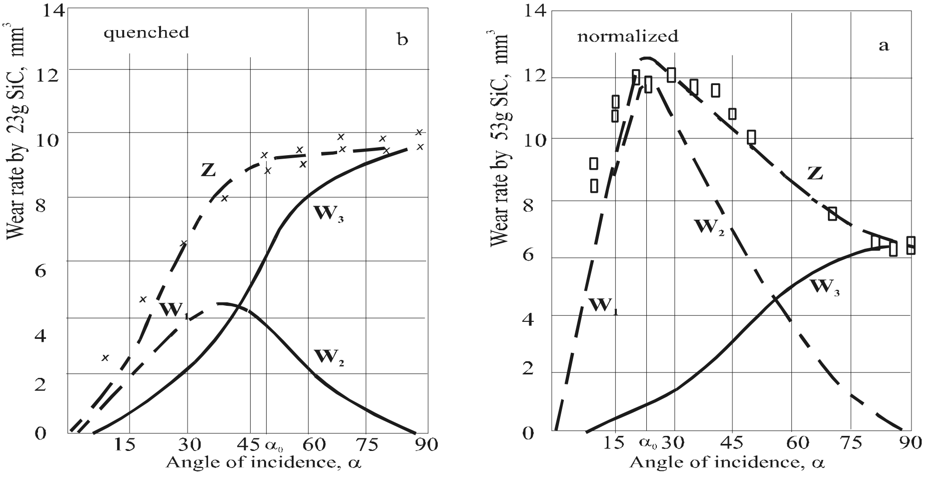

Fig. 1. Wear rate of carbon steel (0.5-0.6% C; 0.6-0.9% Mn); a – normalized, b – quenched; W_1 – wear by microcutting up to boundary angle α_o, W_2 – wear by microcutting above α_o, W_3 – wear by spalling of material microvolumes due to surface fatigue [4]

The wear by microcutting is illustrated by W_1 and W_2 and that due to fatigue by W_3. Total wear rate Z of the material is determined as follow:

$$\alpha \leq \alpha_o \Rightarrow Z = W_1 + W_3; \quad \alpha \geq \alpha_o \Rightarrow Z = W_2 + W_3; \quad \alpha_0 \approx 90° \Rightarrow Z = W_3$$

where: α_o – boundary angle of incidence of the abrasive, i.e. such for which the following conditions are satisfied : $W_1 = W_2$ and $dW_1/d\alpha = dW_2/d\alpha$.

1. Subject and aim of studies

The aim of the studies was to give qualitative determination of an effect of chromium and carbon content on the run of the abrasion wear characteristic curves. Tests were performed on a family of high-chromium ferritic alloys. The wear was induced by a jet of abrasive hitting the surface of specimens at various angles of incidence with temperature kept at a level of 450°C. The effect of the individual wear components on overall wear rate of the examined materials was determined as well.

The examined alloys were cast in the form of plates of dimensions 300x60x5 mm. The content of the individual phase constituents in alloys in raw condition was assumed to be at one of the following five, conventionally adopted, levels: very low – VL, low – L, medium – M, high – H, very high – VH. The results and the chemical composition values are compiled in Table 1.

Table 1. Chemical composition and the phase constitution of the alloys before annealing

No	Chemical composition			The phase constitution			
	C	Si	Cr	α	γ	M_7C_3	$M_{23}C_6$
1	2,21	0,36	47,4	VH	–	VH	–
2	1,02	0,47	37,0	VH	–	H	–
3	2,02	0,20	26,6	M	H	H	VL
4	1,64	0,45	43,2	VH	VL	H	–
5	2,02	0,40	38,6	VH	–	H	–
6	1,31	0,40	32,0	VH	VL	H	L
7	1,74	0,40	36,5	VH	VL	H	–
8	0,16	0,51	26,4	H	H	–	L
9	0,97	0,16	15,8	VL	VH	VL	VL
10	1,02	0,43	35,4	VH	VL	H	–
11	0,56	0,38	21,5	L	VH	L	L
12	0,60	0,38	32,5	VH	VL	H	–
13	1,02	0,28	26,0	H	H	H	–
14	0,76	0,38	27,8	H	H	H	–
P = 0,02–0,03: S = 0,002–0,008: Cu = 0,02–0,04: Al = 0,00–0,27: Mn = 0,01–0,07.							

Table 2. Hardness HV50, carbides content (%K) and their average size (d) in the examined alloys

No	Hardness	Carbides content	Average size of carbides
	HV50	%K	d [10^{-5} mm]
1	430	50,2	2.45
2	336	29,2	1.71
3	429	45,6	0.98
4	418	42,3	2.68
5	402	49,6	2.82
6	307	30,3	1.81
7	383	41,7	2.74
8	196	6,1	0.63
9	232	20,0	0.50
10	330	27,3	1.61
11	211	30,1	0.85
12	280	17,3	1.64
13	268	21,2	0.78
14	236	25,5	1.93

To obtain the structure close to equilibrium state, the alloys were subjected to isothermal annealing for 6 hours followed by slow cooling together with furnace. After annealing the structure was composed of a ferritic matrix with precipitates of eutectic carbides of the type $M_{23}C_6$; in some alloys, secondary carbides of the same type were additionally traced. Alloy no. 8 contained, apart from ferrite and a small amount of carbides, also about 10% of austenite. Microstructures of the examined alloys are shown in Figure 2 against the background of Fe-Cr-C phase equilibrium diagram.

The metallographic specimens were used to measure in the examined alloys hardness HV50, the percent content of carbides (%K) and their average size. The latter parameter was represented by mean length of chord on the specimen polished section (d) (Table 2).

The specimens of dimensions 60 × 6 × 5 mm were cut out and subjected to the abrasive effect of silica stream striking the surface at velocity of 68 m/s.

The tested specimens had the temperature of 450°C. The design of the test stand and test conditions were described in detail in previously published articles [6–11]. The results obtained at various angles of incidence of the abrasive material are compiled in Figure 3. Partial effects of the wear mechanism components described on the plotted curves by symbols W_1 – W_3 were also determined by Bitters theory.

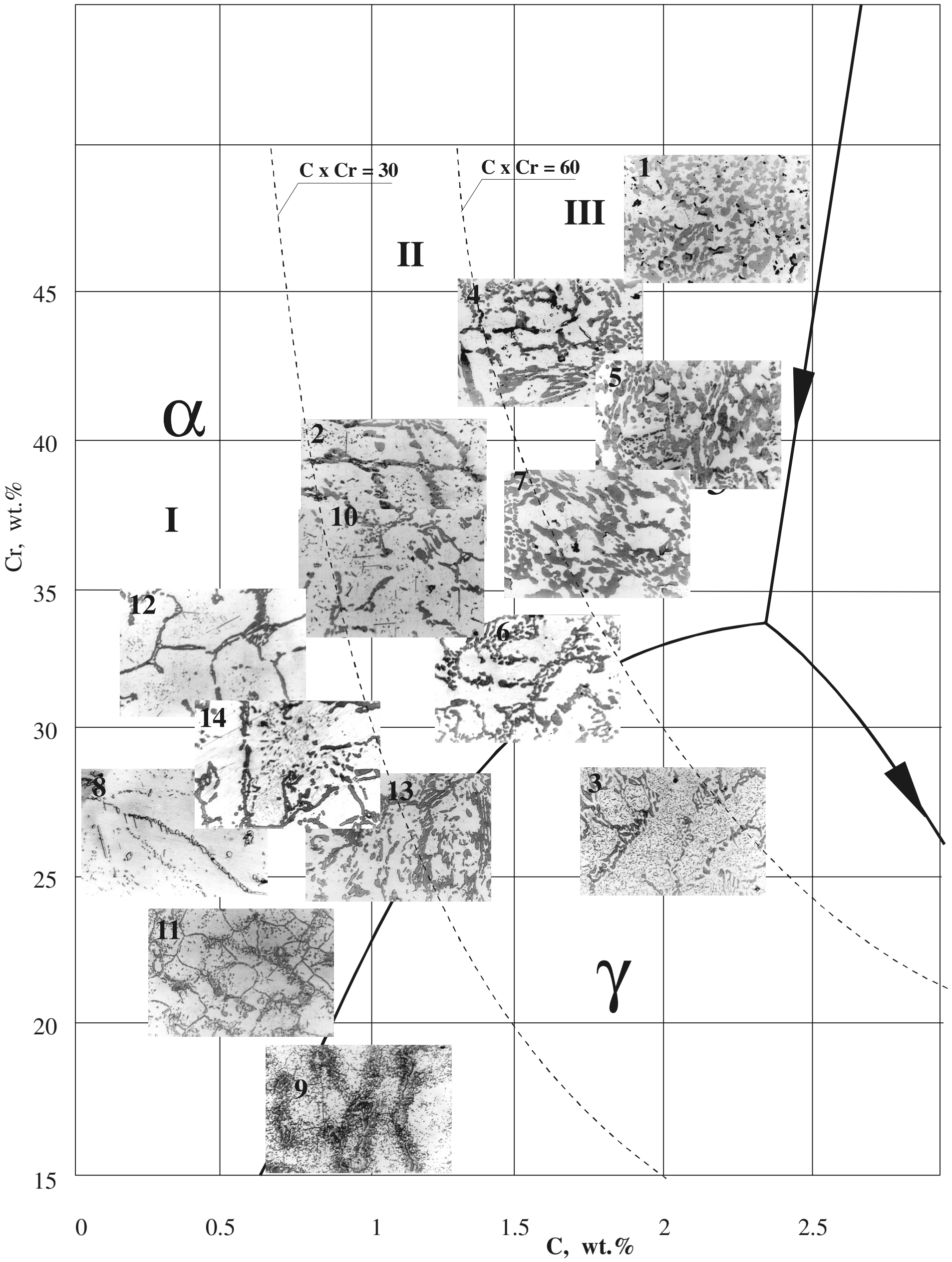

Fig. 2. Microstructures of the examined alloys against the background of Fe-Cr-C phase equilibrium diagram

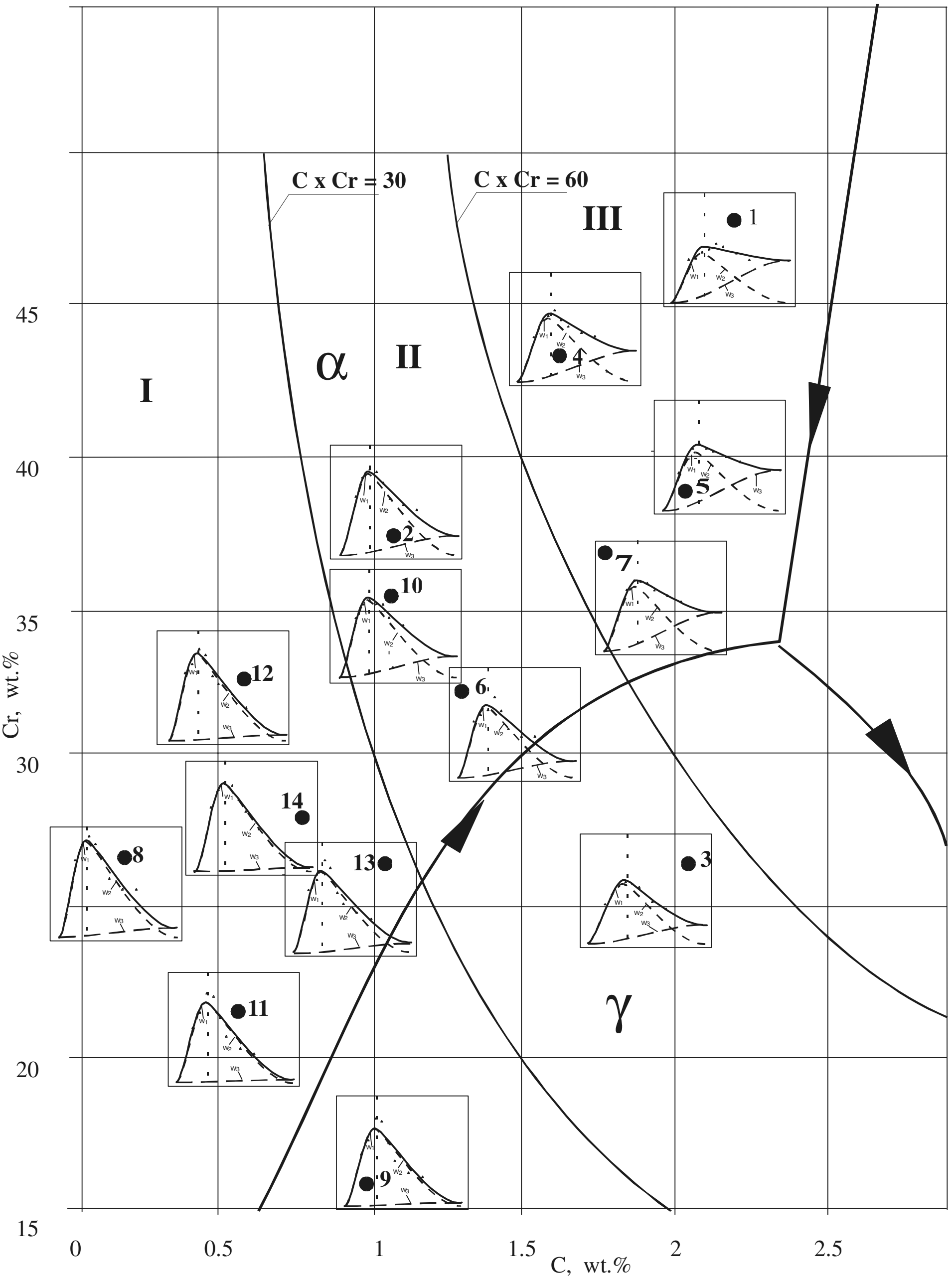

Fig. 3. The developed wear characteristic curves distributed against the projected liquidus plane in Fe-Cr-C phase equilibrium diagram

2. Results and discussion

The output were the wear characteristics Z developed in function of the abrasive incidence angle for all the examined alloys. In respect of their configuration, the plotted curves can be divided into three groups. Figure 4 shows three diagrams typical of each of those groups.

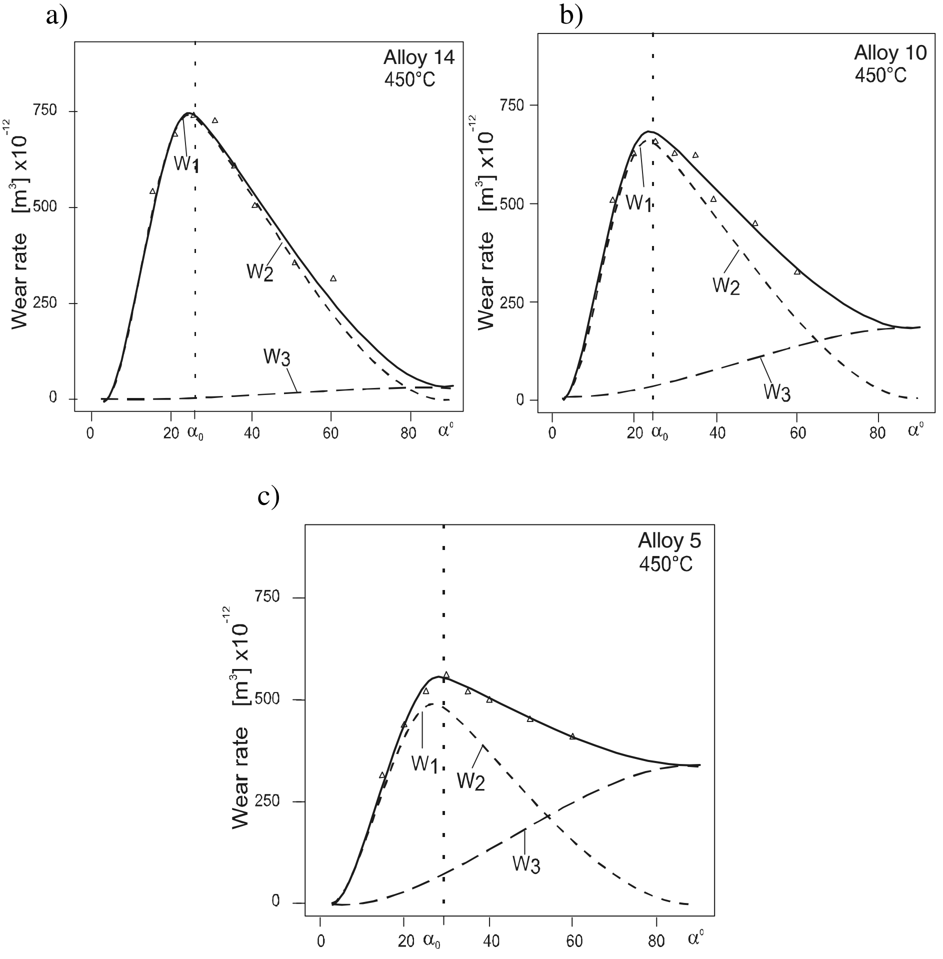

Fig. 4. Typical run of the wear characteristic curves obtained with dry silica sand jet at a temperature of 450°C for alloys from the respective groups : a - group I – alloy 14, b – group II – alloy 10, c – group III – alloy 5

The division can be made adopting as a point of reference the curves for which the value of the product of Cr and C content is constant (see: Fig. 3). The first group includes alloys (8, 9, 11, 12, 13 and 14), for which the product does not exceed the value of 30. In this case, the curves illustrate high values of wear ($\approx 750 \text{ x}10^{-12}\text{m}^3$) for the angle of abrasive incidence $\alpha \approx 25°$ and the wear rate rapidly decreases with increasing value of this angle (Fig. 4a). As follows from the graph analysis, this is due to the fact that over the entire range of the angle α variations, the effect of component W_3 responsible for the share of surface fatigue in overall material wear is rather insignificant. Probably, also the relatively low hardness of these alloys, not exceeding the value of 280 HV50 (Table 2), has contributed to this situation as well.

For the second group formed by alloys (2, 3, 6 and 10) the product of chromium and carbon content is within the range of 30 to 60. Compared with group one, they are characterised, first of all, by an obviously higher value of the wear component W_3 related with surface fatigue (Fig. 4b), due to which for large angles of the abrasive incidence the wear rate is more intense in relation to the first group of alloys. Moreover, in this particular case one can observe a drop in maximum wear rate along with the decreasing content of chromium in alloys. The hardness of these alloys is well above 300 HV50. Alloy no. 13 (included in group I) can be regarded as a transitory between groups I and II, since the effect of component W_3 observed to appear in this alloy is stronger than in other alloys included in the first group and weaker than in alloys included in the second group.

Group three includes the remaining alloys (1, 4, 5 and 7). The product of Cr and C content exceeds in this case the value of 60, and alloys hardness is above 380 HV50. These characteristics indicate much lower wear rate at small angles of the abrasive incidence, going up to 500–600 $\text{x}10^{-12}\text{m}^3$, but much more severe, because the wear rate of $\approx 400 \text{ x}10^{-12}\text{m}^3$ is reached within lager angle range α in respect the remaining alloy groups. This is caused by high share in overall wear of component W_3 originating from the surface fatigue of material (Fig. 4c).

The alloys of group III contain from 40 to 50% of carbides with large dimensions ($d > 240 \text{ x}10^{-5} \text{ mm}^3$) and of uniform distribution (Table 2). These alloys are suitable for operation with the abrasive incidence angle of up to 50°, that is, when the wear is less severe than in the remaining cases. The only competitive counterpart of these alloys is, placed in group II, alloy no. 3 containing 45.6% of carbides, of which about 18% are very fine secondary carbides precipitated in the matrix. This is probably the reason why its hardness is so high (429 HV50), which is typical of alloys from group III. The alloy contains, moreover, much less chromium (26.6%) than alloys in group III, which makes it economically interesting. Within the small and medium values of the angles of the abrasive incidence its wear rate is at the level of alloys from group III, while at large angles it behaves much better than these alloys, presenting a wear rate about two times lower.

The whole group II, with exception of alloy no. 3, is not very interesting from the point of view of their abrasion wear resistance. At small angles α these alloys are characterised by the wear rate much higher than alloys in group III, while at large angles α much better wear resistance have alloys in group I.

Most alloys from group I contain in their structure, apart from eutectic carbides, also secondary carbides; in alloys nos. 12 and 14 they precipitate right in the matrix, while in alloys nos. 9 and 11 they are placed near the eutectic precipitates. The latter two alloys in raw condition contain very large amounts of austenite. All alloys in this group are very attractive in view of their low wear rate within large angles of the abrasive incidence, alloy no. 11 being most interesting in this group due to a low chromium content (it is true that alloy no. 9 contains still less Cr but investigations have proved the presence of intense temper colours at a temperature of 450°C which may suggest possible effect of oxidation on the abrasion wear resistance during long-lasting processes). Two alloys selected from the whole group of the examined alloys, i.e. alloy no. 3 for operation at small angles and alloy no. 11 for operation at large angles of the abrasive incidence, contained in raw condition large amounts of austenite (Table 1). When full annealing was applied, from this highly saturated austenite large amounts of the secondary carbides of very small dimensions were precipitated which, in the author's opinion, has an important effect on the abrasion wear behaviour. This observation should be taken into account when planning further experiments.

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Wpływ zawartości węgla i chromu na odporność na zużycie ferrytycznych wysokochromowych stopów odlewniczych

Streszczenie

Artykuł dotyczy analizy mechanizmów ściernego zużycia erozyjnego oraz możliwości podniesienia odporności na ścieranie. Autorzy opisali procesy zużycia ferrytycznych stopów wysokochromowych, zachodzących pod wpływem materiału ściernego w temperaturze 450°C. Zaprezentowano wyniki, przeprowadzonej przy wykorzystaniu teorii Bittera, analizy intensywności zużycia materiału, prowadzącej do konkluzji, że odporność na zużycie można klasyfikować w oparciu o uzyskane krzywe charakterystyczne, wśród których autorzy wyróżnili i opisali trzy grupy.