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THE FRICTION AND WEAR OF TPS FIBERS
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ABSTRACT

The sliding friction behavior of single filaments of SiO_2, SiC and an aluminoborosilicate glass has been determined. These fibers are used in thermal protection systems (TPS) and are subject to damage during weaving and aero-maneuvering. All fibers exhibited stick-slip friction indicating the successive formation and rupture of strong junctions between the contacting filaments. The static frictional resistance of the sized SiC filament was 4X greater than for the same filament after heat cleaning. This result suggests that the sizing is an organic polymer with a high shear yield strength. Heat cleaning exposes the SiC surface and/or leaves an inorganic residue so that the adhesional contact between filaments has a low fracture energy and frictional sliding occurs by brittle fracture. The frictional resistances of the sized and heat cleaned SiO_2 and glass filaments were all comparable to that of the heat cleaned SiC. It would appear that the sizings as well as the heat cleaned surfaces of the silica and glass have low fracture energies so that the sliding resistance is determined by brittle fracture.

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INTRODUCTION

Fabrics and felts of thermal resistant silica, aluminoborosilicate and silicon carbide fibers are being evaluated for thermal protection systems (TPS) at NASA-Ames for the next generation reentry vehicles. These inherently brittle fibers suffer abrasion damage during processing, especially weaving, and during aero-maneuvering at ambient and upper operating temperatures (1400 °C). This damage occurs when individual fibers move across each other and is especially severe after the loss of protective coatings (sizing) at temperatures of 350°C and lower. However, the micro-mechanics of fiber damage during processing or when a fabric is subjected to stress is poorly understood; especially the effect of fiber sizings. Intuitively, one would expect that protective sizings would reduce the sliding friction. The results reported here suggest that this is not necessarily true.

EXPERIMENTAL

Materials The fibers tested are listed in Table I and were supplied by the Thermal Protection Branch, NASA Ames.

TABLE I

Fiber Designation	Material Type	Sizing
Nicalon NLM-102	SiC	yes
Nicalon NLM-102	SiC	HC[a]
Nextel 312	AlOBSi[b]	yes
Nextel 312	AlOBSi	HC
Astroquartz	SiO_2	yes
Astroquartz	SiO_2	HC

a heat cleaned
b aluminoborosilicate

Apparatus Two single filaments were extracted from a fiber tow one of which was mounted horizontally on a mechanical platform and the other hung vertically from a microbalance as shown in Figure 1. A device was developed to hold the horizontal fiber using minigrabber electronic test clips[c]. The fiber was held at each end by the clips and the clips were glued to vertical Lucite posts mounted on a Lucite stand. The stand was constructed so that the distance between the posts could be varied to adjust the tension on the fiber. As discussed in the next section, control of the tension on the horizontal fiber was critically important in these experiments. The fixture holding the horizontal fiber was itself placed on a precision mechanical stage that could be moved up or down at preset rates and distances. The platform could also be moved in the horizontal direction by a fine thread micrometer stage.

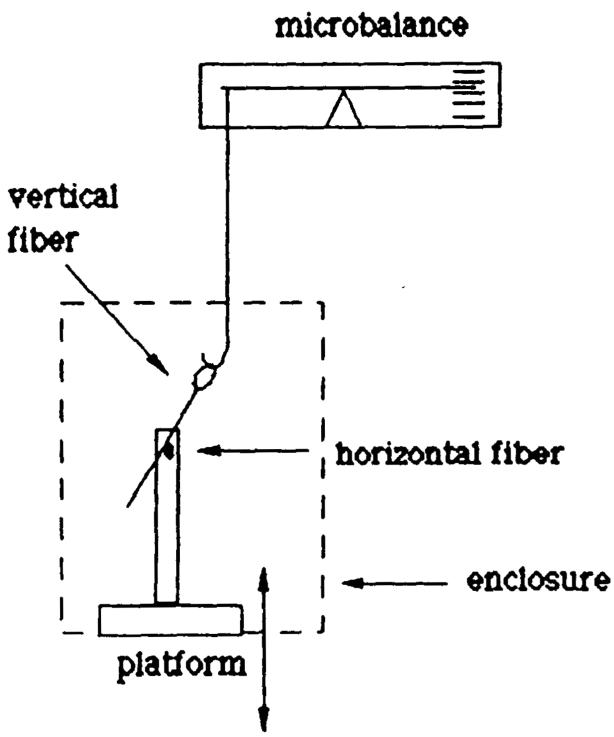

Figure 1 - Schematic of the apparatus used to measure the sliding friction of single filaments. The vertical filament was held from a hook at the end of a stiff wire attached to the microbalance.

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[c] The microclips eliminate the need to glue the fiber ends thus reducing a major source of chemical contamination of the fiber surface. The clips held the fragile filaments without crushing.

The vertical filament was fixed to a wire loop with a small strip of pressure sensitive tape and the loop hung on a hook at the end of the wire connected to the microbalance (Figure 2). The assembly was enclosed in a Lucite box.

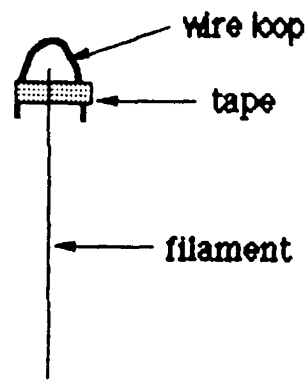
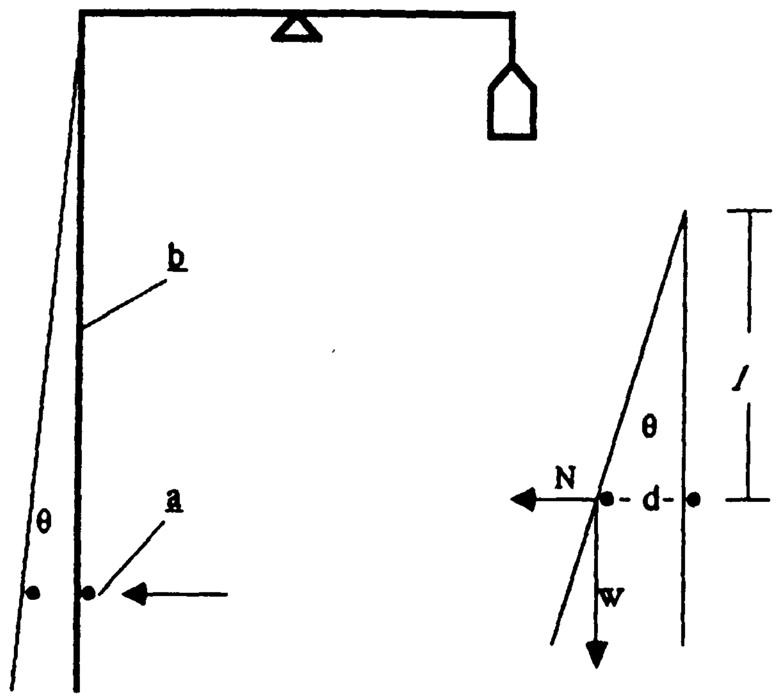


Figure 2 - Method used to attach vertical filament to a wire hoop.

The microbalance was the Cahn Instrument, Model 2000 and the mechanical stage including the motor control was built by Rame-Hart, Inc. (Mountain Lakes, NJ).

Procedure The horizontal filament was gripped by the microclips and the distance between the clips adjusted until there was a slight tension on the filament. This procedure was somewhat arbitrary in that the tension on the filament could not be measured. Through trial and error it was found that the experimental results were most repeatable if the fiber was made just slightly taut by a few turns of the screw mechanism used to adjust the distance between the clips.

Friction measurements were made by first weighing the vertical filament including the wire and tape (W) on the microbalance. Next the horizontal filament was moved against the vertical filament until the latter was displaced the distance d and was at an angle θ to the vertical direction as shown in Figure 3. The angle θ was measured using a telescope fitted with a goniometer eyepiece. The force of the vertical filament against the horizontal filament (N) was calculated using the expression given in Figure 3.



$$\tan\theta = \frac{d}{l} = \sin\theta$$

$$N = W \sin\theta$$

Figure 3 - Force balance for the contacting filaments.

Frictional forces between the two filaments were measured by lowering and then raising the mechanical platform so that the horizontal fiber first moved downward against the vertical fiber than the stage direction was reversed so that the horizontal fiber moved upward. The length of each traverse was about 3mm. Only the data for the initial downward traverse are reported here since they represent the frictional force between "nascent" filaments. The effect of multiple traverses will be reported later.

RESULTS

Preliminary experiments revealed the importance of the tension on the horizontal filament. It the filament is slack than it tends to swing as it slides against the vertical filament. When this occurs the force N is not constant. If the tension on the filament is too great, then a high frequency vibrational oscillation develops in the horizontal filament; the "violin effect". An example of this behavior is shown in Figure 4.

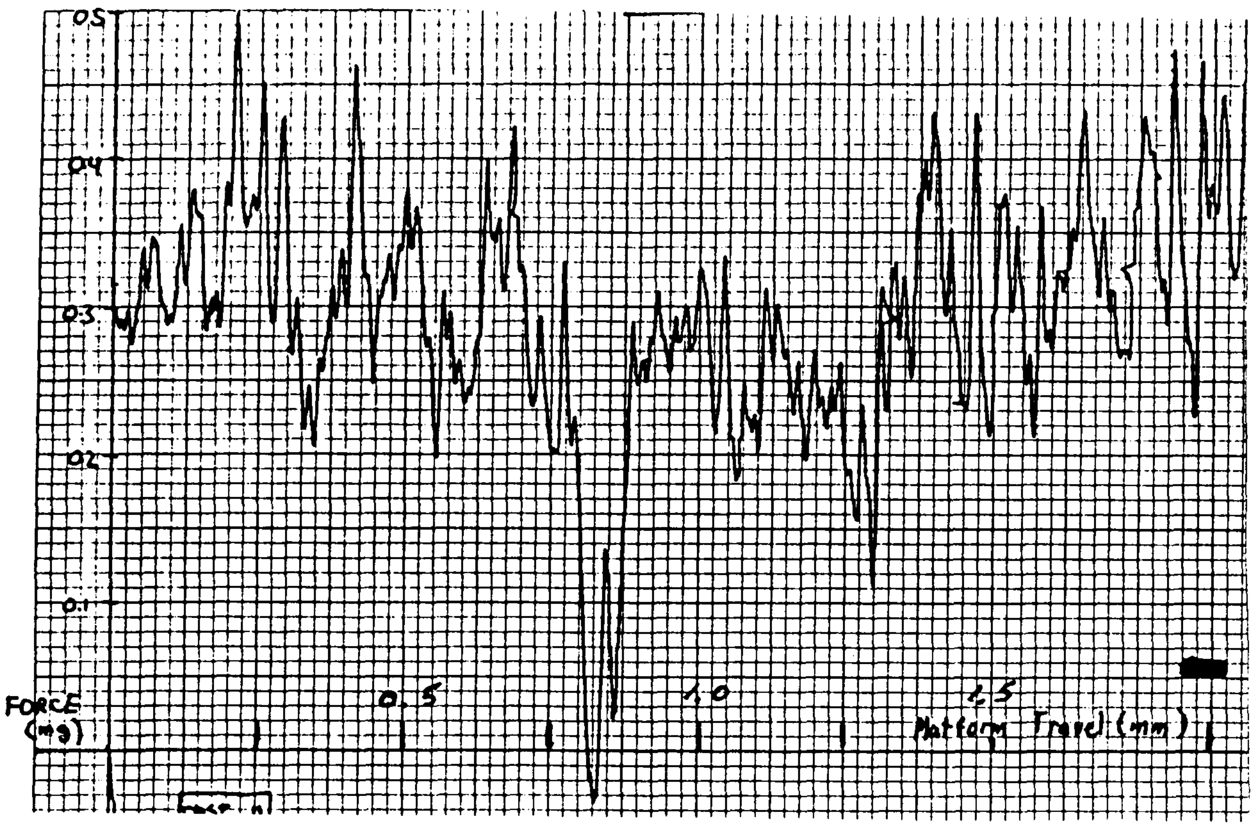


Figure 4 - High frequency vibration observed when the horizontal filament is highly stressed (sized Nextel)

By applying a slight tension to the fiber, just enough to make it taut, a stick-slip behavior is observed as shown in Figure 5 which is assumed to be characteristic of the static and dynamic the sliding friction of filaments respectively. Stick-slip sliding friction of thin filaments has been observed in the extensive work reported by Briscoe (1-5). Moreover, it is reasonable to expect that the frictional sliding of filaments should exhibit a stick-slip behavior.

All of the filaments listed in Table I were tested in this preliminary study and all exhibited these effects of the tension on the horizontal filament.

As discussed in the next section, the adhesion between small diameter filaments is very strong when they come into contact. As the horizontal filament moves against the vertical filament the shearing force between the filaments increases until the junction between the fibers shears or fractures. The fibers then slide against each other, the slip region, until the shear force is reduced to a level that the filaments readhere and the entire process is repeated. The peak heights are an index of the static frictional force whereas the slip region reflects kinetic friction.

All of the fibers were retested at essentially the same contact force (N - 5 to 6mg) and with the horizontal filament under a slight tension. The static frictional force, i.e, the peak heights, were averaged and the results are given in Table II. Each datum point represents the average of six tests with new filaments used in each test. There was a wide distribution in the static contact stress both for a given fiber pair and for different fibers taken from the same tow. The standard deviation (SD) given in Table II, includes the variance in one test and for replicate tests.

Table II

Fiber	Static Friction (mg force)	SD (mg force)
Nicalon (sized)	11.6	9.4
Nicalon (HC)	3.1	0.5
Nextel (sized)	2.2	0.8
Nextel (HC)	2.5	0.92
Astroquartz (sized)	1.46	0.62
Astroquartz (HC)	1.94	0.31

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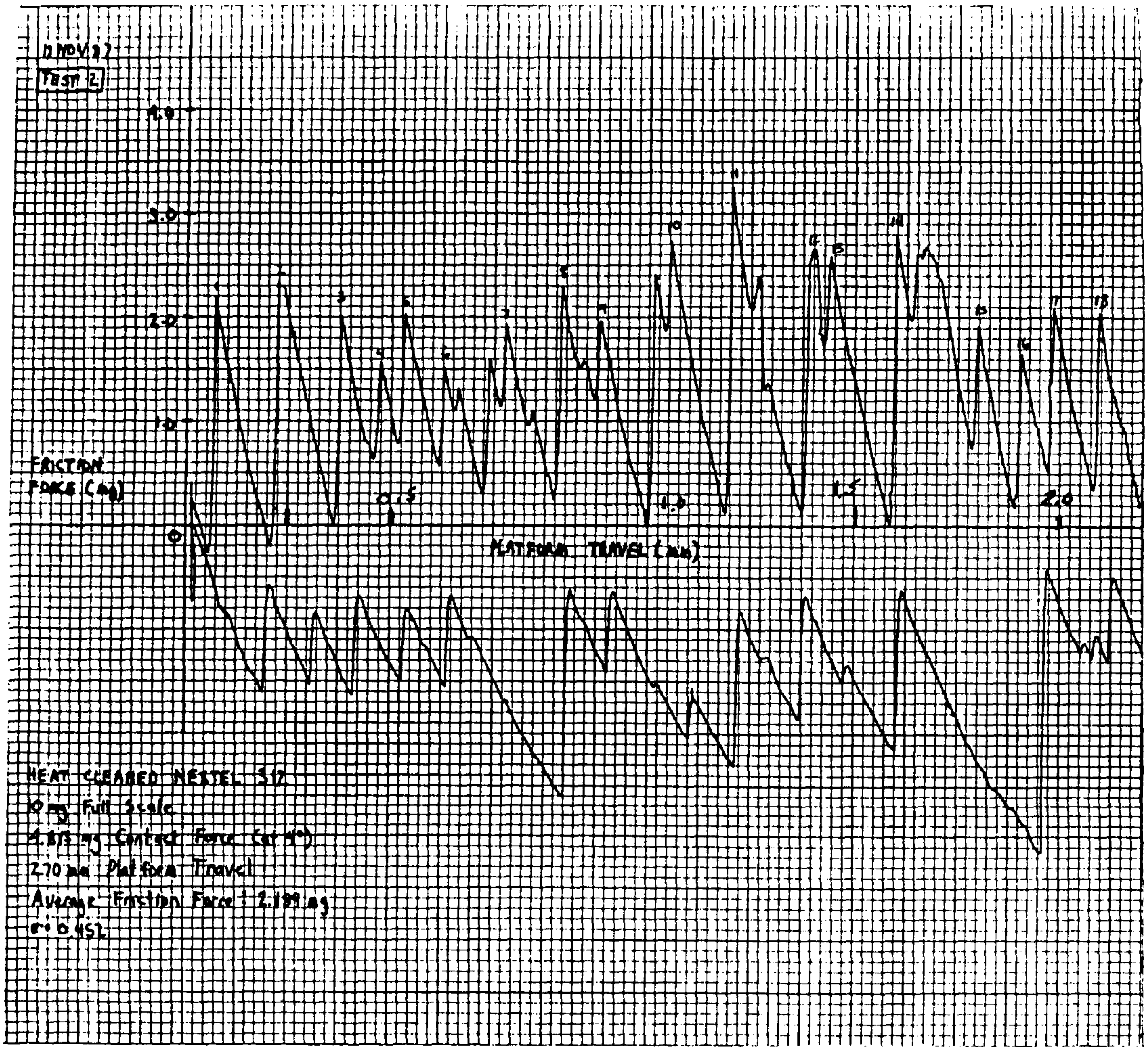

Figure 5 - A stick-slip sliding friction plot for heat cleaned Nextel filaments. The positive (upper) trace corresponds to the downward movement of the horizontal filament. The peak heights are the static frictional force to rupture junctions between the fibers. The curves between peaks are the slip regions that occur as the filaments slide against each other.

DISCUSSION

Static Friction:-The sliding friction between small diameter filaments involves surprisingly high stresses even though the actual forces are relatively small. The geometric area of contact between two 10μm diameter filaments is infinitesimally small. Actually, there is some elastic (and possibly plastic deformation) so that the area of contact is finite as shown in Figure 6. Let us assume that the contact radius is 0.1 μm. If we apply a force of 5mg by pushing one fiber against the other as in Figure 2, then the *stress*, the force divided by the area of contact (F/A), is 108 kg-force/m^2 or about 10^4 psi. Moreover, the actual area of contact is likely to be smaller than the geometric area due to surface roughness. As shown in Figure 7 surface asperities limit the actual contact area. If we assume that the area of contact is actually one-tenth of the geometric area, then the contact pressure is of the order of 10^6 psi.

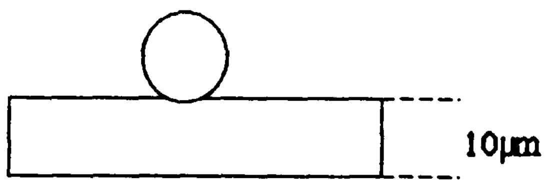

Figure 6 - The dimensions of the contact area between crossed filaments is small compared to the filament diameter.

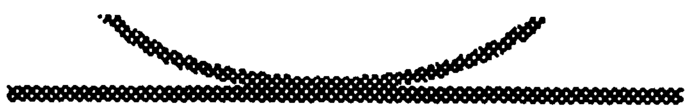

Figure 7 - The actual area of contact is less than the geometric area due to the micro-roughness of the surfaces.

Consequently, when two small diameter fibers are brought into contact under a small applied force the stresses are large enough that they may actually "weld" together. In the case of inorganic fibers such as glass, SiC or SiO_2 it is difficult to envision the chemical nature of this "weld". Most likely the junction would have the same mechanical properties as that of the fibers.

If the fibers are coated with an organic polymer sizing, the high contact stress may cause the polymer coatings to flow together to form a junction that has the same shear strength as the polymer itself.

The strength of a junction formed between two inorganic fibers such as SiO_2 and the strength of a junction formed between two fibers with a polymer coating will be very different. Although the shear strength of SiO_2 is considerably higher than the shear strength of an organic polymer, inorganic solids do not fail in shear but fail by brittle fracture at a significantly lower strength than their shear strength. Polymers, on the other hand fail by shear yielding.

Now we can understand the difference in the static friction results in Table II. The Nicalon fiber is coated with an organic polymer so that when the filaments are brought into contact a junction is formed having a high shear yield strength which would explain the high frictional force for this fiber. Removal of this coating by heat treatment exposes the SiC fiber although the removal of the sizing may not be complete in which case a carbonaceous residue is left on the surface. In either event, the strength of the junction formed by heat cleaned Nicalon filaments is determined by the brittle fracture resistance of the contacting surfaces which is significantly less than the shear yield strength of the junction form by the sized fibers.

The static frictional behavior of the sized and heat treated filaments of both Nextel and Astroquartz filaments were not significantly different. In the case of the Astroquartz, the sizing is known to be a silane coupling agent (aminopropylsilane, Union Carbide A-1100). These silanes form three dimensional, highly crosslinked networks (6) which are very friable and so have fracture energies not greatly different than the fiber itself.

Kinetic Friction: After the junction between two filaments ruptures, the filaments slide against each other; the slip region shown schematically in Figure 8.

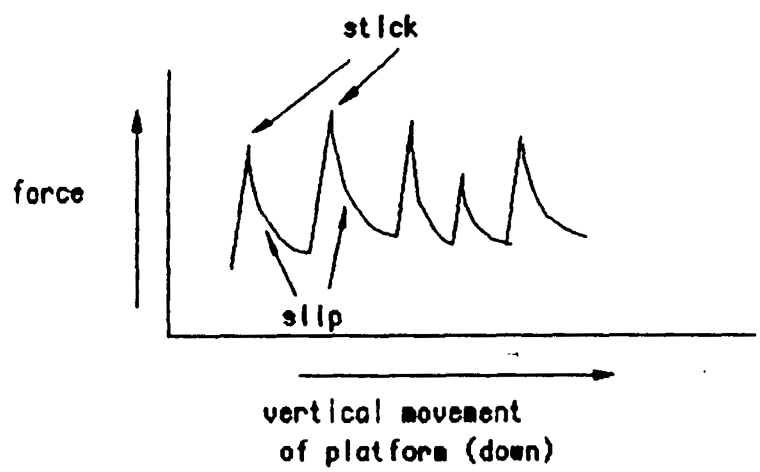

Figure 8 - Schematic of stick-slip friction.

Only in the case of the Nicalon filaments, sized *vs* heat cleaned, was there a distinct difference in the slip behavior. In Figure 9, typical stick-slip traces are shown for sized and heat cleaned Nicalon. The prolonged slip of the sized filament suggests a "plowing" of the organic coating resisting the sliding of the filaments over each other. On the other hand, the duration of the slip of the heat cleaned fiber was short suggesting little resistance to sliding. These differences correlate with the static friction resistance of these fibers.

The slip response of the Nextel and Astroquartz, both sized and heat cleaned, were similar to that of the heat-cleaned Nicalon. This result is consistent with the argument made in the preceding section that the surfaces of these fibers are brittle and so exhibit low kinetic as well as static frictional resistance.

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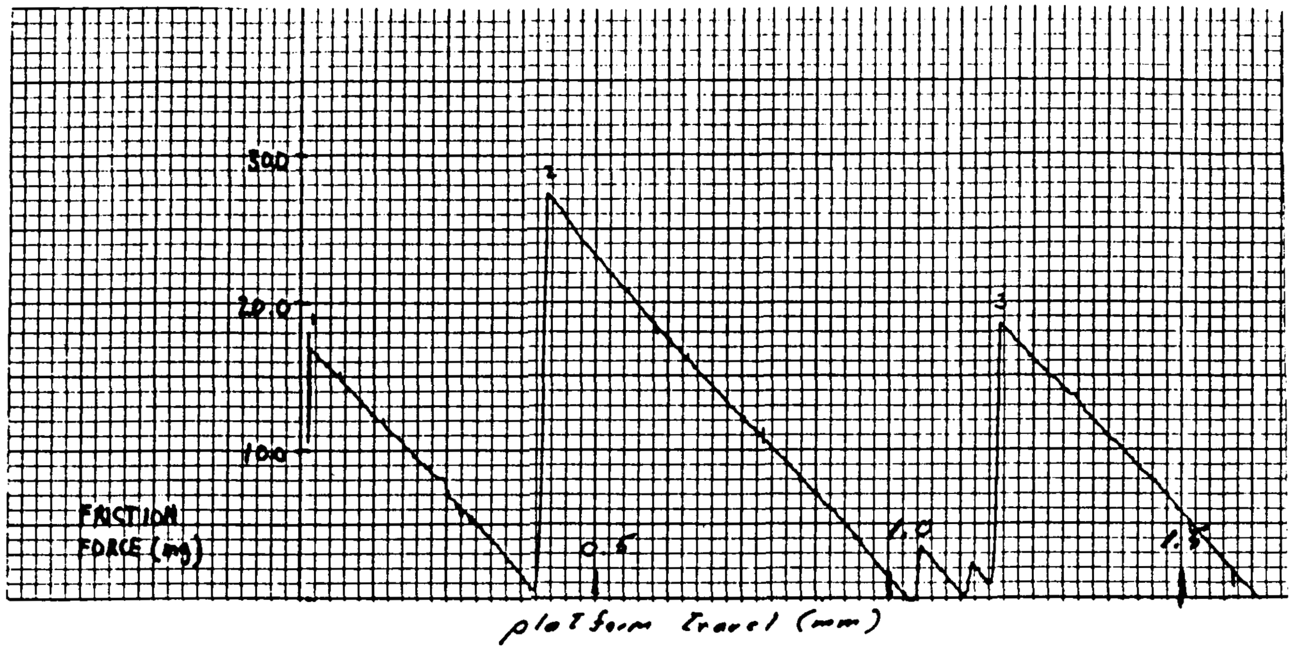

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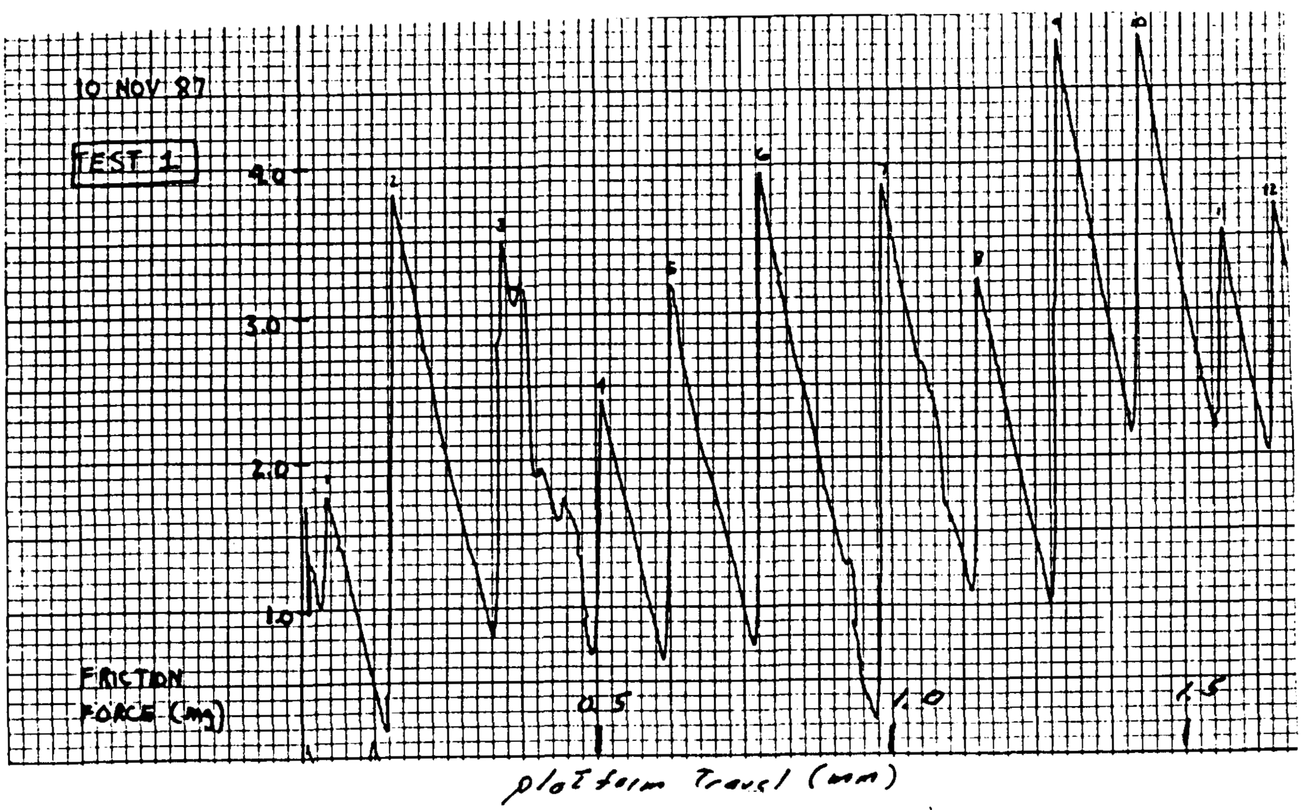

B

Figure 9 - Comparison of the slip region for sized (A) *vs* heat cleaned (B) Nicalon fiber.

CONCLUSIONS

The static and kinetic sliding friction of the high modulus fibers studied here reflect the different mechanical properties of the filament surfaces. Based on what is known about the sized and heat cleaned SiO_2 (Astroquartz) and the aluminoborosilicate (Nextel) fibers, their surfaces are brittle and so exhibit low static and kinetic frictional resistance. The SiC fiber (Nicalon) is sized with a low modulus, high shear strength polymer and so exhibited a static friction force more than 5X that of the other fibers. Removal of this polymer sizing by heat cleaning reduced the static friction to a value comparable to that of the other fibers. The difference in the kinetic friction (slip) between the sized and heat cleaned Nicalon filaments is consistent with the sizing being a tough organic polymer and that after heat cleaning the surface is brittle.

There are unresolved issues from this study that need to be addressed;

a. It would be of considerable interest to observe the wear track that forms as the fibers stick and slide against each other. However, attempts to observe the wear track for sliding polymer filaments even using scanning electron microscopy SEM) have been unsuccessful (7).

b. The effect of multiple traverses of the filaments is of interest since it would provide some indication of surface damage. Also, the wear track after many traverses may be visible using SEM.

c. There was a rather large statistical variation in the static friction force (Table I) and in the shape of the slip traces. This variation may be due to difference is the experimental conditions (contact force), differences in the surface chemical composition of different filaments taken from the same tow, and surface chemical and topographical microheterogeneity.

Some of these issues are being studied.

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