The relationship between the abrasion resistance and the hardness of WC-Co alloys

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Synopsis

This paper reports hardness and abrasive wear resistance test results from a wide range of WC-Co alloys, varying in cobalt content as well as WC grain size. The results show that the abrasive wear resistance increases with increasing hardness and that the rate of increase is higher for larger WC grain sizes. The increase in abrasive wear resistance was found to be parabolic up to a critical hardness value and exponential above that value. The transition from parabolic to exponential behaviour was found to occur at the same contiguity value for all grain sizes, which suggests that at that contiguity value the WC skeleton becomes continuous in all WC-Co alloys.

Introduction

WC-Co alloys (or 'hardmetals') are materials consisting of hard tungsten carbide (WC) grains bonded by a tough cobalt (Co) matrix. A typical microstructure of these alloys is shown in Figure 1. These alloys, which may differ in cobalt content and/or WC grain size, are exposed to abrasive wear in most of their applications and, in general, exhibit good resistance to abrasion. This is attributed mostly to their hardness, which increases with decreasing Co content and with decreasing WC grain size[1].

It was established many years ago that the abrasion resistance of WC-Co tends to increase with increasing hardness[2]. Investigators have found a similar trend even when using different abrasion testing techniques[2]: according to most investigators, when the hardness of the WC-Co alloys increases but is lower than the hardness of the abrasive material, the rate of increase of abrasion resistance with hardness is low, while when the hardness of the alloys is higher than that of the abrasive, the rate of increase is high.

Despite the similar trends observed by different investigators, quantitative relationships between abrasion resistance and hardness have not been established. The reason is that hardness is an intrinsic property of the material, i.e. a property that depends only on composition and microstructure, while abrasion resistance is not an intrinsic property since it may depend also on variables such as the testing technique used, the properties of the abrasive and environmental conditions[3].

Therefore, it is not possible to establish a universal quantitative relationship between abrasion resistance and hardness. It is only possible to establish quantitative relationships that are valid for specific experimental conditions. However, on account of the similar trends in the results from different investigators, the analytical form of all quantitative relationships would be similar and so the relationships would be qualitatively applicable to general experimental conditions.

The work presented in this paper aimed at establishing a quantitative relationship between abrasion resistance and hardness, valid when testing abrasion resistance by means of the ASTM 611–85 abrasion resistance test[4], since this is the internationally accepted standard test for WC-Co and is used in most laboratories where the wear of WC-Co is measured. It must be emphasized that even partial modifications to the ASTM 611–85 test procedure may cause variations in abrasion resistance results[3] and may thus affect numerical constants appearing in the relationships reported in this paper.

Method

This investigation consisted of measuring the abrasion resistance and the hardness of 49 different WC-Co grades, where each 'grade' is characterized by a different combination of cobalt content and WC grain size. Since the hardness and the abrasion resistance of WC-Co is affected by both composition and microstructure[1], the alloys used in this investigation exhibit a wide range of hardness and abrasion resistance values. The cobalt content of the alloys (or 'grades') ranged from 3 to 50 wt% and the WC grain size from about 0.6 to about 5 μm. The 49 alloys can be divided into four groups, each group including grades of similar grain size, as shown in Table I.

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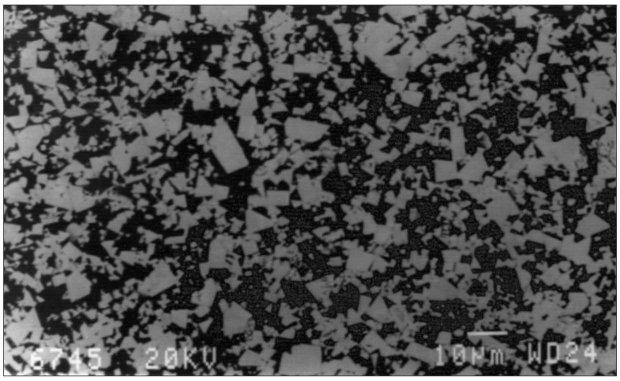

Figure 1—Typical microstructure of a WC-Co alloy: the white phase consists of WC grains of 3 μm mean size and the black phase is the cobalt binder (by courtesy of Mr Thabo Sebeya)

The mean grain size of the individual grades, the cobalt content and the contiguity of the WC grains are given in Table II. 'Contiguity' is the fraction of the surface area of WC grains that is in contact with other WC grains[5], thus it can only range from 0 to 1. The WC mean grain size and the contiguity were measured by linear analysis[6] using the following relationships:

$$d = \frac{V_{WC}}{N_{WC}} \quad \text{and} \quad C = \frac{2N_{WC}}{2N_{WC} + N_{Co}}$$

where :
d = mean WC grain size
V_{WC} = WC volume fraction
N_{WC} = number of WC intercepts per unit length
N_{Co} = number of Co intercepts per unit length
C = contiguity.

The hardness was measured in accordance with the ISO Standard 3878[7] for WC-Co alloys and the abrasion resistance in accordance with the ASTM Standard B 611–85[4]. Both standards are internationally used for the measurement of hardness and abrasion resistance of WC-Co alloys. The abrasion resistance was expressed as the inverse of the measured volume loss (in cm^{-3}).

The abrasion resistance results were plotted against the hardness results for each of the four groups of grades and the graphs obtained were expressed analytically using the mathematical computer package *Mathematica*. The equations were obtained by using a least squares fit for the various lists of experimental data as linear combinations of certain specified basis functions. For each data set, the regression coefficient, R^2, was calculated.

Results and discussion

Table II gives the abrasion resistance and the hardness of the WC-Co grades used for this investigation. Figure 2 shows the plots of the abrasion resistance versus hardness for each of the four groups of grades listed in Table I, as well as the curves that best fit the experimental points. The analytical expressions of the best fitting curves are given in Table III.

Table I

Groups of WC-Co grades used in this investigation

Groups of grades	Mean WC grain size (μm)
UF (Ultra Fine)	0.6 ± 0.04
F (Fine)	1.1 ± 0.18
M (Medium)	3.0 ± 0.37
C (Coarse)	5.1 ± 0.44

Table III and Figure 2 show that in all four groups of grades the abrasion resistance increases parabolically with increasing hardness up to a critical hardness value Hc. The critical hardness value is lower for coarser grained materials than for finer grained ones. Above the critical hardness value, the abrasion resistance increases exponentially.

Within the parabolic region the abrasion resistance does not vary significantly with WC grain size (the coefficients of H^2 are all of the same order of magnitude) but in the exponential region it increases with increasing hardness more rapidly for coarser grades than for finer grades (for the coarser grades, M and C, the coefficient of the exponential is approximately two orders of magnitude larger than for the finer grades, UF and F).

These results agree qualitatively with the results of previous investigators[2] since the previous investigators also observed that the rate of increase in abrasion resistance with hardness is low up to a critical hardness value and then becomes high. However, the present results do not agree with the conclusion that the critical hardness value Hc, below which the material presents little resistance to wear, is approximately equal to the hardness of the abrasive. If this conclusion were correct, the transition from the parabolic to the exponential behaviour (Figure 2 and Table III) would occur at the same hardness for all four groups of grades since the abrasive used for all grades was the same, i.e. alumina particles of same size (0.75 mm average) and shape[6].

By contrast, the transition from parabolic to exponential behaviour occurs at different hardness values for different grain sizes, which suggests that the transition is related to critical changes in microstructure. The mean size of the abrader's particles was more than two orders of magnitude larger than the grain size of all grades tested, thus abrader/microstructure size effects are expected to have a negligible influence on the observed differences in wear rates.

The microstructural parameter that should affect wear most strongly is the contiguity of the WC grains because, at a critical value of the contiguity, the microstructure of the material changes from one of carbide particles dispersed in a continuous cobalt binder to one of a continuous carbide 'skeleton' interlocked with a continuous cobalt binder[5]. Below the critical contiguity, value the plastic deformation induced by the stresses applied to the material during abrasion would be controlled by the cobalt binder, while above the critical contiguity value it would be controlled by the hard carbide skeleton. Therefore it is suggested that the critical hardness value Hc is reached when the contiguity reaches the critical value at which the WC phase forms a continuous 'skeleton'.

This suggestion is supported by the following arguments:

i it has been shown that the contiguity of the WC grains in WC-Co decreases with increasing Co content and does not depend on WC grain size[8]

ii it is well known that if a WC-Co grade of finer grain size has the same hardness as a coarser grade, then the Co content of the finer grade material is higher and so the contiguity is lower (for argument i)

iii if one assumes that the WC phase forms a continuous 'skeleton' at a fixed value of the contiguity for all grain sizes, then this corresponds to a higher hardness for finer grades than for coarser grades (for argument ii).

Table II

Composition, microstructural parameters, hardness and abrasive wear resistance of the WC-Co grades used for this investigation (O'Quigley[6])

WC-Co grade	Co wt%	WC mean grain size (μm)	Contiguity	Hardness (HV30)	Wear resistance (cm^{-3})
UF6	**6**			**2065**	**415.7**
UF8	8			1887	132.4
UF10	10	0.6	0.41	1769	66.8
UF12	12	0.62	0.4	1674	28.9
UF14	14	0.59	0.35	1546	13.7
UF16	16	0.65	0.21	1407	4.7
UF18	18			1298	3.6
UF20	20	0.56	0.33	1239	2.8
UF30	30	0.66	0.25	1008	1.6
UF40	40	0.61	0.25	799	1.4
UF50	50	0.56	0.19	669	1.2
F4	**4**	**1.3**	**0.51**	**1759**	**75.2**
F6	6	1.27	0.47	1659	33.5
F8	8			1620	27.3
F10	10	1.07	0.3	1547	15.8
F12	12			1458	10.8
F14	14	1.17	0.39	1400	6.1
F16	16			1311	4.0
F18	18			1287	3.1
F20	20	0.96	0.29	1240	2.8
F30	30	0.84	0.39	998	1.8
F40	40	0.86	0.29	765	1.4
F50	50	0.96	0.28	503	1.2
M3	**3**			**1611**	**29.4**
M4	4				25.7
M6	6	2.66	0.41	1499	22.6
M8	8	2.65	0.38	1424	15.5
M10	10	2.6	0.41	1369	10.6
M12	12	2.97	0.39	1303	6.1
M14	14			1186	4.0
M16	16			1051	2.7
M18	18	3.47	0.21	989	2.2
M20	20			921	1.6
M30	30			745	1.6
M40	40	3.34	0.25	601	1.2
M50	50	3.27	0.22	496	1.1
C3	**3**	**5.3**	**0.61**	**1323**	**6.9**
C4	4	5.1	0.5	1321	7.2
C6	6	5.32	0.46	1250	5.9
C8	8	5.21	0.32	1181	4.3
C10	10	4.77	0.33	1117	3.5
C12	12	4.89	0.27	1061	2.6
C14	14	5.88	0.27	975	2.1
C16	16	5.1	0.22	921	1.8
C18	18	5.65	0.2	868	1.7
C20	20	5.08	0.23	823	1.4
C30	30	4.86	0.27	647	1.1
C40	40	4.13	0.22	536	1.0
C50	50	4.71	0.23	445	1.0

Table III

Analytical expressions of the curves in Figure 2 as obtained by a least squares fit of the data, with R^2 being the regression coefficients

Groups of grades	Analytical relationship between abrasive wear (W in cm^{-3}) and hardness (H in HV30)	
UF	$W = 8.1 \times 10^{-6} H^2 - 1.25 \times 10^{-2} H + 6.05$	for $H < Hc \approx 1300$ HV30 with $R^2 = 0.977$
	$W = 6.173 \times 10^{-4} \exp(0.0065 H)$	for $H > Hc \approx 1300$ HV30 with $R^2 = 0.999$
F	$W = 3.43 \times 10^{-6} H^2 - 3.8 \times 10^{-2} H + 2.29$	for $H < Hc \approx 1250$ HV30 with $R^2 = 0.996$
	$W = 9.0 \times 10^{-4} \exp(0.0064 H)$	for $H > Hc \approx 1250$ HV30 with $R^2 = 0.992$
M	$W = 5.37 \times 10^{-6} H^2 - 5.84 \times 10^{-3} H + 2.74$	for $H < Hc \approx 1050$ HV30 with $R^2 = 0.900$
	$W = 1.93 \times 10^{-2} \exp(0.0046 H)$	for $H > Hc \approx 1050$ HV30 with $R^2 = 0.958$
C	$W = 5.65 \times 10^{-6} H^2 - 5.98 \times 10^{-3} H + 2.567$	for $H < Hc \approx 1050$ HV30 with $R^2 = 0.964$
	$W = 6.97 \times 10^{-2} \exp(0.0035H)$	for $H > Hc \approx 1050$ HV30 with $R^2 = 0.985$

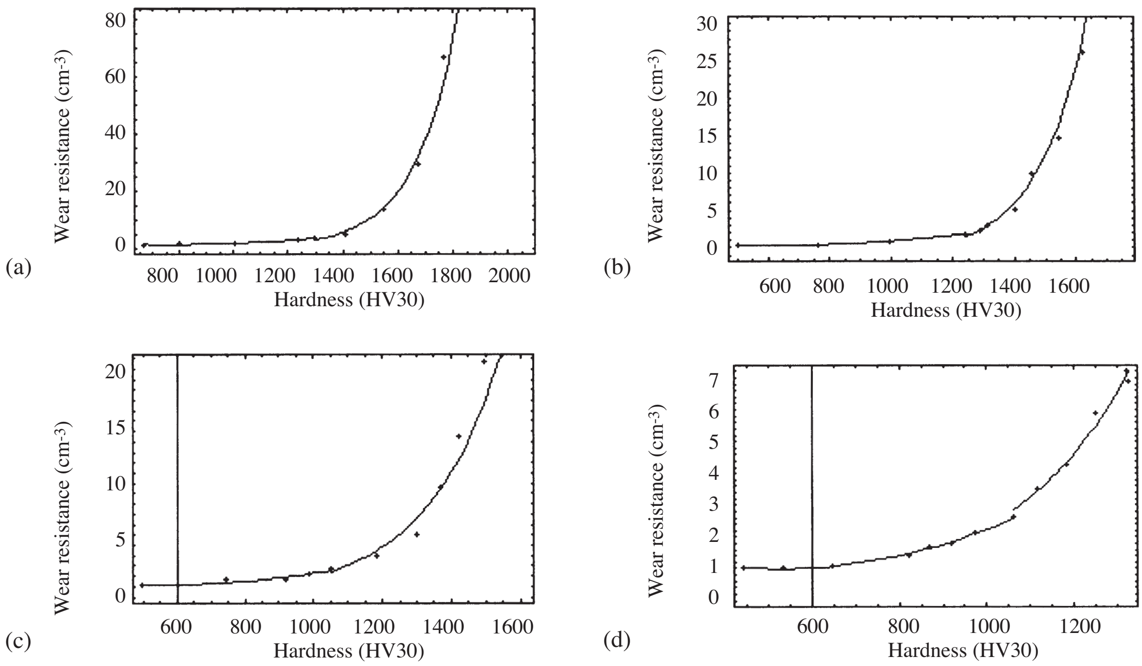

Figure 2—Plots of the abrasion resistance versus the hardness of the four groups of WC-Co grades listed in Table I (a) group UF; (b) group F; (c) group M; (d) group C. The points are the experimental data and the continuous curve sections are the curve sections that best fit the data as determined by a least squares fit. The analytical expressions of the various curve sections are given in Table III

This interpretation is consistent with the results of this investigation, because:

- the critical hardness value Hc has been found to decrease when the WC grain size of the group of materials tested increased
- above the critical value Hc, the wear resistance of coarser grades has been found to be higher than that of finer grades of equal hardness, as a result of the contiguity of coarser grades being higher and so the Co content being lower—and Co removal is known to be the main abrasion mechanism in WC-Co[2].

On the basis of the data in Table II it appears that the critical contiguity value at which the WC 'skeleton' becomes continuous is about 0,3, since this is the approximate value of the contiguity when each group of grades reaches the critical hardness Hc (Tables II and III).

Conclusions

The present investigation has shown that the abrasion resistance of WC-Co alloys increases parabolically with increasing the hardness of the alloys up to a critical hardness Hc, and that above this value the increase in abrasion resistance with hardness becomes exponential. The critical hardness value Hc has been found to decrease with increasing the WC grain size of the group of alloys tested, which is consistent with the interpretation that the value Hc is reached when the WC skeleton in the material becomes continuous and not when the hardness of the material being abraded reaches the hardness of the abrasive, as was previously thought.

On the basis of the present results it has been estimated that the WC 'skeleton' in WC-Co becomes continuous at a contiguity value of about 0.3 at all WC grain sizes.

Quantitative relationships have been established between abrasion resistance and hardness, but the coefficients appearing in the analytical expressions in Table III for the curves that best fit the experimental data in Figure 2 are strictly valid only when measuring abrasion resistance by means of the ASTM Standard 611-85 test. However, the transition from parabolic to exponential behaviour is valid under general experimental conditions on account of the similarity among these results and the results obtained by previous investigators under different conditions.

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