Friction and adhesion of silica fibres

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Sliding friction between orthogonally crossed silica monofilaments was measured as a function of applied normal load using an electronic microbalance. In the adhesion model of friction, the friction is interpreted in terms of shearing the junction. With the assumption that the ploughing term of friction can be ignored, the shear strength can simply be represented by $\tau = F/A$ where F is frictional force, A is the real area of contact, and τ is the interfacial shear strength. Assuming a single point contact between two fibres, the estimation of the real area of contact was made from Hertzian analysis by taking the normal load as a sum of the applied force and independently determined adhesional force. The results showed that the shear strength of freshly drawn silica fibre increases linearly with the contact pressure.

1. Introduction

Fabrics of thermally resistant silica fibres have been evaluated for thermal protection systems for the next generation of re-entry vehicles [1, 2]. Silica fibres suffer abrasion damage during processing, especially weaving, and during aero-manoeuvring at ambient and elevated temperature. The principal abrasion damage occurs when filaments slide against each other. In the absence of any protective coating, it is very likely that micro-cracks form which at worst cause immediate brittle fracture of one or both fibres. In order to develop a rational approach to the selection of fibres and coating materials, it would be helpful to characterize the type of damage that occurs during sliding friction. Also, there is a significant adhesive force, contact adhesion, between these fibres which even in the absence of any applied force can cause abrasive damage.

Adhesion is the result of attractive forces between two surfaces in close contact. When such surfaces are pulled apart or slid against another, separation will tend to occur at the interface [3]. The strength of the adhesive junction will be determined by a balance between the surface attractive forces and bulk elastic forces opposing deformation. Two theories have been proposed to describe such a contact. The first is due to Derjaguin *et al.* [4] which was developed for hard materials. They suggested that under the action of attractive forces the solid is deformed according to the Hertzian equation for the elastic deformation of solid surfaces. The attractive force produces a finite area of contact and is balanced by the corresponding elastic forces in the contact zone. This is referred as the Derjaguin–Muller–Toporov (DMT) model. If an external load N is applied, the area of contact is increased. However, as all the deformations in this model are reversible, the area returns to its equilibrium value when N is removed. If a negative load or force is applied, the area of contact diminishes and the pull-off force (F_c) is given by

$$F_c = 4\pi R\gamma \tag{1}$$

where R is the radius of curvature of the surfaces and γ is their surface energy.

An alternative approach was proposed by Johnson *et al.* [5]. While the DMT analysis ignores modification of the Hertzian deformation by the surface forces, it postulates that under the action of surface forces the surfaces are drawn together and a finite area of contact of radius a_0 is established for zero applied load. However, the shape is quite different from that associated with Hertzian deformation in having a small neck around the contact zone. According to the Johnson–Kendall–Roberts (JKR) model, the pull-off force (F_c) is

$$F_c = 3\pi R\gamma \tag{2}$$

There is much controversy about the validity of the two theories. However, as the surface energies of solids are not known with great accuracy, it is difficult to distinguish between the two models from adhesion experiments. Pashley *et al.* [6] estimated the conditions under which these two models of elastic contact apply by ignoring small numerical factors and suggested that the DMT model is favoured for systems in which R is small, γ is small and Young's modulus is high. Their estimation seems to suggest that the DMT theory is a better model for silica fibres. At present it is not clear which of the two approaches provides a correct estimation of adhesion. In any event the choice does not lead to large errors and the DMT theory is probably more applicable to the present work.

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The frictional force arises from energy dissipation during sliding and can be regarded as coming from an adhesion component and a ploughing term [7]. In the adhesion model of friction, interfacial sliding occurs as a series of discrete events in which adhesive junctions between the two solid surfaces are first formed and then broken. The driving forces for the formation of these junctions are molecular attractive forces such as van der Waals forces, so that the frictional work may be attributed to the fracture energy of junctions formed by the adhesive forces at a single contact point. Thus the interfacial shear strength of the junction is simply given by $\tau = F/A$, where F is frictional force, A is the real area of contact, and τ is the interfacial shear strength.

This work presents the estimation of interfacial shear strength between two silica monofilaments when they slide against each other by measuring the frictional force with the association of contact adhesional force.

2. Experimental procedure

2.1. Materials

Silica fibres having diameters in the range 25–35 μm were formed by drawing the silica rod in an oxygen/natural gas flame at about the silica softening temperature (1300 °C). Care was taken to ensure that the rods were always placed in the same position in the flame. In this way the rods experienced reasonably constant temperature and chemical conditions.

2.2. Adhesional pull-off force measurements

The experimental procedure for the 'pull-off' force measurements involved a pair of silica fibres in an orthogonal configuration as shown schematically in Fig. 1. The upper fibre, in the form of a loop, was held by a alligator clip that was machined to a small enough size so that its weight could be tared out using the electronic balance controller. The alligator clip was hung on a hook at the end of the thin metal wire connected to the balance. A small device was developed to hold the horizontal fibre at both ends for both the adhesion and friction measurements using minigrabbers. The device was placed on a precision mechanical stage that could be moved up or down at a preset speed (6.7 $\mu m\,s^{-1}$). This platform speed was employed in order to avoid complications arising from frictional heating. The fibre holder could also be moved in the horizontal direction using a fine-thread manual-driven micrometer stage. The moment of contact and separation of the two fibres were monitored through a telescope focused at the point of contact. The electronic balance was the Cahn Instrument (model 2000) with a sensitivity of 5×10^{-9} N and the mechanical stage including the motor control was from Rame–Hart, Inc. (Mountain Lakes, New Jersey). The entire unit including fibre holders was enclosed in a plexiglass box for protection from air drafts and aerosol contamination.

To measure the pull-off force, F_c, the lower fibre was brought into contact with the upper fibre. Once in contact, the motion of the platform was reversed and the pull-off force was measured at the moment of detachment of the lower fibre. A typical trace of a pull-off force measurement is shown in Fig. 2, where the change in force was plotted as a function of the travelling distance of the lower fibre.

2.3. Friction measurements

The experimental procedure for the friction measurements involved a pair of silica fibres in an orthogonal configuration in which a horizontally fixed fibre was pushed against the vertical hanging fibre in order to apply a normal load (Fig. 3); the frictional force was measured when the horizontal fibre was pulled down against the vertical fibre. The vertically hanging fibre (length ~ 12 cm) was again held using an alligator clip, and the horizontal fibre was held by the device previously mentioned. Friction measurements were made by first weighing the vertical fibre. Next the horizontal fibre was moved against the vertical fibre until the latter was displaced at distance d and was at an angle q to the vertical direction as shown in Fig. 4. The angle θ was measured using a telescope fitted with a goniometer eyepiece. The load (N) of the vertical

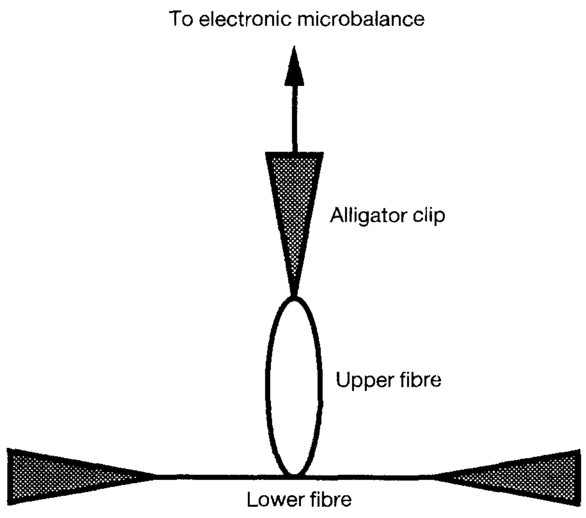

Figure 1 Configuration of silica monofilaments for the pull-off force measurements.

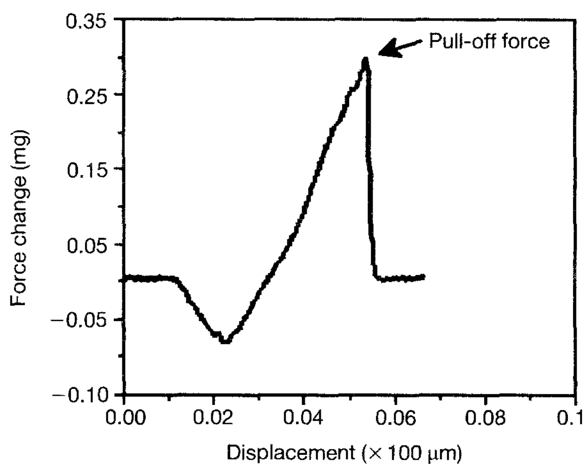

Figure 2 Typical trace of adhesional pull-off force measurement.

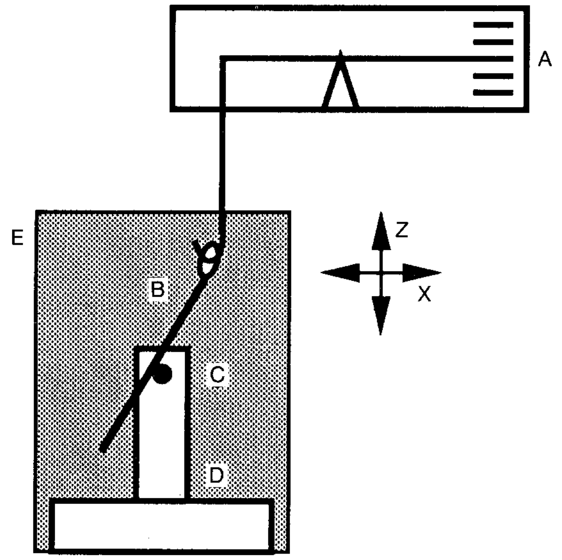

Figure 3 Orthogonal configuration of fibres for the friction measurements. A, microbalance; B, vertical fibre; C, horizontal fibre; D, platform; E, enclosure.

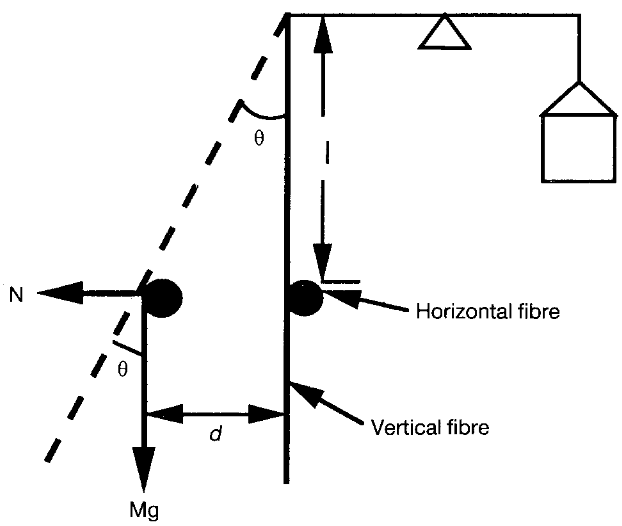

Figure 4 Force balance for fibres in contact. $N = Mg \sin\theta \approx Mg \tan\theta$.

fibre against the horizontal fibre was calculated using the expression given in Fig. 4. The normal load was controlled by changing the angle of deflection of the vertical fibre and the range of angles was small (1–6°) to minimize any change in angle during the fibre movements. For the maximum angle of deflection, the variation of angle during motion was at most $\pm 0.04°$. The total sliding distance along the vertical fibre was 3 mm. Fig. 5 shows a typical friction trace for a pair of silica fibres. Initially we are interested in the static frictional force which is maxima of the spectrum.

An α radiation source was positioned near the fibre contact to minimize surface charging in all the adhesion and friction experiments. All the experiments were done in constant relative humidity (20%) and at constant temperature (23 °C).

3. Results and discussion

This study aims to estimate the interfibre shear strength via the adhesion and friction measurements

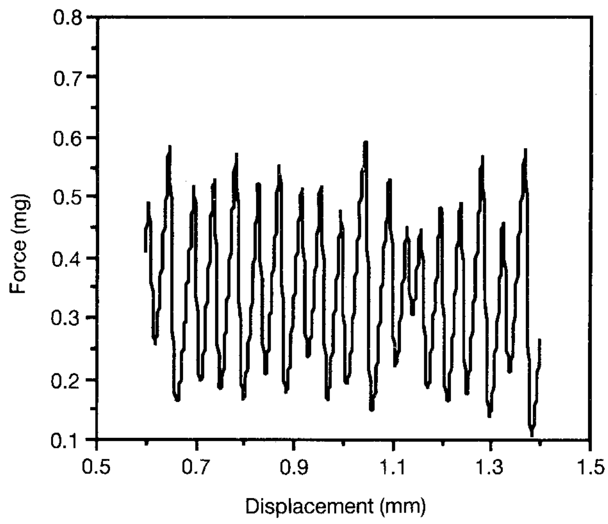

Figure 5 Typical trace of frictional force measurement.

between a pair of fibres. The contact area will be calculated using the Hertzian analyses with the normal load (N) taken as the sum of the applied (F^*) and adhesive force (F_c). The interfibre shear strength can then be estimated with the integration of the area of contact to the frictional force, assuming that the ploughing term is negligibly small in the system.

It is convenient at this point to estimate the force ranges acting between fibres at the contact point before analysing the friction data. Fig. 6 shows the results of adhesion measurements obtained where the pull-off forces are plotted as a function of fibre radius. The fibre diameters were varied by controlling the fibre pulling speed. The surface energy of the silica fibre which can be deduced from the slope of the linear regression line are 25.81 and 34.38 $mJ\,m^{-2}$ using the DMT and JKR theories, respectively. These are unexpectedly low values for the surface energy of fresh silica, as it has been shown from an extrapolation of the data on the surface energy of alkali silicate glasses [8] that the approximate value for the surface energy of silica in air should be at least 200 $mJ\,m^{-2}$. Therefore, we may conclude that with silica fibres, as the normal van der Waals behaviour is observed down to

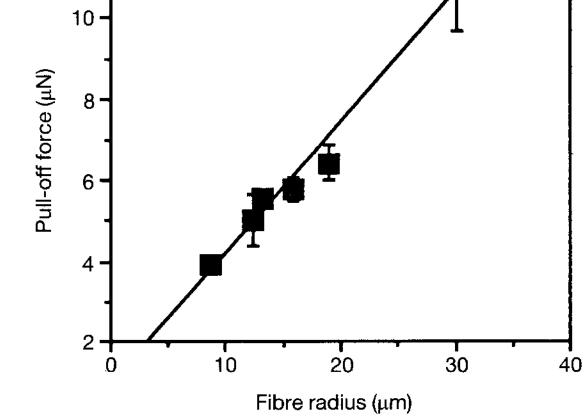

Figure 6 Adhesional pull-off force as a function of fibre radius.

a separation of a few nanometres [9], there must be strong short-range repulsive forces which come into operation at separations appreciably less than a few nanometres. This result confirms the view of Johnson *et al.* [5] that the surface energy and adhesion strength of elastic bodies are related to one another through the action of van der Waals forces. The obtained value is thus reasonable for van der Waals interaction. Similar results in terms of the surface energy have been reported by Kohno & Hyodo [10] for the contact between fused quartz and an optically flat steel surface.

A question arises as to the radius of curvature, as it is known that when plastic materials are brought into contact, pressing may lead to an increase in the force of adhesion, owing to an increase in the true contact area as a result of irreversible deformation [11]. The effect of pressing on the adhesion of elastic particles has been investigated in a number of experimental studies [12, 13]. The observed increase in the force of adhesion of particles of elastic materials, after pre-loading, has been attributed by these investigators to meshing at the contact as a result of irreversible displacement of asperities when the specimens are pressed together. According to this point of view, pressing must be accompanied by a strengthening of molecular interaction as a result of the closer approach of the specimens to each other and the subsequent increase in the number and area of contacts. However, earlier theoretical studies of the influence of contact deformations on the adhesion of elastic particles to a rigid substrate indicated that pressing is incapable of increasing the molecular component of the force of adhesion. In order to verify this problem the adhesional force was measured for increased pressing force (0.1 to 3 μN) and showed that the measured force range was within ± 5% with good reproducibility. This result implies that any increase in pressing force will increase the area of contact but have negligible effect on the adhesional force.

From the Hertzian theory [14] for contact of two spherical bodies within the elastic limit, the pressure p at any radius r and the radius of contact a are given by

$$p = \frac{3N}{2\pi a^2}\left(1 - \left(\frac{r}{a}\right)^2\right)^{1/2} \quad (3)$$

$$a = \sqrt[3]{\frac{3NR}{4E'}} \quad (4)$$

where N is the applied load, R the equivalent radius of curvature given by the relationship,

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \quad (5)$$

E' is the composite elastic modulus defined by

$$\frac{1}{E'} = \left\{\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}\right\} \quad (6)$$

where E_1, E_2 are the elastic moduli for the elastic bodies, μ_1 and μ_2 are their Poisson's ratios, and R_1, R_2 are their radii of curvature. If the one body is planar rather than spherical in profile, R_2 goes to ∞ and $R = R_1$. As the contact area $A = \pi a^2$, the area of the contact circle is

$$A = \pi a^2 = \pi(NRK)^{2/3} \quad (7)$$

where K is a constant. For the deformation of an elastic sphere in the presence of surface adhesional force, the load (N) is given [15] by the sum of the forces of molecular attraction outside the contact circle (F_c) and the applied load (F^*);

$$N = F_c + F^* \quad (8)$$

Fig. 7 shows the frictional force as a function of normal load for freshly drawn silica fibres in the air. Each data point represents the mean of static frictional force observed in the friction spectrum for a pair of fibres. The coefficient of friction, $\mu(= F/N)$ decreases from a large value, up to 10 at very small loads, to about 5.2 at around 2 μN. Extrapolation of the linear regression line to a zero applied load results in a finite force (1.8 μN). Clearly, Amonton's empirical law does not apply when the applied force is comparable to the adhesional force.

By taking experimentally determined frictional forces and the estimation of the real area of contact between two fibres, the shear strength at the contact point was determined. Fig. 8 shows the calculated

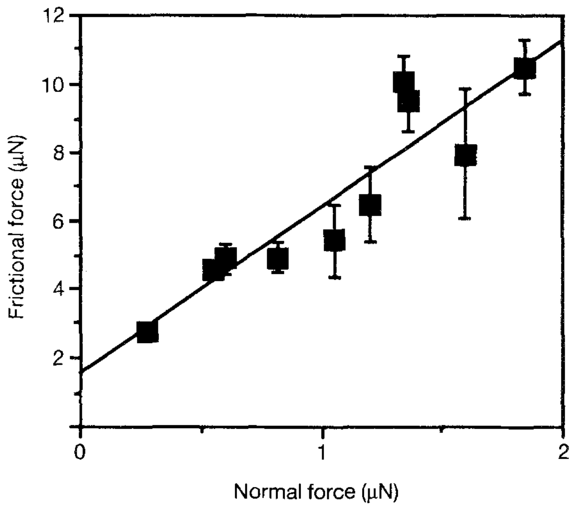

Figure 7 Frictional forces as a function of applied load.

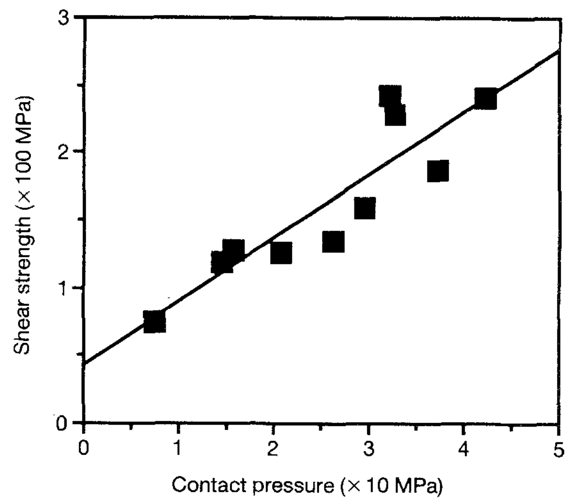

Figure 8 Contact pressure dependence of the shear strength.

shear strength (τ) against contact pressure (P). An extrapolation of the shear strength to zero applied load yields a value of 42 MPa. It is noticed that increasing the contact pressure causes a remarkable increase in the shear strength. Presumably sliding causes microscopic deformation that occurs at the sliding interface, that relieves the stresses and results in an increase in shear strength.

4. Conclusions

The surface energy of silica fibre deduced from pull-off force measurement showed that there are strong short-range repulsive forces that reduce the interaction energy. In the friction experiments, the sliding motions were intermittent and showed stick-slip behaviour which indicates that the junction between two fibres was continuously formed and broken. When the shear strengths were plotted as a function of contact pressure, it was observed that the shear strength increased remarkably with a small increment of the applied load, and was roughly proportional to the applied load.

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