JOURNAL OF MATERIALS SCIENCE 21 (1986) 3548–3550

Effect of hardness on erosion of WC–Co composites

M. T. LAUGIER*
Materials Testing Laboratory, 9 Nova Croft, Coventry, Warwickshire CV5 7FJ, UK

Erosion behaviour of a range of WC–Co composites is investigated using 200 to 500 μm Al_2O_3 grit normally incident at 140 ± 40 m sec^{-1}. A simple relation is obtained linking erosion rate W(g g^{-1}) and hardness H(MPa), $W = 1.44 \times 10^{11} H^{-3.5}$. Current erosion models based on indentation fracture mechanics are not found to apply; an explanation is suggested in terms of an indentation size effect.

1. Introduction

A recent study of erosion in WC–Co composites by Conrad *et al.* [1] found no correlation between erosion rate and hardness for WC–Co materials inpacted at room temperature with 30 μm Al_2O_3 particles incident at 45° at a velocity of 99 m sec^{-1}. Their data did support an earlier finding of Hansen [2], who found that normal incidence erosion of cemented carbides increased with binder content when using 27 μm Al_2O_3 particles at a velocity of 170 m sec^{-1}.

WC–Co composites are widely used in applications requiring good wear resistance; these include dies for extrusion and wire drawing, punches, nozzles for concrete spraying and sand blasting. Materials selection is generally made on the basis of tests designed to simulate key aspects of the wear processes likely to be encountered in applications. Tests include wet and dry abrasion, resistance to abrasive slurries, and particle erosion; performance in all tests tends to improve with increasing hardness.

In view of these results, it was decided to investigate the effect of hardness on the erosion behaviour of a range of WC–Co composites.

2. Models

Some progress has been made recently in describing particle erosion in ceramics using the plastic/elastic indentation fracture model of Marshall *et al.* [3]. Material removal is considered to occur when the lateral cracks intersect the free surface, leading to brittle microchipping.

There are two versions of this model which differ in their treatment of the contact pressure during impact; the quasi-static model of Ruff and Wiederhorn [4] equates contact pressure with the usual hardness, the model of Evans *et al.* [5] is developed in terms of the maximum dynamic pressure which occurs at initial contact.

In each case, the semi-empirical relation $c \sim (P/K_c)^{2/3}$ between crack radius c, maximum normal load resulting from impact P, and toughness K_c, is used to obtain the volume of material removed per impact, $\pi c^2 d$, where d is the depth of cracks beneath the surface.

The resulting expressions for the rate of erosion, given as a volume loss per impact, are

$$W \propto V^{2.4} R^{3.7} \varrho^{1.2} K_c^{-1.33} H^{0.11} \quad (1)$$

(Ruff and Wiederhorn [4])

$$W \propto V^{3.2} R^{3.7} \varrho^{1.3} K_c^{-1.33} H^{-1.25} \quad (2)$$

(Evans *et al.* [5])

where V, R, ϱ are particle velocity, radius and density, respectively.

Wiederhorn and Hockey [6] have compared the predictions of the two models for a range of ceramic materials using 150 μm SiC particles normally incident at velocities in the range 37 to 94 m sec^{-1}. Observed velocity exponents did not agree exactly with predictions of either model; exponents obtained at room temperature were found to cluster about the value 2.4 predicted by the quasi-static model, whilst exponents obtained at higher temperatures (500 and 1000° C) tended to be closer to the value 3.2 predicted by the dynamic model. Both models were found to underestimate the dependence of erosion rate on hardness and on toughness, although a reasonable description of the data could be provided in terms of $(K_c^{-1.33} H^{-0.25})^{1.2}$, (dynamic model), or $(K_c^{-1.33} H^{0.11})^{1.5}$, (quasi-static model).

3. Experimental details

Normal incidence erosion testing was performed at room temperature using 200 to 500 μm Al_2O_3 grit (see Fig. 1) on a range of WC–Co composites, in order to investigate the effect of hardness, H, on erosion. Compositional and properties details of the WC–Co materials used are given in Table I. Specimens of cross section 1.6 × 1.6 cm^2 were positioned 8 cm from the 2 cm diameter exit nozzle (WC–Co) of a commercial compressed air operated grit blasting machine. Visual observation at the 8 cm working distance indicated an intense 2 cm diameter erosion zone with detectable

*Present address: Materials Research Centre, NIHE, Limerick, Republic of Ireland.

0022–2461/86 $03.00 + .12

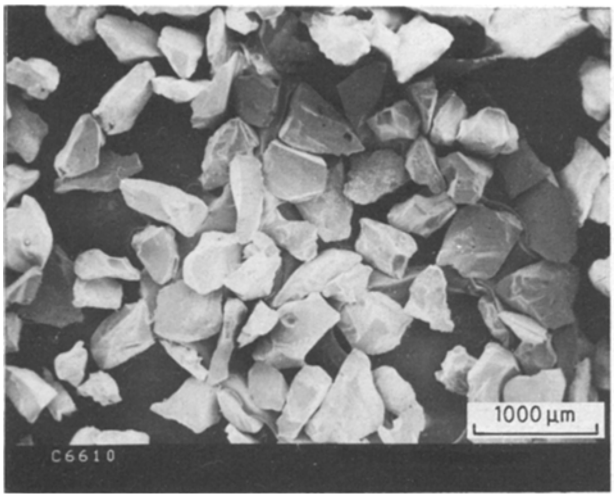

Figure 1 Scanning electron micrograph illustrating angular Al_2O_3 particles used for erosion testing.

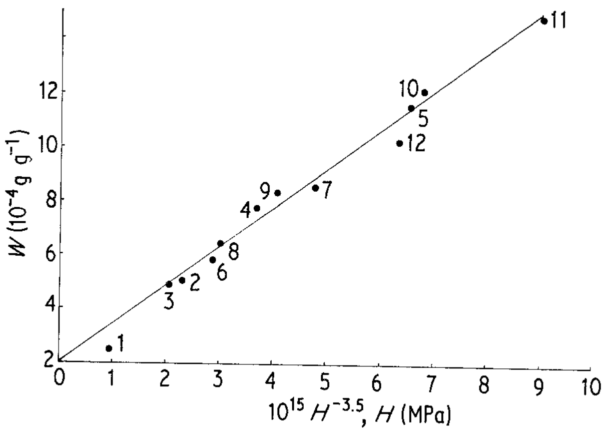

Figure 2 Erosion coefficient, W, against $H^{-3.5}$ where H is hardness, for a range of WC–Co materials. $W = 1.44 \times 10^{11} H^{-3.5}$, $W(\mathrm{g\,g^{-1}})$, $H(\mathrm{MPa})$.

erosion extending over a 4 cm diameter region (at 14 cm working distance the corresponding figures were 4 cm and 6 cm). Particle speed was determined using a time of flight method employing two aluminium discs of variable separation, mounted on a rotatable shaft aligned with the particle beam axis.

Particles passing through a 2 mm diameter hole in the first disc produced a circular erosion zone on the polished face of the second disc; rotating the discs led to angular displacement and broadening of the erosion zone. With a disc separation of 8 cm, the angular displacement of the erosion zones resulting from rotation at 1.81 kHz was about 60°, leading to a particle speed of $140 \pm 40\,\mathrm{m\,sec^{-1}}$.

Particle flux at the target position under operating conditions was remarkably constant ($3.14\,\mathrm{g\,cm^{-2}\,sec^{-1}} \pm 1\%$) target material removal rates were in the range 24 to $624\,\mathrm{mg\,min^{-1}}$ and so were readily measurable; reproducibility was good (coefficient of variation $\sim 10\%$).

4. Results

The experimentally determined erosion coefficient W is also included in Table I (W = mass of target removed in given time/mass of particles incident in target in same time). A plot of log W against log H showed the data points to lie close to a line of slope -3.5 (grade 1, the hardest material, was an exception, giving a relatively low value of W). Fig. 2 shows W plotted against $H^{-3.5}$; the data are seen to lie close to the line $W = 1.44 \times 10^{11} H^{-3.5}$, $W(\mathrm{g\,g^{-1}})$, $H(\mathrm{MPa})$, which provides a good description of WC–Co erosion under the present conditions (200 to 500 μm Al_2O_3 particles normally incident at $140 \pm 40\,\mathrm{m\,sec^{-1}}$). It is noted that the erosion coefficient W for the hardest material, grade 1, a low cobalt material, is only about one-third the predicted value, suggesting a change in erosion mechanism. This possibility remains to be investigated.

TABLE I Compositional and properties data together with erosion rate, W, for a range of WC–Co materials

No.	Grade	H(MPa)	f_β^v(%)	$\bar{l}_\beta^*$† (10^{-6}m)	W ($10^{-4}\mathrm{g\,g^{-1}}$)
1	3 F	19 620	5	0.03	0.5
2	6 M	15 300	10	0.11	3.1
3	10 F	15 700	16	0.10	2.9
4	15 F	13 340	24	0.22	5.9
5	9 C	11 280	15	0.50	9.6
6	7 M	14 320	12	0.15	3.8
7	11 M	12 360	18	0.32	6.6
8	9 M	14 130	15	0.16	4.5
9	6 C	12 950	10	0.25	6.4
10	16 M	11 180	25	0.52	10.2
11	25 F	10 300	37	0.79	12.9
12	15 M	11 380	24	0.48	8.3

†Calculated [8] from $\bar{l}_\beta^* = (H/620)^{-5}$.

5. Discussion

Toughness, K_{Ic}, in WC–Co composites decreases with increasing hardness H; a recent model [7] provides a quantitative link between K_{Ic} and H,

$$K_{Ic} = 2.67 \times 10^7 (E/H)^{0.6} \varepsilon_c(\bar{l}_\beta^*)^{0.6} \times (1 + 0.012\, E/H)^{-0.6} H^{-1.5} \qquad (3)$$

where E is Young's modulus, $\varepsilon_c(\bar{l}_\beta^*)$ is a critical strain (~ 0.02) a distance $\bar{l}_\beta^* = \bar{l}_\gamma f_\beta^v/(1 - f_\beta^v)$ ahead of the crack tip ($\bar{l}_\gamma$ is the mean linear intercept of a random line with the WC phase – Heyn's grain size; f_β^v is the cobalt volume fraction; subscripts β and γ refer to properties of the cobalt and WC phases, respectively). The term $(E/H)^{0.6}$ is slowly varying in WC–Co materials (E/H is a plasticity index), so that $K_{Ic} \sim H^{-1.5}$. Using this result the expressions for the erosion rate W of Ruff and Wiederhorn (quasi-static) and of Evans *et al.* (dynamic) become

$$W \propto v^{2.4} R^{3.7} \varrho^{1.2} H^{2.1} \text{ (quasi-static)} \qquad (4)$$

$$W \propto v^{3.2} R^{3.7} \varrho^{1.3} H^{0.7} \text{ (dynamic)} \qquad (5)$$

These formulae are clearly at variance with the observations of the previous section which confirm the inverse hardness dependency of erosive wear in WC–Co ($W = 1.44 \times 10^{11} H^{-3.5}$, $W(\mathrm{g\,g^{-1}})$, $H(\mathrm{MPa})$). A connection with microstructure may be made through the relation [8] $H = 0.79\, G\, (\boldsymbol{b}/\bar{l}_\beta^*)^{0.2}$, where H is the hardness of WC–Co, $G = 6.5 \times 10^4$ MPa is the shear modulus of cobalt, $\boldsymbol{b}$ is a Burgers vector for cobalt and $\bar{l}_\beta^*$, f_β^v are as given above. This relation which is valid for $\bar{l}_\beta^* \gtrsim 1 \times 10^{-6}$ m takes the numerical form $H = 620\,\bar{l}_\beta^{*-0.2}$, H(MPa), $\bar{l}_\beta^*$(m), so that an expression for the erosion rate W is $W = 24\,\bar{l}_\beta^{*0.7}$, W(g g^{-1}), $\bar{l}_\beta^*$(m).

Some insight into the reasons for the failure of the plastic/elastic models in this case may be gained from a consideration of the scale of the indentation damage. The maximum volume of an impression caused by particle impact is $mv^2/2H \sim 0.4 \times 10^{-12}$ m^3 ($\varrho = 4.0 \times 10^3$ kg m^{-3}, $R = 300 \times 10^{-6}$ m, $v = 140$ m sec^{-1}, m = mass of particle, $H = H_{min} = 10^4$ MPa) under quasi-static condition with no work hardening, if all the energy is dissipated in plastic work. This would correspond to a crater depth close to 20×10^{-6} m and a diameter close to 200×10^{-6} m.

Fracture can only occur when the strain energy release rate is sufficient to provide the energy associated with crack extension, and Puttick [9] has shown how this leads to a size effect for fracture under conditions of inhomogeneous loading. Laugier [10] has applied the theory of Puttick to the case of Palmqvist cracking in WC–Co composites resulting from Vickers indentation. It is predicted that cracking will not occur for impression sizes smaller than $\sim 10^3\,\bar{l}_\beta^*$. From the hardness/microstructure model [8], values of $\bar{l}_\beta^*$ for the WC–Co materials investigated are in the range 0.1 to 0.8×10^{-6} m (grade 1 is an exception; $\bar{l}_\beta^* \sim 0.03 \times 10^{-6}$ m) (see Table I), so that in most cases the crater size is expected to be well below the critical size for brittle fracture (the reverse is true for grade 1 which shows an anomalously low erosion rate, this point requires further investigation).

Finally, the models under discussion require the presence of lateral cracks; there is some doubt about lateral crack generation in WC–Co materials under usual indentation conditions [11] (which, of course, produce Palmqvist cracks).

It is noted that assuming erosion rate proportional to impression volume gives the observed inverse hardness dependency (but not, of course, the observed hardness exponent).

6. Conclusion

Erosion testing at room temperature of a range of WC–Co composites using 200 to 500 μm Al_2O_3 grit normally incident at 140 ± 40 m sec^{-1} confirmed the inverse hardness dependency of erosion rate. Under these conditions, a simple relation was obtained between erosion rate W(g g^{-1}) and hardness H(MPa), $W = 1.44 \times 10^{11} H^{-3.5}$; equivalently erosion rate may be written in terms of the microstructural parameter $\bar{l}_\beta^*$(m), $W = 24\bar{l}_\beta^{*0.7}$.

Current theories of erosion based on indentation fracture have been found inapplicable; a possible explanation for this failure has been suggested in terms of an indentation size effect.

Acknowledgement

Experimental work was performed whilst the author was with Sandvik Hard Materials UK Research Centre.

References

1. H. CONRAD, D. McCABE, G. A. SARGENT, in "Science of Hard materials", edited by R. K. Viswanadham, D. J. Rowcliffe and J. Gurland (Plenum Press, New York, 1983) p. 775.
2. J. S. HANSEN, in "Erosion: Prevention and Useful Applications", ASTM STP 664, edited by W. F. Adler (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1979) p. 148.
3. D. B. MARSHALL, B. R. LAWN and A. G. EVANS *J. Amer. Ceram. Soc.* **62** (1982) 561.
4. A. W. RUFF and S. M. WIEDERHORN, in "Treatise on Materials Science and Technology", Vol. 16, edited by C. M. Preece (Academic Press, New York, 1979) p. 69.
5. A. G. EVANS, M. E. GULDEN and M. E. ROSENBLATT, *Proc. Roy. Soc. London A* **361** (1978) 343.
6. S. M. WIEDERHORN and B. J. HOCKEY, *J. Mater. Sci.* **18** (1983) 766.
7. M. T. LAUGIER, *Powder Metall.* in press.
8. *Idem, Acta Metall.* **33** (1985) 2093.
9. K. E. PUTTICK, *J. Phys. D. Appl. Phys.* **13** (1980) 2249.
10. M. T. LAUGIER, to be published.
11. *Idem,* to be published.

Received 4 July
and accepted 18 December 1985