JOURNAL OF MATERIALS SCIENCE 27 (1992) 4732–4740

Effects of surface preparation on the friction and wear behaviour of silicon nitride/silicon carbide sliding pairs

P. J. BLAU
Metals and Ceramics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831–6063, USA

Silicon carbide and silicon nitride specimens were fabricated to provide three different surface finishes. They were subjected to sphere-on-flat (pin-on-disc) testing in order to determine the interaction of load, velocity, disc surface finish, and material effects on unlubricated friction and wear. Tests were conducted in air using applied loads of 1 and 10 N, velocities of 0.1 and 0.5 $\mathrm{m\,s^{-1}}$, and surface preparations of 150-grit grinding, 220-grit grinding and fine polishing. The test duration was kept constant at 1000 m of sliding distance for the pin specimen. In half the tests silicon nitride was the pin material and silicon carbide was the disc material. For the other half, the pin and slider materials were reversed. There was a much greater effect of normal force on steady-state friction coefficient than of either surface finish or material pairing. Increasing the sliding velocity raised the friction coefficient for both material pairings and for all surface roughnesses. Higher wear resulted when the velocity increased, but the effect of surface finish on wear ranged from none in some cases to about a factor of 10 in other cases. A trend of increasing run-in period duration with increasing smoothness was observed. The results are interpreted in terms of material properties, the Lim and Ashby model, and the friction force–velocity product.

1. Introduction

Successful research and development programmes over the past few years have led to marked improvements in the properties of advanced engineering ceramics. Current interest in the use of those ceramics in wear-critical applications have generated serious concern over their manufacturing costs, especially as regards the determination of surface finish requirements appropriate to specific applications. Current and proposed applications in the automotive industry, a major potential market, include engine water-pump seals, valves, valve seats and guides, cam roller followers and piston rings.

The relationship of the surface finish of ceramic parts to their friction and wear characteristics is a matter of concern from several standpoints. In general, the more stringent the surface smoothness requirements are, the higher the finishing cost. In addition, there is a need to understand better how ceramic surfaces with various finishes perform in service with respect to both friction and wear. The optimal service condition may not necessarily be the smoothest finish because the flow and distribution of lubricants may require other than perfectly smooth surfaces. Furthermore, the ability of ceramic wear surfaces to achieve an effective run-in condition is different from that of their metal counterparts [1].

Work on a surface roughness-based wear model for ceramics was conducted and reported by McCool [2, 3]. In conjunction with this work, validation tests were conducted in our laboratory using several polycrystalline ceramics with three different surface roughnesses. Unlubricated pin-on-disc tests were performed at several loads and sliding velocities to study the friction and wear behaviour of the differently finished surfaces. This paper describes a portion of those tests; specifically, those in which silicon carbide against silicon nitride comprised the sliding pairs. This combination of materials was of particular interest because it permitted the study of two sliding bodies that exhibited significant differences in hardness, elastic modulus and thermal conductivity (see Table I). Thus, reversal of ball (pin) and flat (disc) materials produced differences in the heat flow characteristics of the sliding contact. Also of interest in this study was the

TABLE I Some properties of silicon carbide and silicon nitride

Property	Unit	SiC	Si_3N_4
Modulus of elasticity	GPa	207–493	304
Poisson's ratio		0.19	0.24
Hardness (Knoop), disc	GPa	39.5	22.9
Hardness (Knoop), ball	GPa	29.3	25.9
Thermal conductivity	$\mathrm{W\,m^{-1}K^{-1}}$	63–155	9–30
Density	$\mathrm{g\,cm^{-3}}$	3.21	3.18

Microindentation hardness data (values ± 5%) were obtained on the ball and disc specimens in our laboratory using a 0.981 N (100 g) indentor load. Other property data are from [11].

run-in behaviour and the relationship of the energy expended during sliding to the wear rates of the various couples.

2. Materials and procedure

The materials used in these experiments are listed in Table II. The disc specimens were obtained as flat tiles, whereas the balls were fabricated from rod stock. Despite the fact that the pin and disc specimens were not fabricated from the same lot of material, we did not expect this difference to be as important to the friction and wear results as would be the effects of load, velocity and initial surface finish. A discussion of using different material stocks for balls and for flat specimens is further described in [4].

Some disc specimens were prepared by grinding and others by both grinding and metallographical polishing. Typical surface conditions of the disc specimens are shown in Fig. 1. As the figure shows, grinding marks were oriented at about 30° to one another. The surface roughness parameters were obtained on a Talysulf 10 instrument using a 2.5 µm tip radius diamond stylus and are listed in Table III. Values represent the average of at least three traces taken at angles of 0, 45 and 90° with respect to one another.

TABLE II Specimen materials

Material	Form	Description
Silicon carbide	Sphere	Fabricated from fine-grained rod stock of Hexaloy SA by Industrial Techtonics, Inc.
	Flat tile	Cut from a fine-grained bar of Hexaloy SA and ground or polished
Silicon nitride	Sphere	Grade 10 ball purchased from Norton Company (NBD-100)
	Flat tile	Norton Company NBD-100 cut from a fine-grained bar and ground or polished

The wear tests were performed using a pin-on-disc arrangement (Fig. 2). The "pin" specimens were polished, 9.53 mm diameter spheres clamped in the slider holder. Standard test conditions were those adopted by the Versailles Project on Advanced Materials and Standards (VAMAS) international wear-testing program [5]: 10.0 N load, 0.1 m s^{-1} sliding velocity and 1000 m total sliding distance per test. Four unlubricated tests were conducted for each material pairing (silicon carbide on silicon nitride and vice versa) and for each of three disc surface roughnesses using the above test parameters. Additional tests using 1.0 N load and 0.1 m s^{-1} sliding velocity, and 10.0 N load and 0.5 m s^{-1} sliding velocity were also conducted; however, only two tests were run for each of the non-standard conditions. The lower-load experiments were included to determine whether the effects of initial surface roughness would be more prominent if the normal load were reduced. The higher-speed tests were included to see whether the effects of thermal property differences between the pin and disc specimens would be more significant when frictional heating was increased.

Tests were run in air at 55 ± 15% relative humidity. Although there have been recent studies suggesting an effect of relative humidity on the friction and wear of certain ceramics [6, 7], an analysis of both friction and wear data for individual tests did not reveal any trends linking the variation of test data with humidity level within this range (see Appendix A). Therefore, subsequent data are reported without reference to specific humidity levels.

3. Results

Friction and wear results are reported separately. Friction data, except those referring specifically to running-in, are given in terms of the nominal ("steady-state") friction coefficient. Wear data for both pin and disc specimens are given as traditional "wear factors" in units of wear volume normalized by test load and

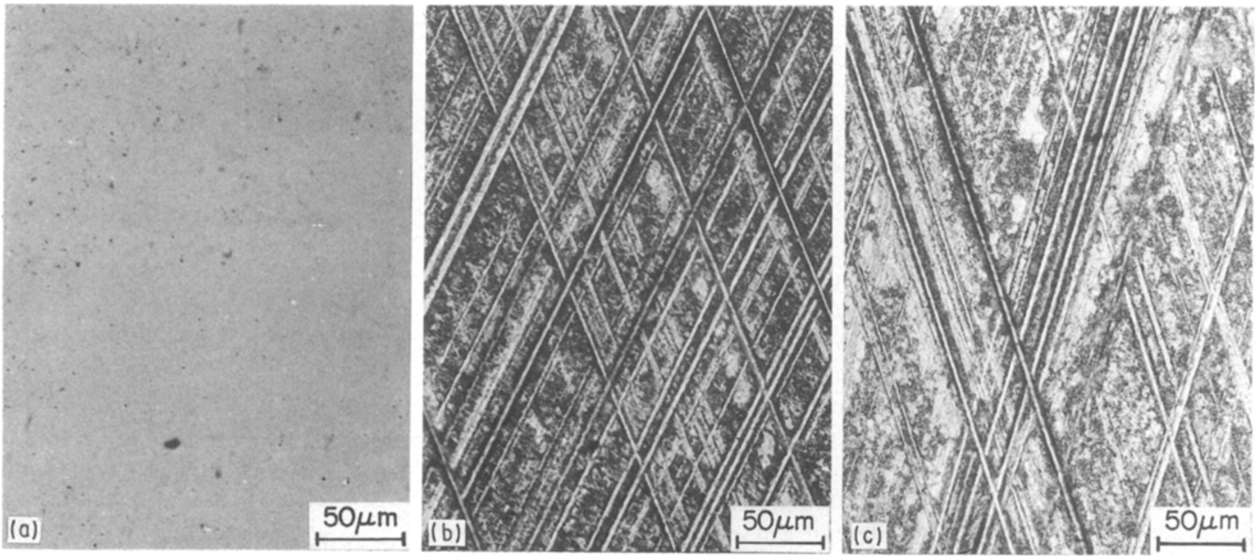

Figure 1 Typical surface conditions of the disc specimens: (a)metallographically polished, (b) 220-grade finish and (c) 150-grade finish.

TABLE III Surface roughness parameters for the disc specimens (average of three directions across the surface at 0, 45 and 90 ° to one another)

Material	Finish	Parameter[a]			
		R_a (μm)	R_q (μm)	R_t (μm)	delQ (degrees)
SiC	150-grit	0.40	0.67	6.43	4.88
	220-grit	0.05	0.08	1.03	1.60
	Polished	0.03	0.04	0.43	0.66
Si_3N_4	150-grit	0.39	0.49	3.03	5.05
	220-grit	0.35	0.44	2.67	5.23
	Polished	0.02	0.02	0.13	0.20

[a] R_a, arithmetic average roughness; R_q, root-mean-square average roughness; R_t, peak-to valley height; and delQ, root-mean-square asperity slope.

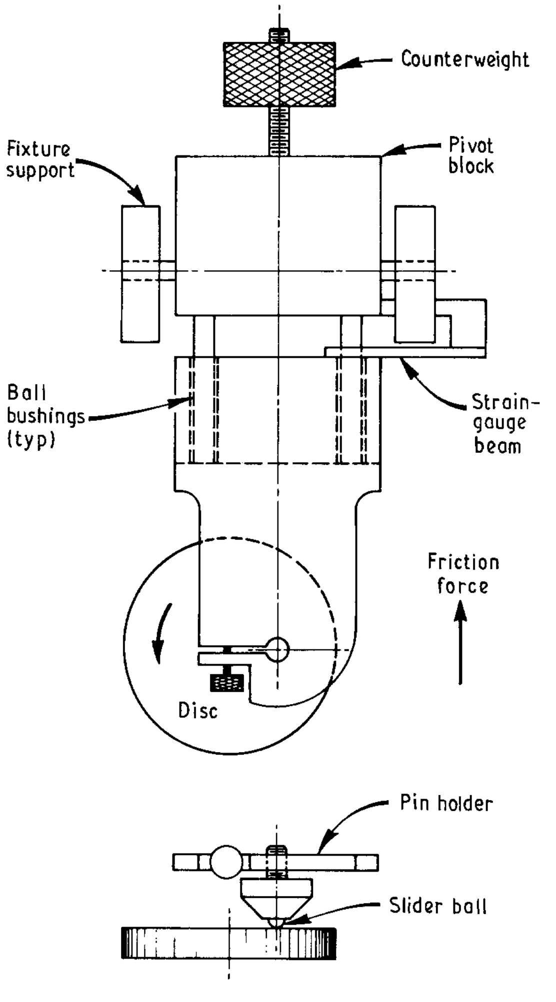

Figure 2 Schematic diagram of the pin-on-disc tribometer.

sliding distance. The wear volumes for the pin specimens were calculated based on the diameters of the circular wear scars on the pin tips. Wear volumes for the disc specimens were obtained by averaging three readings of wear track cross-sectional area on each track (obtained by stylus profilometry) and multiplying the average area by the track circumference. These wear factors are not without certain ambiguities (for a discussion see [8]), but they do represent a commonly accepted means of reporting wear data in the literature.

For the purposes of this paper the test couples are referred to using SiC/SiN to mean silicon carbide pin on silicon nitride disc and SiN/SiC to mean silicon nitride pin on silicon carbide disc.

The effect of test load and disc surface finish on the steady-state friction coefficient (velocity 0.1 m s^{-1}) is shown in Fig. 3. Friction coefficients for the 10.0 N load were about one-third lower than those for the 1.0 N load. For all but the SiC/SiN couple at 1.0 N load there appeared to be a minimum in friction for the intermediate surface finish.

The effect of sliding velocity and surface finish on the steady-state friction coefficient (load 10.0 N) is shown in Fig. 4. Compared with the 0.1 m s^{-1} data, higher sliding velocities resulted in higher friction coefficients in every case. The SiC/SiN couple did not show the same minimum in friction coefficient at intermediate roughness as the 0.1 m s^{-1} tests did; however, there was relatively little significant effect of surface finish differences on the friction coefficient

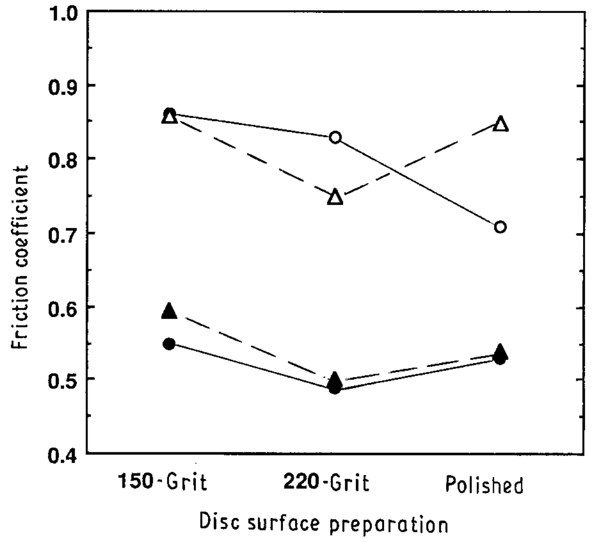

Figure 3 Effect of load on friction of dissimilar ceramic pairs, velocity 0.1 m s^{-1}: (circles) SiC/SiN and (triangles) SiN/SiC; load (closed symbols) 10 N and (open symbols) 1 N.

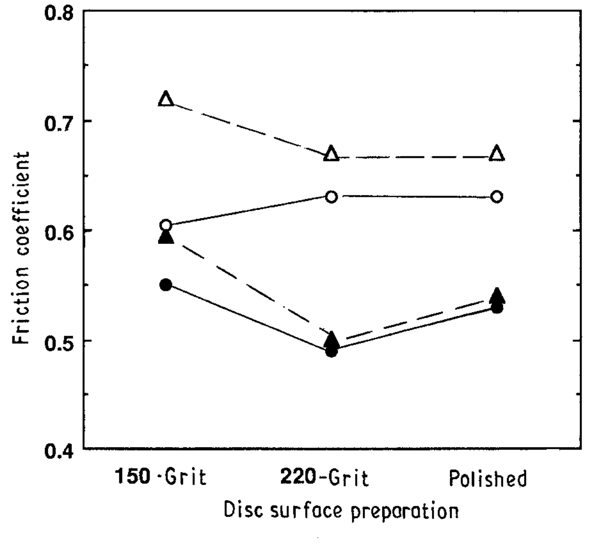

Figure 4 Effect of velocity on friction for dissimilar ceramic pairs, load 10 N: (circles) SiC/SiN and (triangles) SiN/SiC; velocity (closed symbols) 0.1 m s^{-1} and (open symbols) 0.5 m s^{-1}.

within each set of load and velocity tests on the same material pairing.

The frictional running-in period was defined as the time required for the friction coefficient to reach its steady-state level. The running-in period for each test was determined by laying a straight edge on the steady-state portion of the chart-recorder record and observing the first point towards the beginning of the test at which the trace deviated from its nominal steady-state value. The length of the running-in period was converted to revolutions of the disc, given the measured wear track radius and the running time of each test. As indicated in Fig. 5, which plots the running-in period for 10.0 N load, 0.1 m s^{-1} velocity tests, the initial disc surface finish had a significant effect on the length of the running-in period. The 150- and 220-grit ground surfaces had about the same running-in period; however, the SiC/SiN couples required about twice as long to run in. The SiC/SiN couples also took longer to run in the polished case, but the difference was small. The largest effect of surface finish on the running-in period was between the ground and polished surfaces. Ground surfaces in the SiC/SiN case ran in about 30% sooner than when polished. For the SiN/SiC case, ground disc surfaces ran in more than 50% faster than polished surfaces. No analytical correlations were obtained between the length of the running-in period and the various surface roughness parameters. This was because the causes for running-in behaviour involve interfacial phenomena more complex than surface geometry alone [1].

The effect of applied load on the wear factor of the pin specimen at constant 0.1 m s^{-1} velocity is shown in Fig. 6. Each point represents the average of four tests at 10.0 N load or two tests at 1.0 N load. At 10.0 N load there was no significant effect of surface finish on the wear of either material pairing; however, the SiC pins wore considerably less than the SiN pins. At the 1.0 N load the largest difference between material pairings in wear was at 150-grit. The SiC pin wear declined as the surface roughness improved, but no such trend was observed for the SiN pin wear.

The effect of applied load on the disc specimen wear could not be established quantitatively. At 1.0 N load there was insufficient wear damage on the disc specimens to be measured accurately by stylus profilometry. It can be stated only that there was considerably less disc wear for all conditions and material pairings at 1.0 N load.

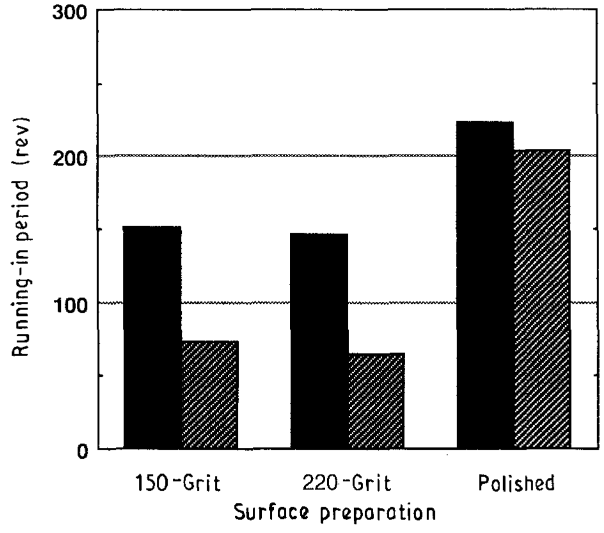

Figure 5 Effect of finish on run-in: (■) SiC/SiN and (▨) SiN/SiC.

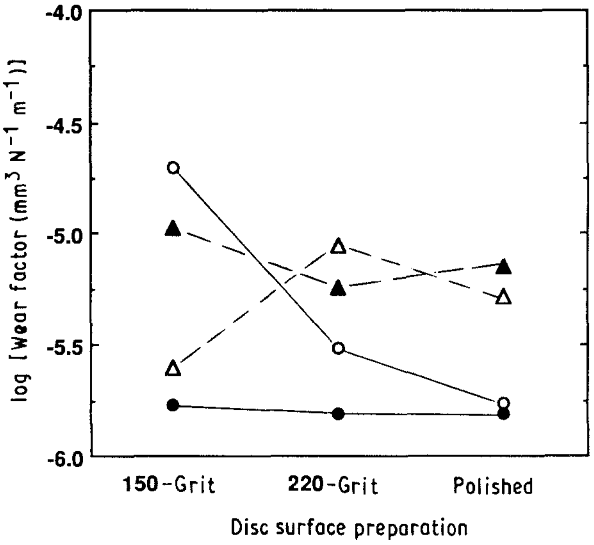

Figure 6 Effect of load on the wear of dissimilar ceramic pairs, velocity 0.1 m s^{-1}: (circles) SiC/SiN and (triangles) SiN/SiC; load (closed symbols) 10 N and (open symbols) 1 N.

The effect of sliding velocity on the wear of the pin specimens is shown in Fig. 7. For SiC/SiN there was no effect of surface finish on pin wear; however, the wear factor was increased by a factor of about 1.8. For SiN/SiC there was a slight indication that wear decreased as the surface finish improved, and that the higher velocity increased the wear rate. The effect of velocity on the pin wear rate was not as significant for SiN/SiC as it was for SiC/SiN.

The effect of sliding velocity on the wear of the disc specimens is shown in Fig. 8. With the possible exception of the polished SiN/SiC pair at 0.1 m s^{-1}, there was no apparent effect of disc specimen surface preparation on wear at a given load and velocity.

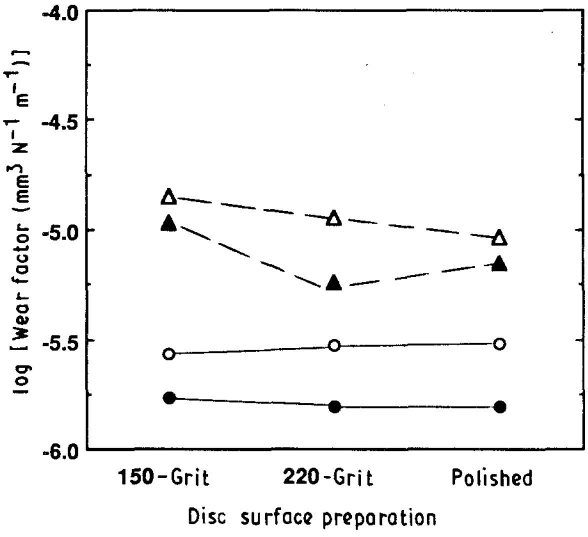

Figure 7 Effect of sliding velocity on wear of dissimilar ceramic pairs, load 10 N: (circles) SiC/SiN and (triangles) SiN/SiC; velocity (closed symbols) 0.1 m s^{-1} and (open symbols) 0.5 m s^{-1}.

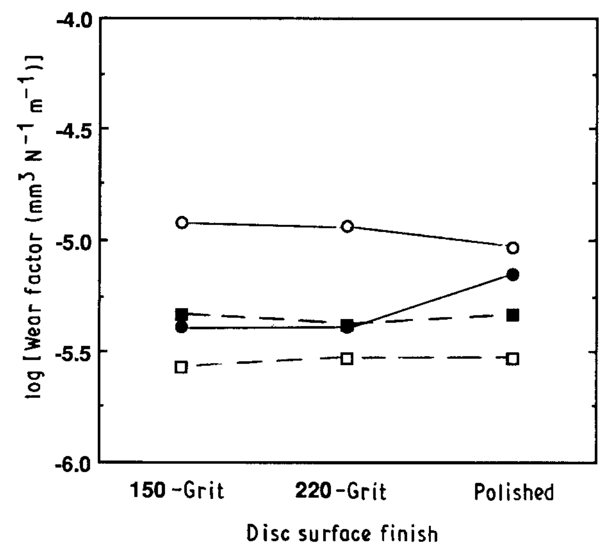

Figure 8 Effect of velocity on disc wear for dissimilar ceramic pairs, load 10 N: (circles) SiN/SiC and (squares) SiC/SiN; velocity (closed symbols) 0.1 m s^{-1} and (open symbols) 0.5 m s^{-1}.

Measurements of surface roughness parameter changes due to wear were made on the specimens run at 10.0 N load and 0.1 m s^{-1} velocity. These are summarized in Table IV. In general, the smoother the finish is, the greater the change in both the root-mean-square (r. m. s.) roughness and the r. m. s. slope of the asperities. It is interesting to note that the data for the ground silicon carbide discs seemed to vary more systematically with surface roughness than that for silicon nitride, for which there was essentially no difference between 150- and 220-grit disc surfaces. As might have been anticipated, the largest change in roughness parameters due to wear was for the polished cases, in which even a small amount of wear-induced roughness was much greater than the initial roughness.

4. Discussion

The experimental results embodied a number of significant findings regarding the effects of surface finish, specimen material reversal, normal force and velocity on friction and wear. Classical approaches to understanding solid friction do not directly address the case where the same materials are used but in opposite geometrical positions. Contributions to solid friction on which most classical models are based involve such things as adhesion, tendencies toward ploughing and the geometry of the interacting asperities.

TABLE IV Surface roughness parameter changes due to wear (average of three directions across the surface at 0, 45 and 90 ° to one another)

Material	Finish	Ratio (worn/unworn)		Running-in period[a] (rev)
		R_q (μm)	delQ (degrees)	
SiC	150-grit	0.54	2.34	73
	220-grit	2.08	4.74	65
	Polished	11.92	17.53	204
Si_3N_4	150-grit	0.64	1.78	151
	220-grit	0.67	1.63	146
	Polished	13.17	34.63	223

[a] Number of disc revolutions to reach steady-state friction.

If mechanical interlocking were the only factor in determining friction, then the discs with the largest initial surface roughness would have the highest initial friction coefficient and, furthermore, the friction would tend to decline as the sharper asperity peaks were truncated during running in. Comparing the initial surface roughness parameters in Table IV with the initial friction coefficients listed in Table V (for 10 N, 0.1 m s^{-1} tests) no systematic correlation between the initial surface roughness and the initial friction coefficient could be found. Four of the six test conditions did show higher initial than steady-state friction; however, of the remaining two, one was polished and the other was coarsely ground. Other factors in this behaviour include the presence of atmospheric contaminants and more-subtle differences in surface topography than the measured parameters could reveal. Since the relative lay of the surface with respect to the sliding direction changed as the disc specimens rotated, there were no systematic effects of lay observed.

There was a pronounced relationship between the length of the running-in period and the change in R_q for the 10.0 N, 0.1 m s^{-1} tests (Fig. 9). The ground

TABLE V Relationship of wear-induced surface roughness changes to frictional behaviour

Material	Finish	Coefficient of friction		Change in R_q from wear[a] (μm)
		Initial	Steady State	
SiC	150-grit	0.59	0.60	0.307
	220-grit	0.66	0.50	0.273
	Polished	0.65	0.54	− 0.437
Si_3N_4	150-grit	0.69	0.55	0.177
	220-grit	0.72	0.49	0.147
	Polished	0.51	0.53	− 0.243

[a] Pretest surface minus post-test track roughness; average of four tests, stylus traces in three directions on each disc specimen.

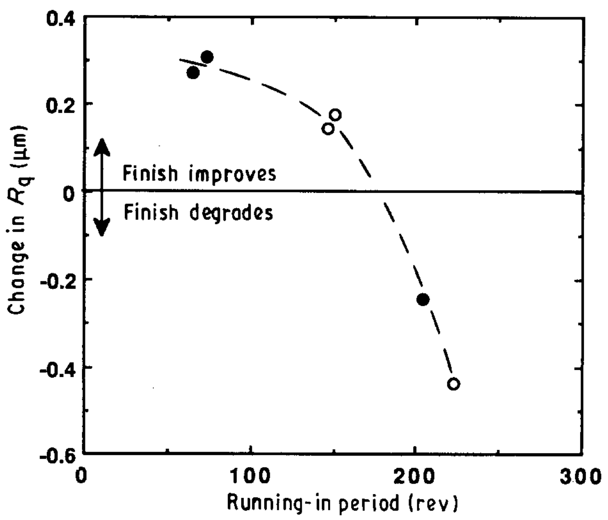

Figure 9 Relationship between running-in period and change in R_q, load 10 N, velocity 0.1 m s^{-1}, average of four tests: (o) SiC/SiN and (●) SiN/SiC.

surfaces became smoother and the polished surfaces rougher due to wear. An interesting implication of this behaviour is that a running-in period of about 175 revolutions would occur even if there were no change in R_q. Therefore, it may not always be possible to define frictional run-in strictly in terms of a measurable change in R_q. Perhaps a less ambiguous roughness parameter could be found. Bengtsson and Ronnberg [9] attempted to find a satisfactory roughness parameter to measure run-in using reciprocating sliding of flat blocks, but of the five parameters they examined none was completely unambiguous in defining the completeness of run-in.

Fig. 10 shows worn disc surfaces, some of which exhibit some traces of the initial surface features, including the direction of the grinding marks (lay). Implications for wear models that incorporate surface roughness parameters, such as that of McCool [3], are that, depending on the material wear rate, the initial surface roughness parameters may not correspond in any meaningful way to those present during the majority of the lifetime of the component and that any apparent correlation with the initial roughness parameters in such cases would be fortuitous.

To determine whether frictional heating played a significant role in the wear of the different ceramic couples, a computer program (T-MAPS) written by Ashby *et al.* [10] was employed. The output of the program is a plot of bulk and flash temperature contours as a function of normalized velocity and normalized pressure. The calculation is explained further in Appendix B. Fig. 11a and b plots the three test conditions (loads and velocities) and the two material combinations used in this study on temperature maps. Measured average friction coefficients and material hardness values were used in these calculations. Calculated bulk temperatures in all cases were $< 50\,^{\circ}\mathrm{C}$. The SiC/SiN couple had the highest localized flash temperature (about $400\,^{\circ}\mathrm{C}$), but the wear of the pin specimens in this couple was almost one-tenth that of the pin wear for the couple with the lower flash temperatures. Disc wear was similar for both couples. Based on these calculations, temperature was found not to be a conclusive factor for determining the wear of either pins or discs.

Temperature rises are only one manifestation of the dissipation of sliding energy. A more fundamental quantity, which assumes no *a priori* partitioning of the sliding-induced thermal energy, is the friction force–velocity (Fv) product. In the present case its units are $\mathrm{N\,m\,s^{-1}}$, in other words, the rate of energy expenditure. This quantity turned out to be extremely useful in understanding the relative increase in wear rates that occurred as the sliding velocity increased. Fig. 12 is a plot of the Fv ratio for 0.5 and $0.1\ \mathrm{m\,s^{-1}}$ velocity tests versus the corresponding ratio of the pin

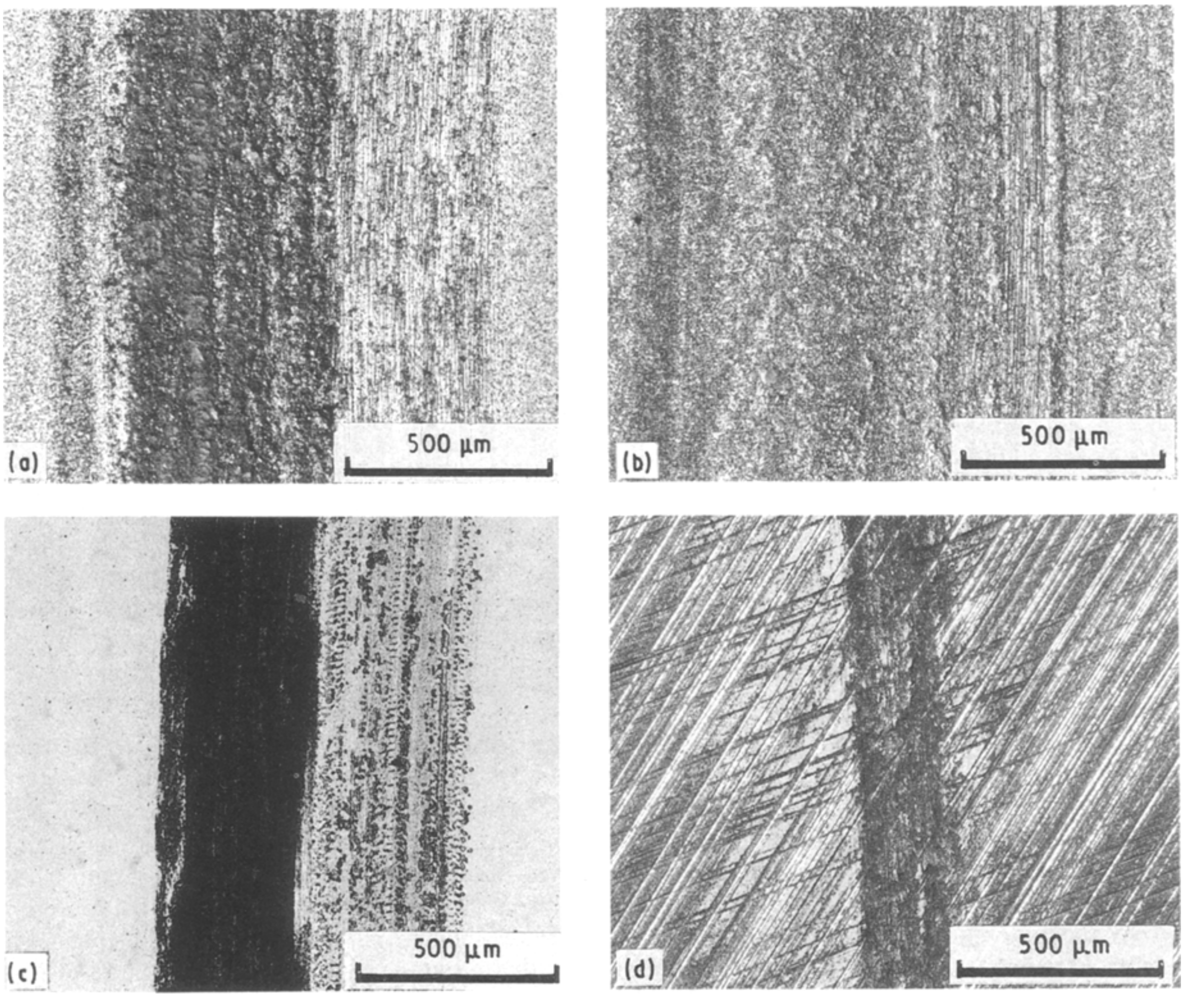

Figure 10 Worn disc surfaces: (a and b) SiC and (c and d) SiN; (a and c) polished and (b and d) 220-grit ground.

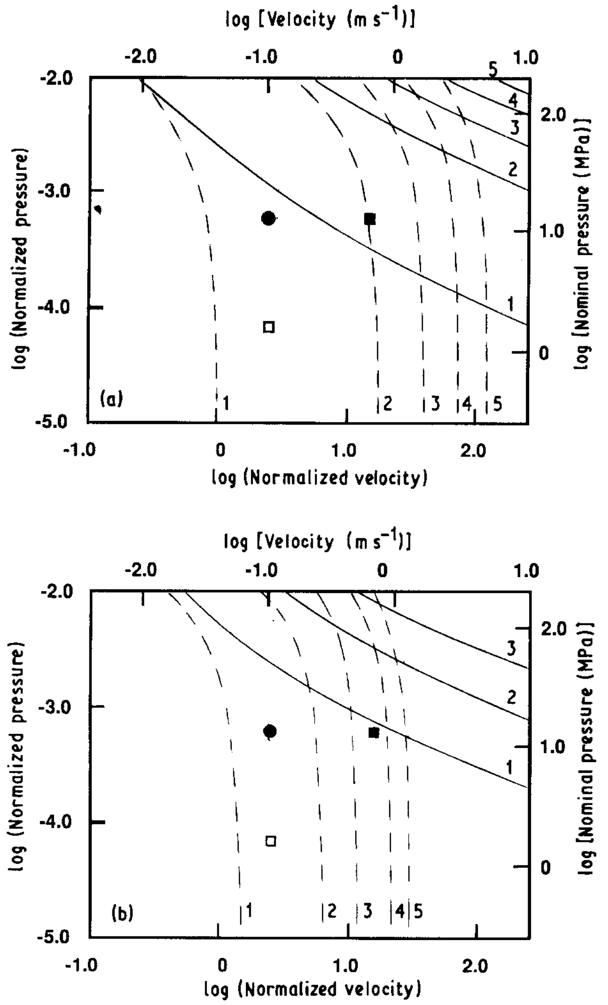

Figure 11 Temperature maps for the three test conditions and the two material combinations used in the study. (a) 1, 50; 2, 150; 3, 300; 4, 450; 5, 650 °C. (b) 1, 30; 2, 100; 3, 200; 4, 350; and 5, 550 °C.

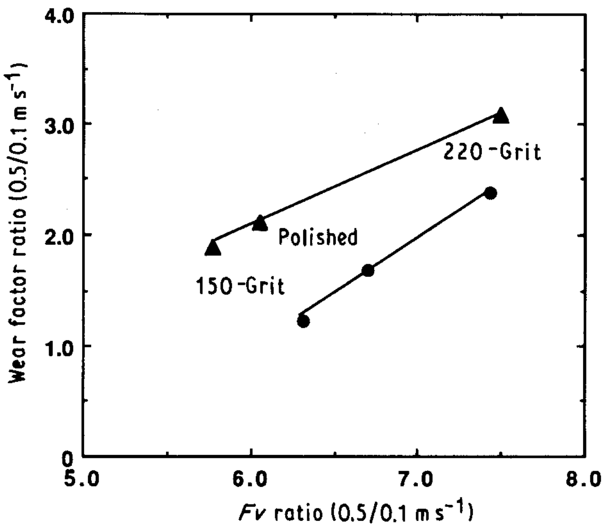

Figure 12 Relationship between *Fv* ratio and wear factor ratio, load 10 N, velocity 0.1 and 0.5 m s^{-1}, average of four tests: (●) SiN/SiC and (▲) SiC/SiN.

wear factors for those tests. A linear relationship occurs for both material pairings and, interestingly (as shown by the annotations on Fig. 12), there was no apparent correlation with the initial disc surface finish.

Based on the present results, it is concluded that the quantity *Fv* is a meaningful one in terms of understanding the manner in which frictional energy is dissipated. The fact that the *Fv* line for SiC/SiN is above that for SiN/SiC means that the wear rate is more sensitive to velocity for the former specimen configuration, i.e. when the material with higher thermal conductivity is used as the slider (nominally constant contact) than as the disc (each point on the wear path experiences intermittent sliding contact). Since the flash temperature for the SiN/SiC case is predicted to be higher than that for SiC/SiN, the greater velocity sensitivity of SiC/SiN cannot be justified in terms of temperature rise. Instead, the frictional energy available to produce wear must be partitioned into the creation of new surface (by microcrack initiation and growth) and into the creation, storage and movement of lattice point and line defects within the near-surface layers. In the presence of wear debris there may be yet another contribution, namely the energy required to shear the debris compact and permit relative motion to continue.

5. Conclusions

Experiments on the effects of specimen reversal, surface finish, load and velocity on silicon nitride and silicon carbide friction and wear have led to the following conclusions.

The friction and wear behaviour of SiC/SiN sliding combinations depended on which was the pin material and which was the disc material.

Both lower normal forces or higher sliding velocities resulted in higher sliding friction for both material couplings, but there was little effect of surface finish on the steady-state friction coefficient.

Running-in periods in all three surface finishes were longer for SiN/SiC couples. The running-in periods were not greatly affected by grinding grit size in both material couples, but they were much longer for the polished condition than for the ground condition.

The running-in period was related to the change in R_q resulting from wear. Ground surfaces grew smoother whereas polished surfaces grew rougher during wear.

No direct correlation of wear results could be made with the calculated flash or bulk temperatures, but the effect of higher velocity on raising the wear rates was clearly related to the ratios of the *Fv* products for those tests. Energy dissipation into doing work on the material rather than into sensible heat is the suggested explanation.

Appendix A: Effects of relative humidity on friction and wear

The relative humidity of the laboratory was routinely measured with a wet/dry bulb hygrometer during wear testing. Values varied between 45 and 69% for the present experiments. Due to an initial concern that relative humidity fluctuations over the course of the testing programme might influence the results, plots were made of the friction and wear versus relative humidity to see whether any trends emerged. Fig. A1

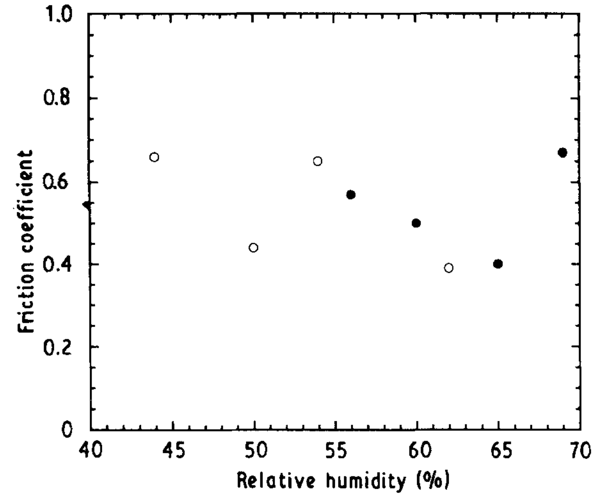

Figure A1 The steady state friction coefficient did not show a correlation with relative humidity for either sliding combination.

shows friction coefficients for four tests of each material pairing at 10.0 N load and 0.1 m s^{-1} velocity on polished disc surfaces. Moisture was expected to have the most pronounced effects, if any, on polished surfaces. Figs A2 and A3 are similar plots of pin wear factors and disc wear factors, respectively, as functions of relative humidity. No obvious effects of relative humidity on either friction or wear are indicated for the range of conditions in which the current work was performed. Work such as that in References 6 and 7, however, describes significant humidity and moisture effects on the wear and friction of ceramics such as alumina and silicon nitride, especially in the extremes of very low or very high relative humidities.

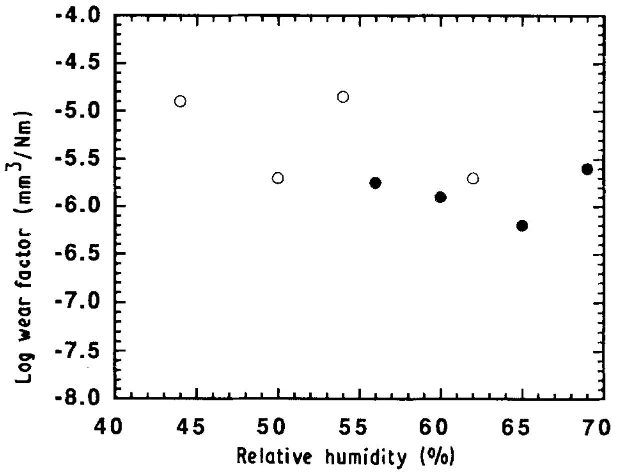

Figure A2 The wear factors of the silicon nitride pins and the silicon carbide pins were not humidity-dependent within the range of % RH experienced in these tests.

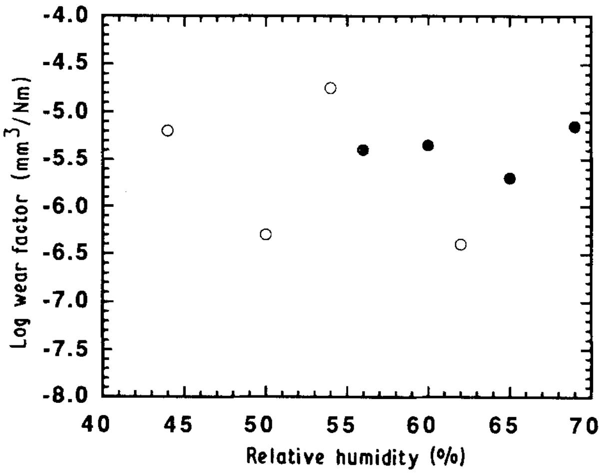

Figure A3 No correlation between relative humidity and disc wear factors was observed in these tests.

Appendix B: Calculation of bulk and flash temperature

The T-MAPS, Version 2.0, desktop computer software used to calculate bulk and flash temperatures for this paper was developed by M. F. Ashby, J. Abulawi and H. S. Hong of the Engineering Department, Cambridge University, UK. It is based on the original derivation by Lim and Ashby [10] for pin-on-disc tests. Only the normalized parameters used for the plotting axes are defined here. For the details of the derivation, its assumptions and its limitations, the reader is referred to [10].

Two parameters are used in the wear map: the normalized pressure (F_n) and the normalized velocity (V_n). The normalized pressure is defined as the applied force (P) divided by the nominal contact area (A_n) and the hardness of the softer of the two surfaces in contact (H_0)

$$F_n = P/H_0A_n \qquad \text{(B1)}$$

The normalized velocity takes into account the thermal consequences of frictional heating as the velocity increases by incorporating the effective thermal diffusivity (a_e)

$$V_n = vr_0/a_e \qquad \text{(B2)}$$

where v is the sliding velocity and r_0 is the radius of the nominal contact area. a_e is defined as the average of the thermal conductivities of the materials in contact.

It should be pointed out that various assumed quantities, such as the distance from the heat source to the heat sink and the average radius of contacting asperities, are required for the calculation and, without prior knowledge of these quantities for the materials involved, we kept them constant for both cases (SiC/SiN and SiN/SiC). The nominal contact radius was assumed to be 500 µm, the asperity radius to be 2.0 µm and the friction coefficient to be 0.50.

The Lim and Ashby model can be modified to account for thin surface films (i.e. oxides on sliding metals), but has not been developed to account for the presence of debris layers. It is expected that wear debris would alter the heat flow pattern significantly and may invalidate many of the assumptions used to develop the model. Having frequently observed debris generation when conducting the subject tests, the Lim and Ashby model may not provide the type of analysis required in many cases.

Acknowledgements

This work was supported by the Office of Advanced Transportation Materials, Tribology Project, US Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. All specimen materials were supplied through a subcontract with SKF–MRC Bearings, John McCool, Principal Investigator. The help of C. E. DeVore (Oak Ridge National Laboratory) and Devon C. Stair (Washington State University, Pullman, Washington) is greatly appreciated.

References

1. P. J. BLAU, "Friction and wear transitions of materials" (Noyes, Park Ridge, New Jersey, 1989).
2. J. I. McCOOL, *Wear* **107** (1986) 37.
3. *Idem*, in "Mechanics of coatings", edited by D. Dowson, C. M. Taylor, and M. Godet (Elsevier, Amsterdam, 1990) p. 157.
4. P. J. BLAU, *Wear* **151** (1991) 193.
5. H. CZICHOS, S. BECKER and J. LEXOW, *ibid.* **114** (1987) 109.
6. T. E. FISCHER and H. TOMIZAWA, in Proceedings of the International Conference on Wear of Materials, Vancouver, Canada, April 14–18, 1985 (ASME, New York, 1985) p. 22.
7. N. WALLBRIDGE, D. DOWSON and E. W. ROBERTS, in Proceedings of the International Conference on Wear of Materials, Reston, Virginia, April 11–14, 1983 (ASME, New York, 1983) p. 202.
8. P. J. BLAU, in "*Detection, diagnosis and prognosis of rotating machinery*", edited by Shives and Mertaugh (Cambridge University Press, Cambridge, 1988) p. 61.
9. E. J. BENGTSSON and A. RONNEBERG, *Wear* **109** (1986) 329.
10. D. S. LIM and M. F. ASHBY, *Acta Metall.* **35** (1987) 1.
11. W. J. LACKEY, D. P. STINTON, G. A. CERNY, L. L. FEHRENBACHER and A. C. SCHAFFHAUSER, in Proceedings of the International Symposium on Ceramic Components for Heat Engines, Hakone, Japan, October 17–19, 1983, edited by S. Somiya, E. Kanai and K. Ando (KTK Scientific Publishers, Tokyo) p. 770.

Received 1 May
and accepted 12 September 1991