

DOE/NASA/50306-3
NASA TM-106348

111-50
191152
13P

The Friction and Wear of Ceramic/ Ceramic and Ceramic/Metal Combinations in Sliding Contact

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(NASA-TM-106348) THE FRICTION AND
WEAR OF CERAMIC/CERAMIC AND
CERAMIC/METAL COMBINATIONS IN
SLIDING CONTACT (NASA) 13 p

N94-15769

Unclass

October 1993

G3/23 0191152

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

THE FRICTION AND WEAR OF CERAMIC/CERAMIC AND CERAMIC/METAL COMBINATIONS IN SLIDING CONTACT

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SUMMARY

The tribological characteristics of ceramics sliding on ceramics are compared to those of ceramics sliding on a nickel-based turbine alloy. The friction and wear of oxide ceramics and silicon-based ceramics in air at temperatures from room ambient to 900 °C (in a few cases to 1200 °C) were measured for a hemispherically-tipped pin on a flat sliding contact geometry. In general, especially at high temperature, friction and wear were lower for ceramic/metal combinations than for ceramic/ceramic combinations. The better tribological performance for ceramic/metal combinations is attributed primarily to the lubricious nature of the oxidized surface of the metal.

INTRODUCTION

Ceramics are serious contenders for use as bearing and seal materials because of their high melting point, chemical inertness, and in some cases their low density. High melting point is important in low heat rejection diesel engine and turbine engine applications. The oxide ceramics, in particular are inert to oxidative attack at high temperature. The light weight of some ceramics is especially attractive for components requiring low dynamic inertia such as those in valve trains.

Reported results of tribological studies of ceramic/ceramic combinations have been disappointing. Friction coefficients are generally high, on the order of 0.5 to 1.0 (refs. 1 and 2). Also, wear rates are often high in spite of a polished surface finish prior to sliding and the high hardness level of many ceramics. A frequently observed wear mode is one of microfracture, typically grain boundary fracture. The causative factors for this wear mode in ceramics appear to be low tensile strength coupled with low ductility and high friction. Friction during sliding generates tensile stresses in the plane of the sliding surface (refs. 3 and 4). These tensile stresses initiate cracks that propagate along grain boundaries. The grains debonded from the structure work out of the surface in the form of microfracture wear debris that is further attrited during continued sliding.

It is the purpose of this paper to compare the friction and wear properties of ceramic/metal sliding pairs with those of ceramic/ceramic pairs. Some metal alloys are known to form oxide surface films that are lubricious at high temperature. For example, some nickel base and cobalt base turbine alloys exhibit much lower friction and wear in air at high temperature than at low temperature because of the lubricating property of their naturally formed oxides when hot (ref. 5). Also, it has been shown that doping of certain ceramics by ion mixing with metals that form lubricious oxides reduces high temperature friction compared to the undoped ceramic (ref. 6). Further, recently reported studies show that alloying ceramics with titanium carbide or nitride improves frictional properties under oxidizing conditions via the formation of lubricious titanium dioxide on the surface under hot, oxidizing conditions (ref. 7). It appears reasonable, therefore to expect that some ceramic/metal combinations might have improved friction and wear properties compared to the same ceramics sliding against themselves or another ceramic.

The scope of the research reported in this paper includes the results of bench tests to measure the friction and wear of ceramics sliding against themselves and against a nickel base alloy, Inconel 1718. Tests temperatures were 25 to 800 °C in air.

MATERIALS

Metal Alloy

Inconel 718.—This is a nickel-chromium alloy that is precipitation hardened to $H_v = 520 \text{ kg/mm}^2$ at a 100-g indenter load. The nominal chemical composition by weight percent is: Ni 53, Cr 18.5, Fe 18.5, Nb 5, Mo 3.1, Al 0.4, Si 0.3, Mn 0.2, and C 0.04.

Oxide Ceramics

Typical chemical compositions and physical properties of the oxide ceramics are listed in table I. They are further described below.

Mullite.—Mullite is a mineral name for the stoichiometric composition $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$. The material tested in this program is a commercial grade of mullite consisting of mullite and another phase. EDS spot analyses and XRD show that the microstructure consists of crystalline mullite cemented with a silica glass that contains substantial amounts of K, Ti, and F. This type of structure is common to many ceramics. The mullite tested in this program is very porous with only 84 percent of full density. The porosity contributes to a rough surface of 1 to 1.3 $\mu\text{m rms}$ and is the roughest material tested.

Alumina (aluminum oxide).—This is a sintered, polycrystalline, high purity, fully-dense commercial grade of aluminum oxide, Al_2O_3 . It contains traces of Fe_2O_3 and TiO_2 . XRD analyses reveals an alpha aluminum oxide crystal structure. Surface finish is 0.25 to 0.4 $\mu\text{m rms}$.

Aluminum oxide-silicon carbide whisker composite.—This material is a commercial composite of alumina containing 25 vol% SiC whiskers. The whiskers are 0.25 to 1.25 μm in diameter and are 5 to 12 μm long. XRD reveals alpha alumina and alpha SiC. The material is fully-dense and has a surface finish of 0.1 to 0.2 μm .

Partially stabilize zirconia.—This is a transformation toughened material. It is designated by the supplier as the MS or maximum strength grade. The stabilizers are MgO and HfO_2 . XRD and microstructural analyses reveal that the matrix has a cubic crystal structure with fine, ellipsoidal-shaped tetragonal precipitates uniformly dispersed in the cubic grains. A monoclinic phase also exists within these grains and at the grain boundaries. Porosity is 1 to 2 percent in the form of fine pores.

Silicon Ceramics

Properties of the silicon-base ceramics in this study are listed in table I.

Silicon nitride, (Si_3N_4).—This ceramic contains 8 percent Y_2O_3 , tungsten, and magnesium. XRD shows a minor WSi_2 phase and a predominate beta- Si_3N_4 phase. Surface roughness is 0.25 to 0.38 $\mu\text{m rms}$.

Silicon carbide (SiC).—This is a sintered material with the alpha SiC crystal structure. It is highly stoichiometric with no excess Si. The microstructure is only very slightly porous and the material is extremely hard with a typical $H_v = 2500$. Surface roughness is 0.25 to 0.38.

EXPERIMENTAL PROCEDURE

Friction and wear tests were performed using a pin on disk specimen geometry. Some reference data from previously reported tests using a double rub block on disk specimen geometry are included for comparison (ref. 8). Detailed studies of ceramic rub blocks sliding on Inconel 718 disks are reported in references 9 and 10. Schematics of both specimen geometries are shown in figure 1. Friction is recorded continuously during each test duration of 1 hr. After each test, wear volumes are calculated from the diameters of the circular wear scars worn on the hemispherically tipped pins and from profilometer traces of the worn surfaces of the disks.

The unit of wear in this paper is the wear factor, k , which is defined as the wear volume divided by the product of the load and the sliding distance. The algebraic expression is:

$$k = (\text{mm})^3 (\text{Nm})^{-1}$$

The use of this factor implies that the wear volume is linearly proportional to the load and to the sliding distance. Although this assumption is an over-simplification, it has been found to be reasonable for a range of loads and sliding velocities over which the wear mechanism does not change. Comparison of wear factors allows one to estimate the relative wear resistance of various sliding combinations tested under identical conditions. The factors can also be used predictively with fair success when the wear mechanism in the application is the same as that in the tests used to obtain the k factors. The wear mechanisms for known combinations of speed and load can sometimes be predicted from published wear maps (e.g., refs. 11 and 12). If wear maps for the material combination are not available, the similarity of wear mechanisms in the test and in the application may be determined by comparative microscopic examination of the worn surfaces.

Wear factors in this study varied from 10^{-3} to 10^{-7} mm^3/Nm with 10^{-3} indicating unacceptably high wear for any application, and 10^{-5} or lower (depending on wear rate requirements) needed for engineering applications. Wear is measured with a surface profilometer equipped with an area measuring computer program. Wear factors are presented as bar graphs in this paper. Where replicate tests were performed, the top of each data bar is the average of two or three tests and the error bar is the maximum wear factor in the data scatter.

EXPERIMENTAL RESULTS AND DISCUSSION

The friction and wear characteristics of oxide-base and of silicon-base ceramic/ceramic pairs were determined in air at temperatures from room ambient to 900 °C (in a few tests to 1200 °C). The friction and wear of alumina-base ceramic/metal combinations were also determined for comparison with the results for the corresponding ceramic/ceramic pairs.

Variable Temperature Experiments

Friction coefficients for monolithic alumina against itself and against Inconel 718 are compared in figure 2(a). The experiments were conducted under relatively mild conditions of a 4.9 N load and a 0.38-m/s sliding velocity. Friction coefficients are very high for the ceramic/ceramic pair beginning at 0.60 ± 0.10 (very erratic) at room temperature and steadily increasing with temperature to above 1.0 at 900 °C. The friction coefficient for the ceramic/metal pair is about the same as that of the ceramic/ceramic pair at room temperature, but remains constant with increasing temperature to around 500 °C, then drops dramatically to 0.3 ± 0.03 at 750 and 900 °C. This marked decrease in friction coefficient corresponds to the conditions at which an adherent nickel-chromium oxidation product forms on the wear track of the Inconel 718 disk.

Analogous experiments were performed with alumina composites containing 25 wt% of SiC whiskers. A similar effect of friction reduction by metal oxides is seen in figure 2(b). However, the beneficial effect on friction is much less than it is for monolithic alumina. This may be due to the abrasive action of the SiC whiskers in more rapidly wearing away the metal oxides as they form.

The beneficial effect of metal oxidation products has been frequently observed and found to be quite general for turbine alloys in sliding contact under hot oxidizing conditions (e.g., ref. 5). Figure 3 from reference 8 shows that for three silicon base ceramics, three oxide base ceramics, and Inconel 718 rub blocks sliding against Inconel 718 disks, the friction coefficient is sharply reduced under hot, oxidizing conditions. While friction coefficients vary considerably for the different materials at room temperature, they are nearly identical at 800 °C. We conclude that the oxides on the nickel-chromium alloy are lubricous and control the friction of all these sliding material combinations at 800 °C.

Constant Temperature Experiments

A series of tests were performed in order to obtain pin and disk wear factors k_p and k_d and a measure of the scatter in friction coefficients during tests of 1 hr duration at various constant temperatures. These tests were run at a higher sliding velocity and a higher load than were the ramped, variable temperature tests. The tests were at a load of 10 or 27 N and a sliding velocity of 2.7 m/s. The wear mode was found to be the same at 10 and 27 N. Therefore, the data are combined for tests at the two loads.

Alumina base ceramics.—Figure 4(a) gives the friction-temperature characteristics of the alumina base ceramics: aluminum silicate (mullite), alumina, and alumina with 25 wt% SiC whiskers. Average friction coefficients for monolithic alumina is around 0.5 to 0.7 at all temperatures. Friction is about the same for the alumina-SiC composites but much more erratic with large scatter bands in the data. Friction coefficients for mullite are substantially lower in the range of about 0.35 to 0.50 from room temperature to 800 °C, and very steady with small scatter bands in the data. This may be attributed to the relatively low hardness of mullite ($H_v = 950$) compared to alumina ($H_v = 1606$) and alumina-25 SiC ($H_v = 2200$). However, the lower hardness of mullite may be expected to result in higher wear. The wear factor data of figures 4(b) and (c) show that this is the case. The pin and disk wear factors are seen to be considerably higher than they are for alumina, which in turn wears more rapidly than the alumina-SiC composite.

Mullite on Inconel 718.—Figure 5(a) compares the friction at 25 and 800 °C of: (1) mullite pins on mullite disks; (2) Inconel 718 pins on mullite disks; and (3) the reverse configuration of mullite pins on Inconel 718 disks. Friction coefficients are the same for both metal versus ceramic configurations. At 25 °C, friction is about 20 percent higher for the ceramic versus metal configurations than for mullite on mullite.

At 800 °C, on the other hand, friction is lower for the ceramic versus metal pairs compared to mullite on mullite. This is consistent with the results from rub block on disk tests shown in figure 3 from reference 8. The lower friction at 800 °C is attributable to the formation of lubricous oxides on Inconel 718 at high temperature.

Pin and disk wear factors are shown in figures 5 (b) and (c). Wear factors for pins and disks are lower at 25 °C and at 800 °C for mullite on Inconel 718 than for mullite versus mullite.

Alumina-25 SiC composite on Inconel 718.—Figure 5(a) shows that in contrast to the results with mullite, the specimen configuration has a strong influence on friction at 800 °C. Metal oxidation did not have a beneficial effect for Inconel pins on composite disks, but did provide a substantial benefit for the reverse specimen configuration. Apparently, the composite abraded the metal oxide on the small, continuous contact area of the metal pins at too high a rate for a lubricous film to develop. The relatively large, discontinuous contact area on the metal disks however, allowed an adequate lubricous oxide film to develop.

Wear factors are given in figures 5 (b) and (c). Although metal oxidation reduced friction for the composite pin versus metal disk geometry, it did not provide an equivalent benefit in reducing metallic wear. In general, composite wear was low and metal wear was high for this material combination.

Partially stabilized zirconia, silicon carbide, and silicon nitride.—Figures 6 (a) and (b) show that these three ceramics have characteristically high friction coefficients at all test temperatures. Friction coefficients for Si_3N_4 is the highest overall averaging about 0.7 at room temperature and exceeding 0.8 at 400 and 800 °C. Friction coefficients for SiC are consistently about 20 percent lower. The scatter bands on the data show that the friction is moderately erratic during the duration of the tests. The friction coefficients for zirconia are also very high and considerably more erratic than for silicon carbide and silicon nitride.

Wear factors are given in figures 6 (c) and (d). Wear is moderate to high in most cases. Exceptions are the surprisingly low pin and disk wear of SiC at room temperature and the low disk wear of zirconia at room temperature.

The high friction and wear of ceramics sliding on ceramics has been reported by others (refs. 1 and 2). This study further confirms the critical need for suitable lubrication of ceramics if they are to be used as sliding contact bearing materials. It is known that high friction coefficients markedly increase surface tensile stresses within the sliding contacts of brittle materials (refs. 3 and 4). The high localized tensile stresses are largely responsible for the microfracture wear mode common in ceramics. In this study, we show that friction and wear of ceramics is less for ceramics sliding on a nickel-chromium turbine alloy than against a like ceramic counterface material. This is especially apparent under hot oxidizing conditions where lubricous oxides form on turbine alloys.

CONCLUSIONS

1. Under most sliding conditions, unlubricated ceramics as a class exhibit high friction and wear.
2. Under hot, oxidizing conditions, friction and wear are considerably lower for ceramics sliding on a nickel-chromium alloy (Inconel 718) than for ceramics sliding against a like ceramic counterface.

3. Tenacious nickel-chromium oxide films are lubricous at high temperature for the monolithic-ceramic/metal combinations studied in this program. Less benefit is seen for a composite of alumina with 25 vol% SiC whisker content, probably because the metal oxide film is abraded away by the SiC whiskers.

4. The generally poor friction and wear properties of unlubricated ceramics emphasizes the need for additional research to develop lubricative coatings or surficial treatments for them. This is especially important in order to exploit the high temperature stability of ceramics in practical sliding contact applications.

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TABLE I.—COMPOSITION AND PROPERTIES OF CERAMIC WEAR SPECIMENS

Material	Composition	Phases detected by XRD	Tested surface roughness	Bulk den-g/cm ³	Vickers hardness at 25 °C, kg/mm ²
Mullite (sintered)	27.5Al, 0.3Fe 19.1Si, 0.5Ti	Mullite (3 Al ₂ O ₃ ·2SiO ₂)	40 to 50 μin. (1 to 1.25 μm)	2.70 ≈84 percent TD ^a	926±56 (100 g load)
Al ₂ O ₃ (polycrystalline, sintered)	52.6Al, <0.05 ppm Fe <0.03 ppm Ti	α-Al ₂ O ₃	10 to 15 μin. (0.25 to 0.38 μm)	3.78 ≈95 percent TD	1607±8 (100 g load)
Al ₂ O ₃ +25 vol% SiC whiskers (hot pressed)	25 vol% SiC 75 vol% Al ₂ O ₃	α-Al ₂ O ₃ α-SiC	4 to 5 μin. (0.1 to 0.12 μm)	3.73 3.74	2193±30 (100 g load) 2125
ZrO ₂ PSZ (MS-grade) (sintered)	HfO ₂ 2-3 MgO 3.3-3.4 SrO 0.25 max TiO ₂ 0.15 Al ₂ O ₃ 0.03 Fe ₂ O ₃ 120 ppm	Cubic ZrO ₂ Monoclinic ZrO ₂	4 to 5 μin. (0.1 to 0.12 μm)	5.64 5.74 (1 to 2 percent porosity)	1175±149 (100 g load) 1120
Si ₃ N ₄ (C) (hot pressed)	8Y ₂ O ₃	β-Si ₃ N ₄ (S) Y ₂₀ N ₄ Si ₁₂ O ₁₈ (W)	10 to 15 μin. (0.25 to 0.38 μm)	3.25 to 3.29 ≈100 percent TD	1320±102 (100 g load)
SiC (sintered)	SiC 98 B 0.6 Al 0.07 Fe 0.3 C 1	α-SiC	10 to 15 μin. (0.25 to 0.38 μm)	3.13 ≈97.5 percent TD	2418±180 (200 g load)

^aTheoretical density.

(S) Strong

(W) Weak

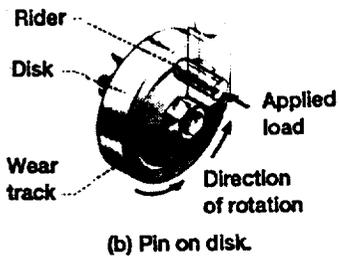
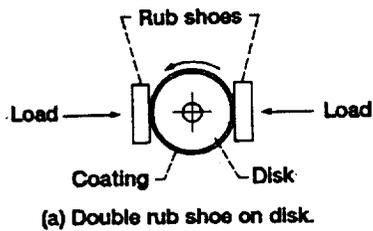


Figure 1.—Friction and wear test specimen configurations.

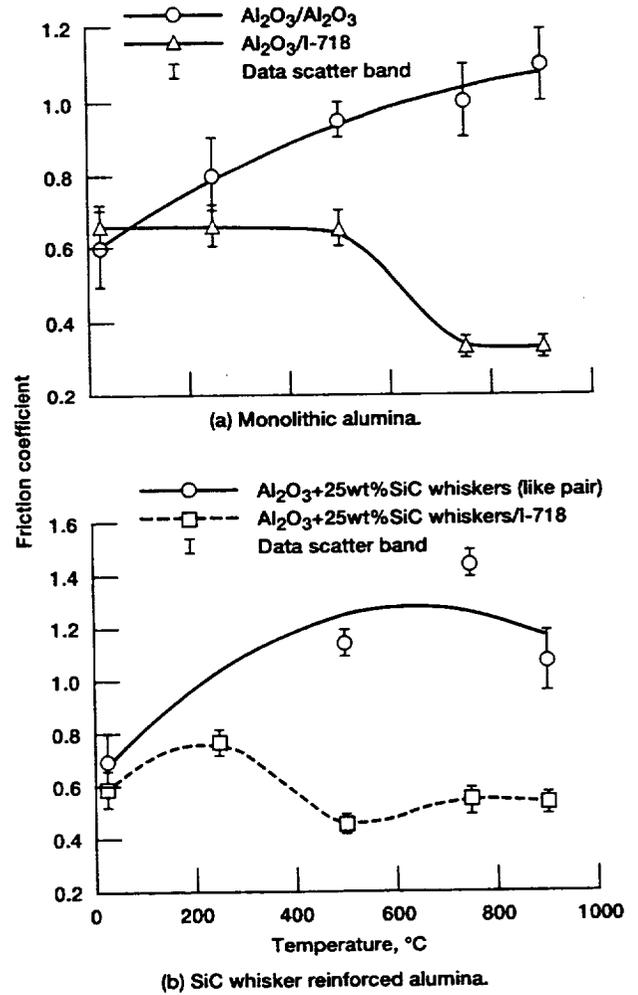


Figure 2.—Comparative friction-temperature characteristics during low velocity pin/disk tests of ceramic/ceramic and ceramic/metal pairs. Air atmosphere, 5N load, 0.38 m/s sliding velocity.

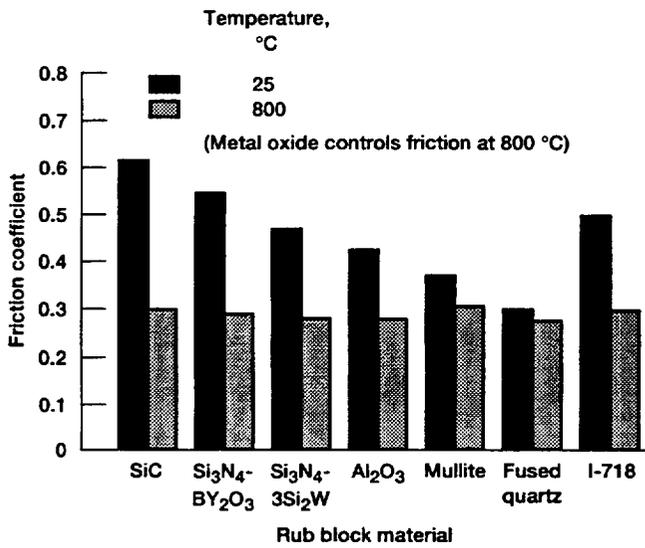
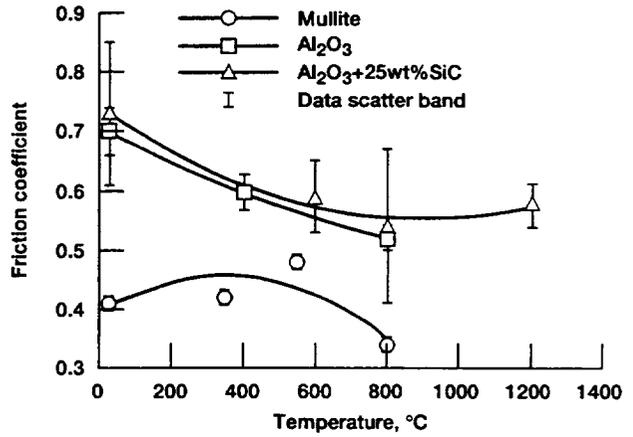
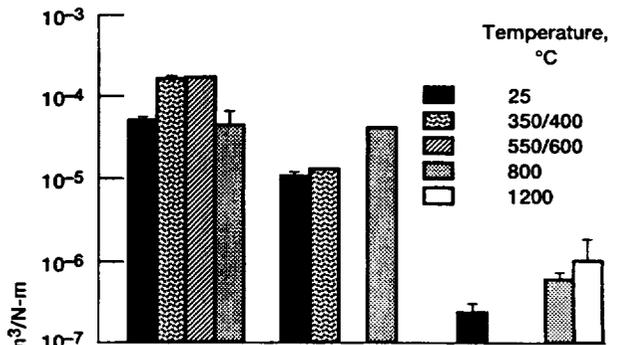


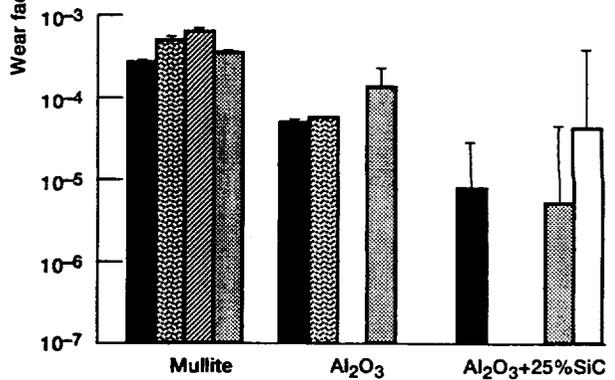
Figure 3.—Friction of various ceramics and of Inconel 718 sliding on Inconel 718 in air (50% R.H.) at room temperature and at 800 °C, 0.18 m/s, 67 N load (from reference 8).



(a) Friction.

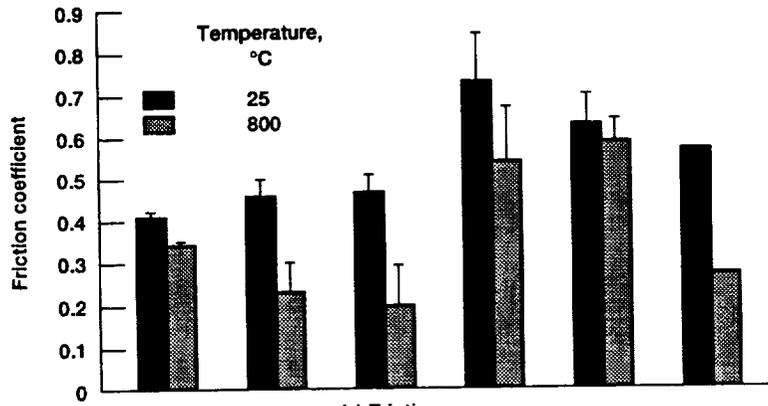


(b) Pin wear.

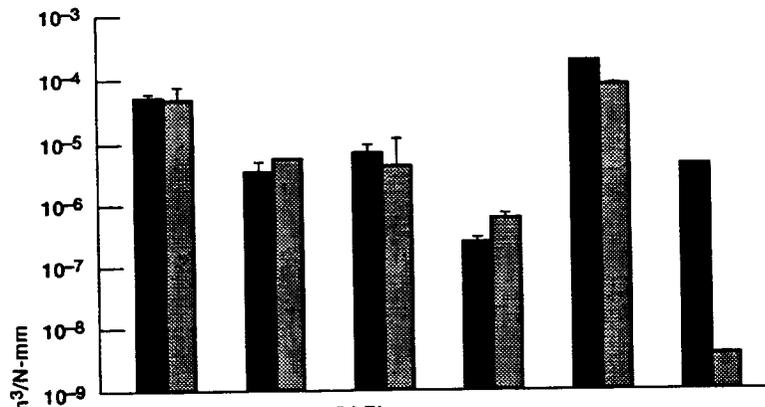


(c) Disk wear.

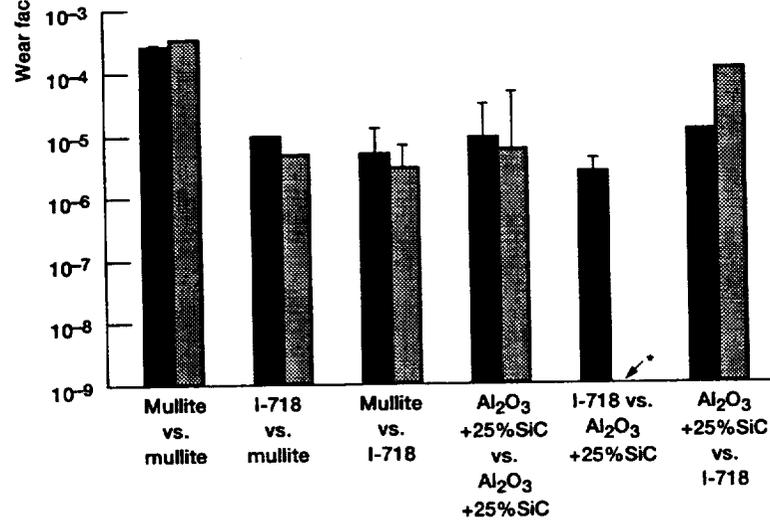
Figure 4.—Friction and wear pin/disk data for like ceramic/ceramic pairs of alumina-based ceramics in air at 2.7 m/s. Note: each bar graph gives average for 2 or 3 tests. Top of error bar is maximum in data scatter.



(a) Friction.



(b) Pin wear.



(c) Disk wear.

Figure 5.—Friction and wear pin/disk for ceramic/metal pairs in air at 2.7 m/s.
 * Transfer of pin material resulted in negative wear factor. Note: Each bar graph gives average for 2 or 3 tests. Top of error bar is maximum in data scatter.

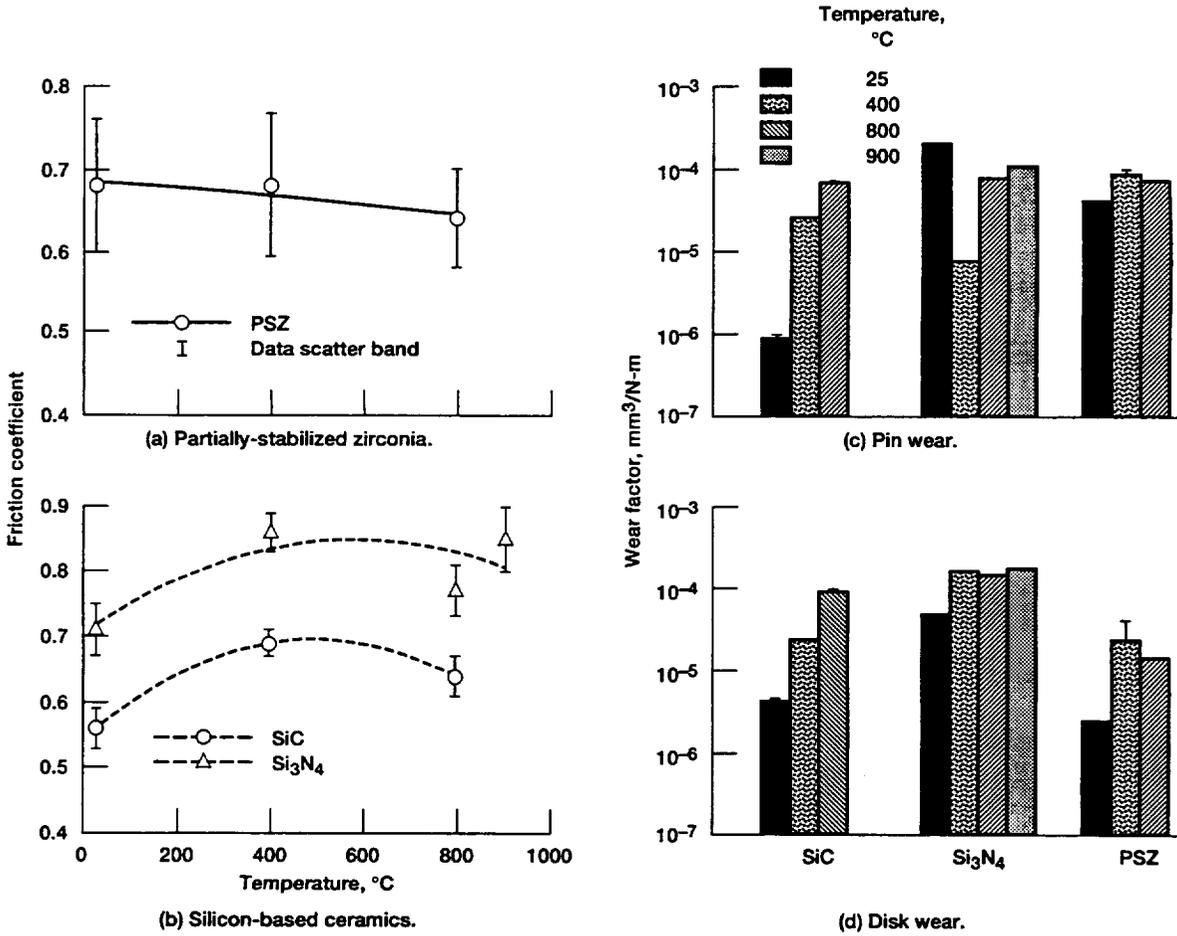


Figure 6.—Friction and wear characteristics for like pairs of monolithic ceramics in air at 2.7 m/s sliding velocity.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 1993	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE The Friction and Wear of Ceramic/Ceramic and Ceramic/Metal Combinations in Sliding Contact		5. FUNDING NUMBERS WU-505-63-5A	
6. AUTHOR(S) Harold E. Sliney and Christopher DellaCorte		8. PERFORMING ORGANIZATION REPORT NUMBER E-8121	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-106348 DOE/NASA/50306-3	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001		11. SUPPLEMENTARY NOTES Prepared for the STLE-ASME Tribology Conference sponsored by the Tribologists and Lubricant Engineers, New Orleans, Louisiana, October 24-27, 1993. Responsible person, Harold E. Sliney, (216) 433-6055.	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 23		12b. DISTRIBUTION CODE DOE-UC-373	
13. ABSTRACT (Maximum 200 words) The tribological characteristics of ceramics sliding on ceramics are compared to those of ceramics sliding on a nickel-based turbine alloy. The friction and wear of oxide ceramics and silicon-based ceramics in air at temperatures from room ambient to 900 °C (in a few cases to 1200 °C) were measured for a hemispherically-tipped pin on a flat sliding contact geometry. In general, especially at high temperature, friction and wear were lower for ceramic/metal combinations than for ceramic/ceramic combinations. The better tribological performance for ceramic/metal combinations is attributed primarily to the lubricious nature of the oxidized surface of the metal.			
14. SUBJECT TERMS Ceramic friction; Ceramic wear; Ceramic/ceramic tribology; ceramic/metal tribology		15. NUMBER OF PAGES 12	
17. SECURITY CLASSIFICATION OF REPORT Unclassified		16. PRICE CODE A03	
18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

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Space Administration**

**Lewis Research Center
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