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TRIBOMATERIAL FACTORS IN SPACE MECHANISM BRAKE PERFORMANCE

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ABSTRACT

The asbestos/phenolic pads of SRMS brakes are unsuitable for use in long-life space mechanisms because their friction decreases on extended sliding in high vacuum. Dehydration of the material and accumulation of wear debris in the conforming interface of this tribosystem induces the permanent friction changes. Other polymer and some ceramic based materials exhibit similar frictional torque behaviour due to the development of minimal contact patches by the interfacial debris. In contrast, high friction occurs when other ceramics form many small contacts throughout fine debris beds. Generating this latter interfacial structure during run-in ensures that the in-vacuo friction remains stable thereafter. Such materials with low wear rates are potential candidates for friction elements in SSRMS and similar mechanisms.

INTRODUCTION

The friction elements of Shuttle Remote Manipulator System (SRMS) brake and clutch assemblies are pairs of annular pads of an asbestos/ phenolic composition. These components meet all the performance requirements, such as those of back-up arrest of arm motion or joint holding, anticipated for short duration Shuttle missions. However, when extensively slip tested under load, these pads can exhibit a greatly diminished friction output in-vacuo [1,2], which fully recovers on return to atmosphere. It was initially thought that this was an anomaly which occurred unpredictably when sliding in vacuum. However, it is now known [3] that a reduced friction torque is the normal output from this tribosystem after equilibrium in the vacuum environment has been attained. This torque variability means that asbestos/phenolic material is not suitable for friction elements in mechanisms subject to long exposure to space vacuum, such as those of the Space Station Remote Manipulator System (SSRMS).

Studies have been carried out to seek materials which will exhibit stable, high friction behaviour in this conforming contact in high vacuum. Simulation testing is described and the results for both SRMS brake, and these other, materials are presented and discussed in relation to the wear debris microstructure which develops at the sliding interfaces in this tribosystem.

EXPERIMENTAL

The materials investigated included polymeric and ceramic based composites, ceramic coatings and cermets. Ring specimens bonded to, or coatings sprayed on, backing discs were ground flat and test surfaces lapped with diamond slurry (ceramics) or SiC paper(polymerics).

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A high vacuum tribometer, Figure 1, was evolved to simulate both the chemical environmental aspects (air, vacuum and residual gas species) and mechanical ones such as load, sliding speed and, most importantly, the contact geometry, self-alignment and stiffnesses of the mechanism components. The friction and wear behaviour of materials was determined from tests involving continuous unidirectional, or bi-directional (60s CW/10s off/60s CCW), sliding of one specimen against the other at 100 r.p.m. under normal loads up to 70 N (bearing pressures to ≈ 0.14 MPa) for long periods. Although speed and loads were similar to those of SRMS operation and qualification slip testing [1], the present simulation was both more intensive, because of the higher rate of slip accumulation, and much more extensive.

Tests were performed under hydrocarbon-free conditions, below 1.3×10^{-4} Pa (10^{-6} Torr). Friction torque was monitored throughout all experiments and wear was measured by specimen weight loss. Specimen surfaces were examined by optical and scanning electron microscopy, and by stylus profilometry.

RESULTS AND DISCUSSION

SRMS Brake Material

Extended in-vacuo sliding friction trends for the asbestos/phenolic brake pad specimens (under SRMS loading of 43N) are shown in Figure 2. Whether from unidirectional or bi-directional sliding, these components typically exhibit a drastic reduction in friction torque to about 20% of the run-in value, followed by a slow but only partial, recovery to some value below the minimum allowable level. Even then, further small decreases can occur in frictional torque output, either spontaneously or after some event disturbing the tribosystem.

It has been shown previously [2] that the first stage of this friction torque characteristic, i.e. the drop to minimum levels, is initiated by a reduction in the water vapour concentration available to the sliding interface upon dehydration of the hygroscopic brake composition. The variable onset of the torque drops in Figure 2 reflects different degrees of moisture saturation of the brake material specimens. Although drying must precede it in SRMS material, the low slip torque regime develops as a result of microstructural changes at the sliding interface. Wear debris is generated at the rubbing surfaces and trapped in the conforming contact of this tribosystem, Figure 3, and it is the structure and properties of this dry debris layer which controls the system's in-vacuo properties [2,3]. The minimum and partly recovered friction torque levels result from variations in the extent of this "third-body" [4] debris layer in the interface.

Clearly, low and variable friction torque is inevitable from the extended use of SRMS brake pads in vacuum. Similar tests with several alternative types of materials sliding in this unique tribosystem gave the following results.

Other Polymeric Based Materials

Friction trends from the polymeric materials studied are illustrated in Figure 4. They all developed low friction output on sliding in the high vacuum, much earlier than the asbestos/phenolic composition. The low friction torque of these other polymeric based materials is related to the ready formation of localized wear debris features, Figure 5, on worn specimen surfaces. Microscopic and profilometric examination show these to be proud of the surfaces. It is inferred that such structures bridge the interface during sliding, separating the original sliding surfaces and confining the nominal load-bearing contact to a small fraction of the brake pad area. Although debris shear strength will also have an influence, the low torque output of the system is mainly due to this greatly restricted contact area.

Ceramic Based Materials

Ceramic based materials were found to exhibit widely different sliding friction trends in this high vacuum conforming contact system [5]. After run-in, friction either remained steady at high, moderate or low values over long sliding distances or it behaved in a very unstable manner, as shown in Figure 6. These friction trends were also related to the debris morphology found on worn surfaces. When specimen surfaces had a matte appearance, e.g. as in Figure 7a, friction torque was moderate to high. This was considered to be mainly due to the many, finely distributed, load-bearing debris features on such surfaces, Figure 7b, providing a large total contact footprint during sliding [3,4]. In contrast, low frictional output was obtained when the interface developed relatively few contacts at raised wear debris islands, Figure 8, similar to the polymeric materials. The variable friction of the SiC/TiB_2 material may reflect sliding locus changes from the periodic shedding of parts of these bridging streaks as debris flakes [5].

Engineering the Interface

The behaviour of some ceramic materials in this tribosystem is more complex than was originally reported [5]. Because friction trends were similar in repeat tests, they were thought to be characteristic of a particular material. However, different sliding friction torque trends have now been found with some ceramic specimens in separate tests, e.g. as shown in Figure 9. The correlation between friction trend and wear debris morphology still applies; high friction torque resulting from "full" interfacial contact via the matte debris structures, Figure 7, and low torque output from the system when contact is limited to debris streaks, as in Figure 10. The latter are only $\approx$ 1 μm thick, yet they can still separate the sliding surfaces.

Whether it is the dense, fine debris bed or the isolated streaks which begin to form during the earliest stages of sliding depends on initial conditions in some way not yet understood. This, and other aspects, including the study of model interfaces, need to be researched further. However, from a practical perspective several important facts about this tribosystem have been established, viz.:

-- the desired matte textured surface, and hence interface debris morphology, is more readily achieved, using appropriate running-in procedures, with some ceramic materials than others

-- this type of beneficial debris morphology cannot be generated on the polymeric, and some of the ceramic, materials studied

-- once the matte debris bed has been established on run-in surfaces, friction remains stable thereafter, in either uni- or bi-directional sliding in high vacuum.

Thus, the interface between some ceramic-based brake material specimens can be tailored to provide stable high friction torque output from this conforming contact geometry tribosystem.

Wear of Candidate Materials

The sliding wear rates of various materials measured in the present in-vacuo sliding experiments are listed in Table 1. These reflect the wear debris eliminated from the conforming contact during sliding plus any loose debris air blown from specimen surfaces after the tests. Values range above and below those of the asbestos/phenolic composition. Although SSRMS brake slip requirements have not been defined, some of these wear rates should provide long life since the light loads used in space mechanisms ensure that large sliding distances can be sustained before the pads wear away. For example, a material with a specific wear rate of 10^{-4} mm^3/Nm would require two million slip revolutions under SRMS loads to wear through 1.5 mm thick pads. However, minimization of loose wear debris accumulation in brake housings favours use of the lowest wearing materials.

CONCLUSIONS

From these tribological studies of materials in conforming contacts in the vacuum environment, it is concluded that:

- the low friction anomaly of SRMS asbestos/phenolic brake material is an inevitable consequence of its extended use in-vacuo. The friction loss, though partly recoverable, is permanent in a dry environment.

- the in-vacuo friction behaviour of the asbestos/phenolic material is determined first by residual moisture level and then by the extent, structure and properties of a dry interfacial wear debris layer.

- all polymeric compositions studied also develop permanent, very low friction torque from this sliding system, through development of minimal contact patches of wear debris within the brake pad area.

- ceramic materials exhibit various frictional outputs from this tribosystem, depending on interfacial wear debris characteristics. Limited contact area at a few debris islands gives low friction torque while high friction results from more extensive contact at fine debris features distributed throughout the brake pad area.

- the sliding surfaces of some ceramic materials can be tailored, by appropriate run-in procedures, to give the finely distributed wear debris morphology which ensures a stable high friction torque.

- some ceramic-based compositions with stable in-vacuo high friction and low wear rate in the conforming contact brake configuration may be suitable candidates for use in mechanical brakes in long-life space mechanisms, e.g. in Space Station Remote Manipulator Systems.

ACKNOWLEDGMENTS

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TABLE 1.

Wear of polymeric and ceramic based materials in high vacuum conforming contact sliding tests

Material	Specific Wear Rate* (X 10^{-5} $mm^3/N\ m$)
Polyimide (SP 1)	29
Asbestos/phenolic	1.5 (High μ)
"	1.0 (Mixed μ)
Non-asbestos/phenolic	1.1 (Mixed μ)
PEEK/Glass fibre	0.7
Al_2O_3/TiO_2	43
Si_3N_4/SiC	15 (High μ)
WC/Co	13
Al_2O_3/SiC	11 (High μ)
Al_2O_3	7.5
$Si_3N_4/SiC/TiN$	6.5
SiC/TiB_2	4.5
$Cr_3C_2/NiCr$	0.8
$MoS_2/Nb/Mo/Cu$	0.6
Cr_2O_3	0.6
Si_3N_4/SiC	0.5 (Low μ)
(Cr_2O_3 vs. 440C steel	0.4)
(Al_2O_3 vs. 440C steel	0.2)

*Mean value of two sliding specimen discs

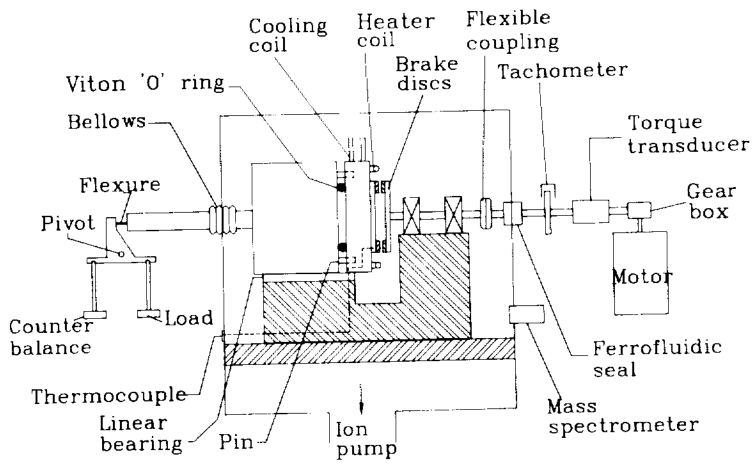


Figure 1. Schematic of the high vacuum tribometer.

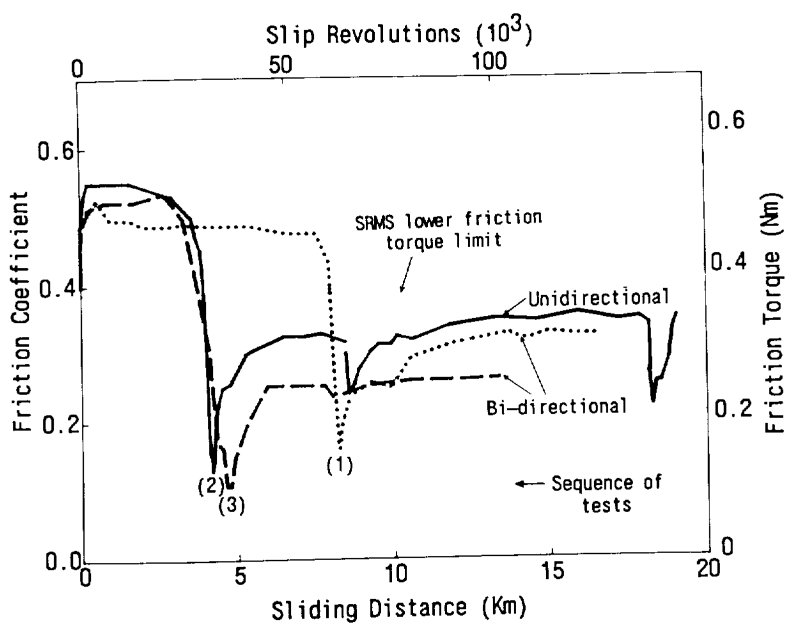
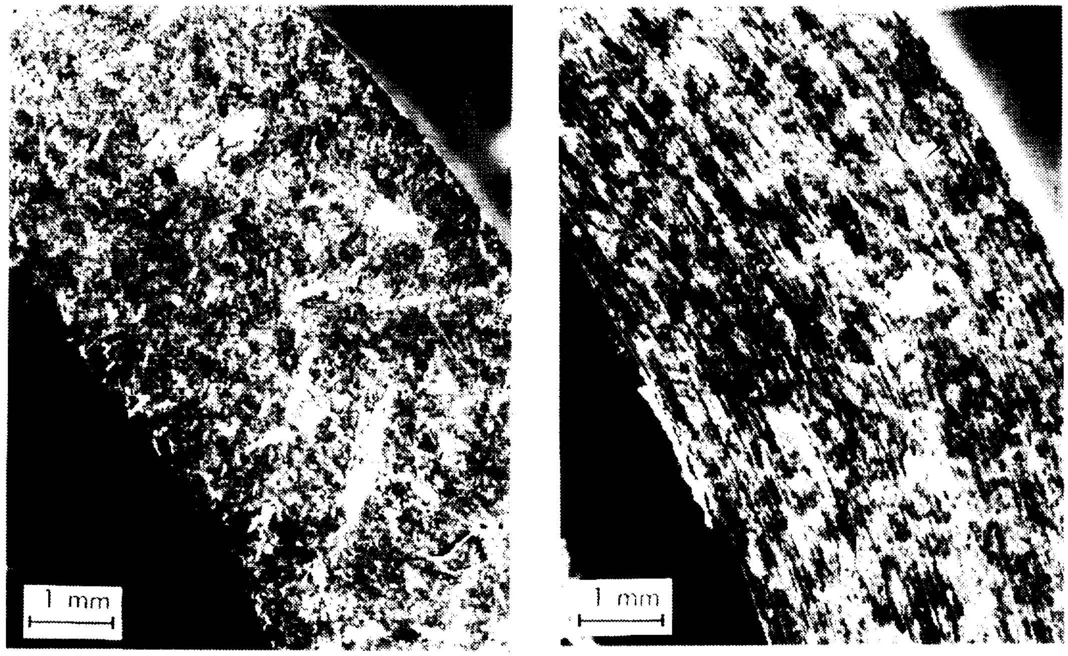


Figure 2. Friction trends from slipping of SRMS brake material in vacuum. First 2 Km (test 1) and 0.2 Km (test 3) were unidirectional run-in.



(a) (b)

Figure 3. Asbestos/phenolic specimen surfaces before (a) and after (b) bi-directional sliding at low friction in vacuum.

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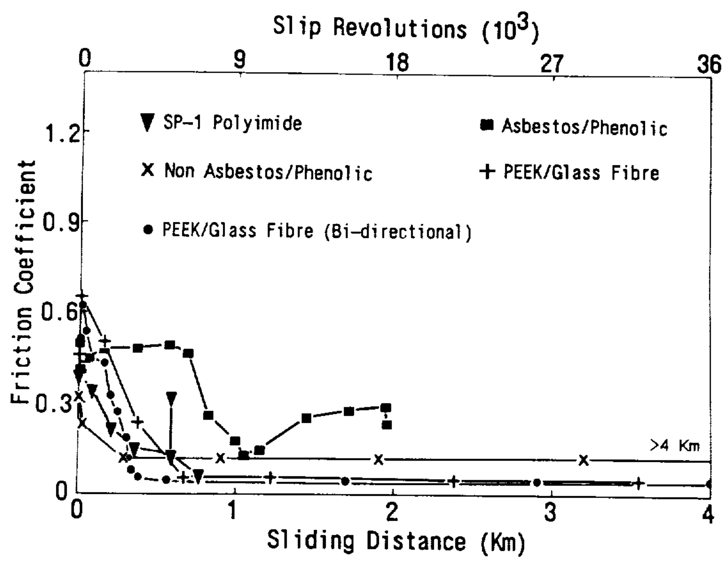
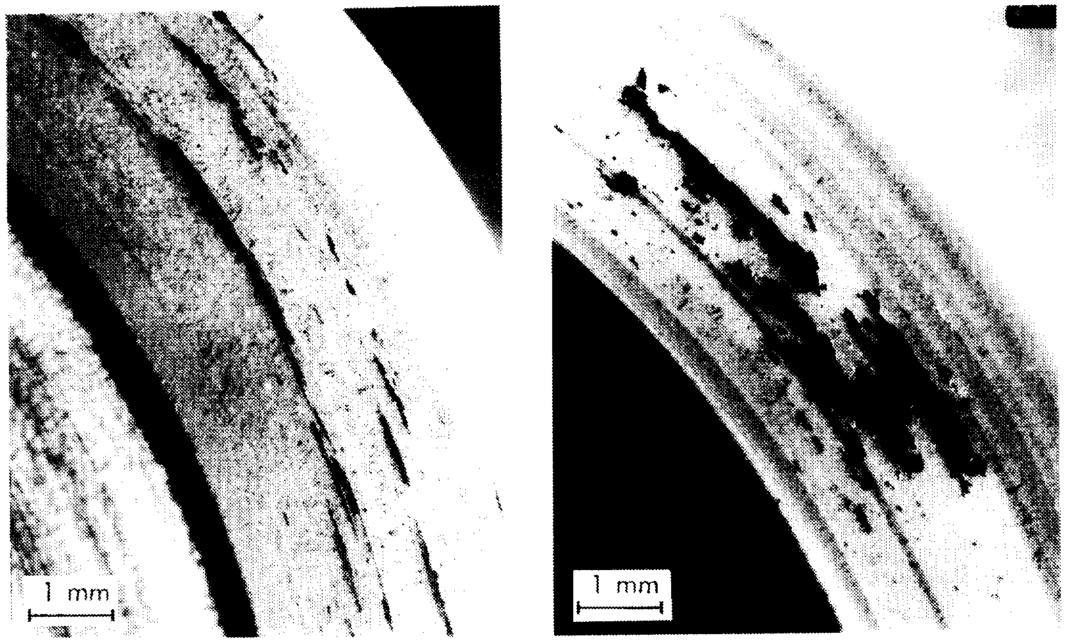


Figure 4. Friction trends from sliding of various polymeric compositions in vacuum.



(a) (b)

Figure 5. Wear debris structures on PEEK/glass fibre specimen surfaces after (a) uni- and (b) bi-directional sliding at low friction in vacuum.

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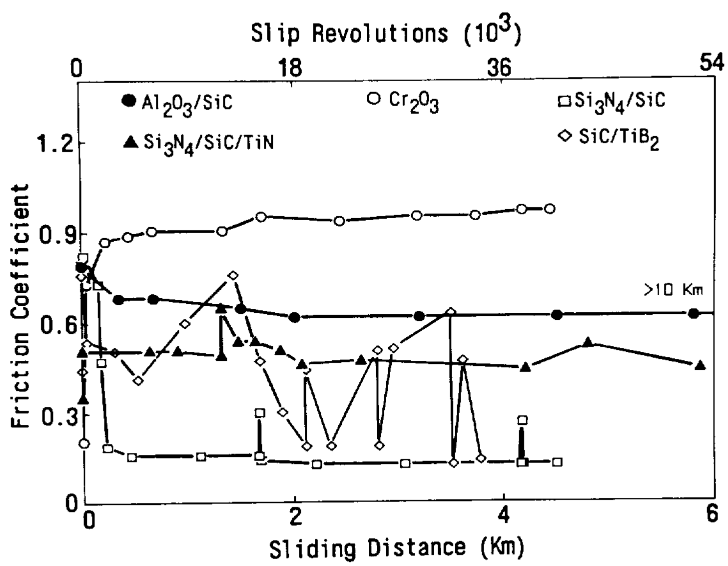
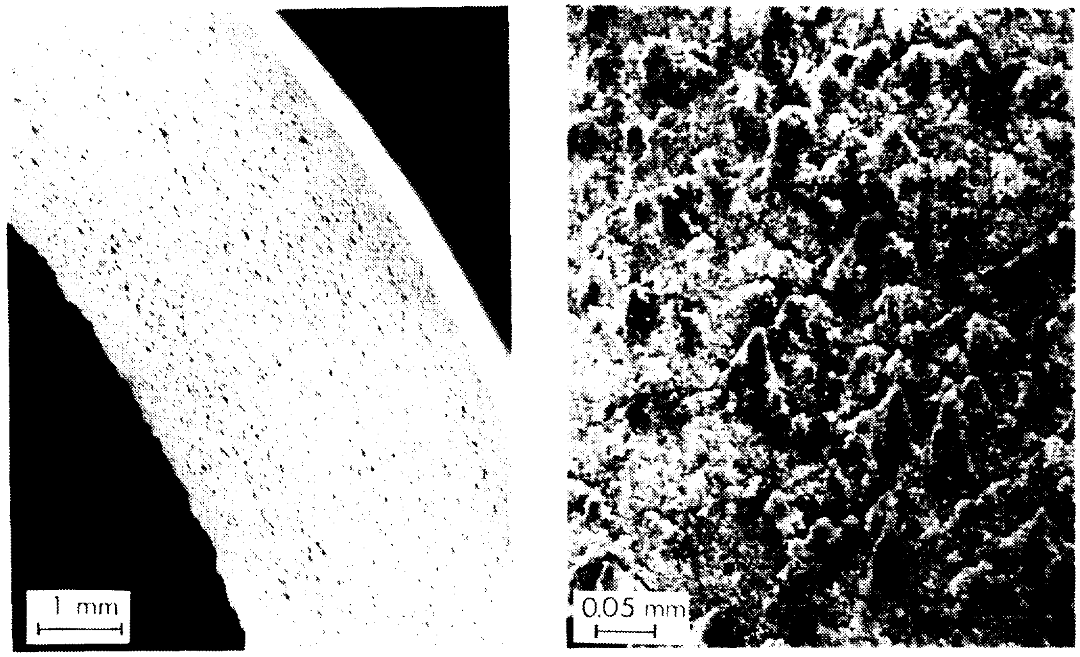
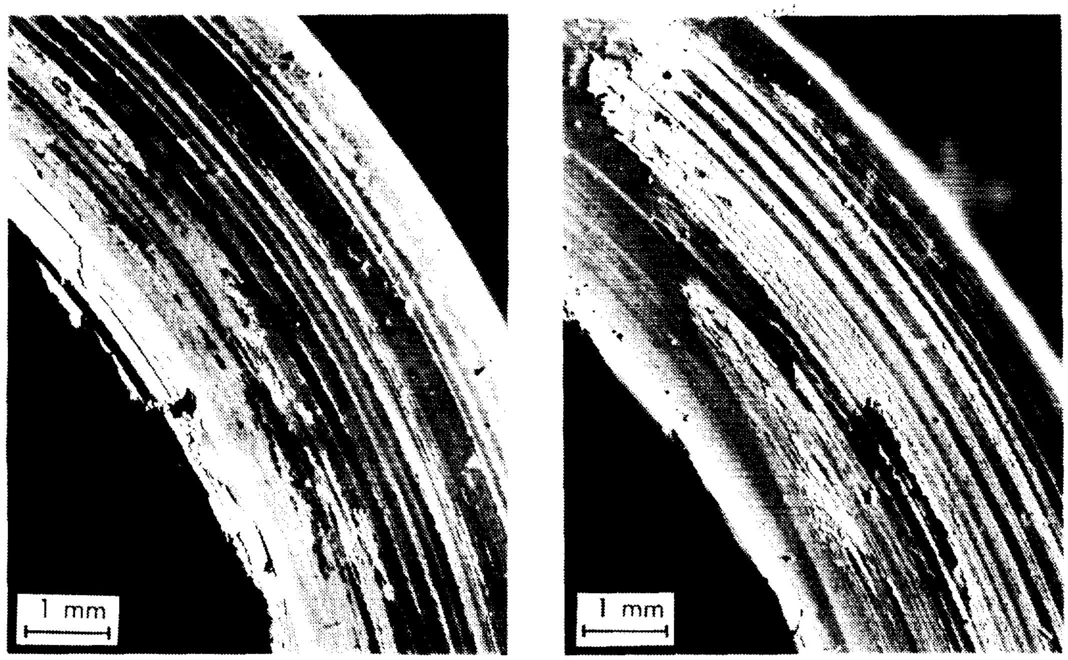


Figure 6. Friction trends of ceramic-based materials from sliding in vacuum.



(a) (b)

Figure 7. Finely dispersed wear debris texture on Al_2O_3/SiC specimen surfaces after sliding at high friction in vacuum.



(a) (b)

Figure 8. Worn static (a) and rotating (b) specimens of Si_3N_4/SiC after sliding together at low friction in vacuum.

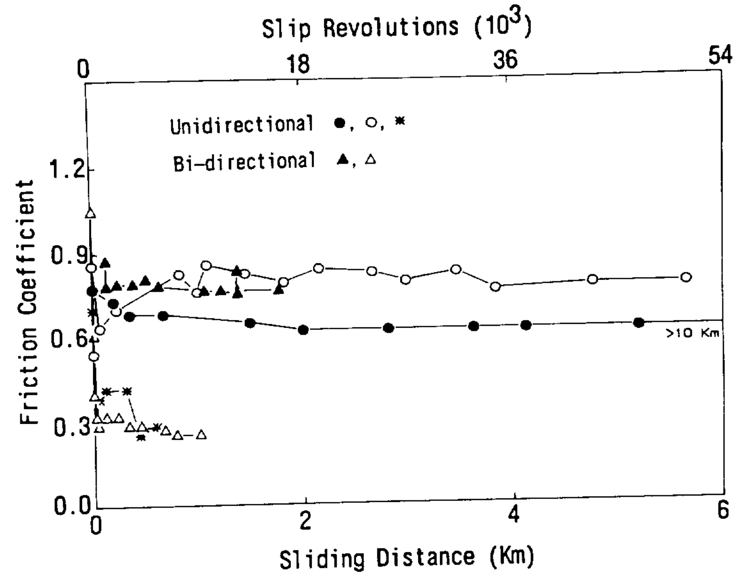


Figure 9. Different in-vacuo friction trends from separate tests of the same pair of Al_2O_3/SiC specimens.

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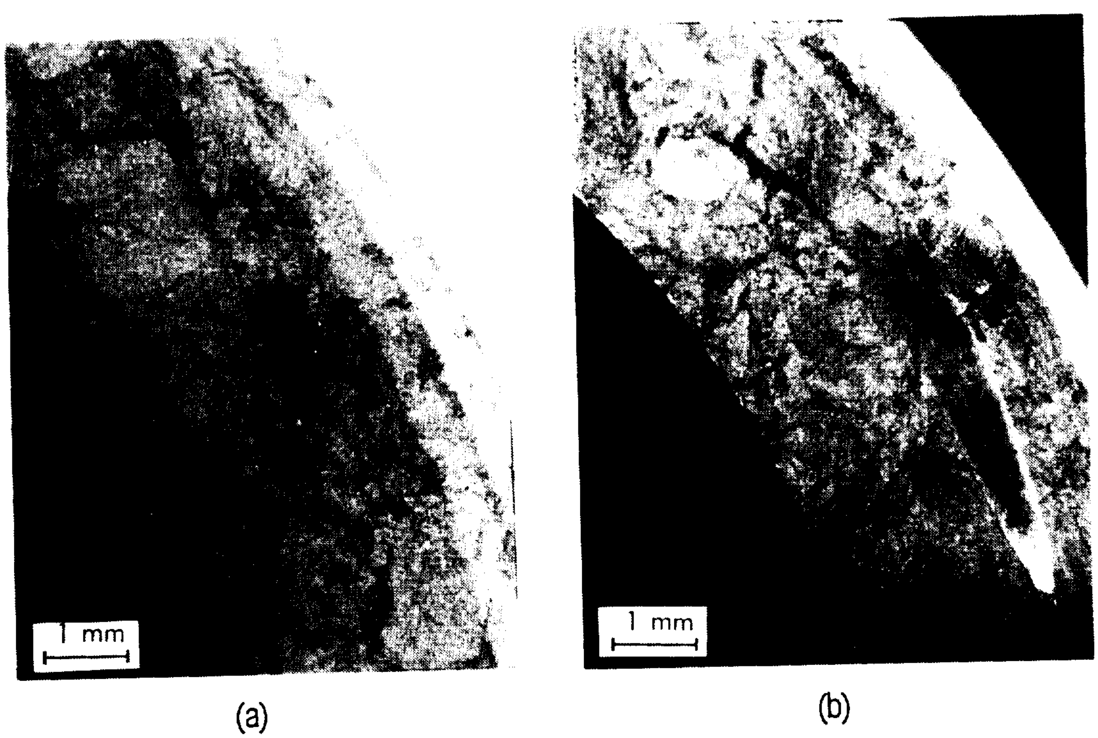

Figure 10. Wear debris patterns on Al_2O_3/SiC specimen surfaces after sliding at low friction in (a) uni- and (b) bi-directional tests in-vacuo.