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Optical observations of "junction growth" in asperities of copper, aluminium, PTFE and nylon under combined normal and tangential stresses

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An experimental investigation is described in which the phenomenon of "junction growth" in model conical and spherical asperities of copper, aluminium, PTFE and nylon has been examined optically. The test asperity was first normally pressed against a smooth flat surface of soda-lime glass and the contact observed through the glass surface. In the presence of the normal load the asperity deformed plastically. When a tangential force was applied, the size of the real area of contact between the two solids, as measured *in situ*, was found to increase for all the asperities used. Depending upon the geometry and material of the test asperity, the increase in the size of the contact area was up to 40%. The behaviour was compared with an analytical expression for junction growth in the case of a right circular cylindrical asperity. The closest agreement between the measurements and the theory was found for the 60° conical asperities of work-hardened copper and for nylon spheres. The sliding of the asperity on the glass plate caused transfer of the material of the former to the latter. This occurred for all the asperities used. Moreover, the sliding of the metallic asperities resulted in up to $\sim 5\,\mu$m deep grooves on them as well as on the glass plate. These observations have also been briefly discussed.

1. Introduction

When a solid is pressed against another under a normal load, contact occurs only at the microscopic asperities present on the two solids [1, 2]. Generally, the real area of contact between the two solids is much smaller than the apparent one. If the applied normal load is sufficiently high, plastic flow of the asperities occurs. In the presence of this normal load, if a tangential load is also applied, it has been observed with metals that the real area of contact increases. This was first reported by McFarlane and Tabor [3], who defined the phenomenon as junction growth, and independently by Parker and Hatch [4]. The latter used an arrangement (i.e. metal sliding on glass) similar to that employed in the present investigation. Junction growth with metals, such as gold, platinum, tin, indium, and mild steel, has been studied quantitatively by Courtney-Pratt and Eisner [5] by measuring the electrical resistance between the contacting metallic surfaces. However, junction growth has hitherto not been observed with polymers [6].

The growth of junction with metals has been ascribed to the combined effect of normal and tangential stresses on the plasticity at the interface, and several empirical relations have been derived. They are of the form

$$P^2 + \alpha S^2 = P_0^2 \tag{1}$$

where P_0 and P are the normal pressures in the absence and presence, respectively, of the tangential stress S, and α is a constant, the value of which has been experimentally found to lie [7] in range 3 to 25.

In a later paper, Johnson [8] applied slip-line field theory to the case of a two-dimensional wedge-shaped asperity of a soft metal loaded against a hard flat and derived a value of α of ~ 12. More recently, Chaudhri [9] has analysed the behaviour of a right circular cylinder (see Fig. 1) of a non-work-hardening isotropic material of critical shear stress, k, pressed against a hard flat surface and, using the Tresca criterion of yielding, has derived the relation

$$P^2 + 4S^2 = P_0^2 \tag{2}$$

Whereas P_0 for the cylinder is $2k$, this is not the case for conical, pyramidal, or spherical specimens [10, 11]. No analytical solutions for junction growth have been derived for such specimens. It appears, however, that for cones of small included angles (e.g. 30°, 45°) for which P_0 is close to $2k$, e.g. work-hardened copper, Equation 2 may apply approximately.

The electrical method of monitoring the junction growth has some serious limitations: (i) it cannot be applied to insulating solids, and (ii) surface films (in the case of metallic solids) may be disrupted due to sliding in an unpredictable manner and thus may give rise to a wrong value of the area of contact (see, for example, Courtney-Pratt and Eisner [5]).

In the investigation described below we have used an optical technique for measuring the true area of contact *in situ* between two solids simultaneously subjected to normal and tangential stresses. Single asperities of copper, aluminium, PTFE and nylon of

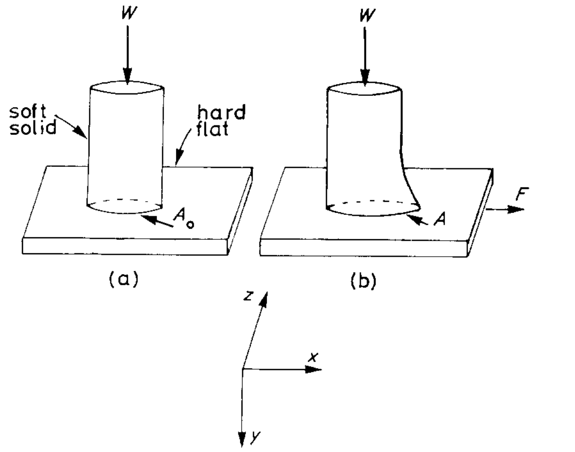

Figure 1 Schematic representation of the junction growth. In (a) a right circular cylinder of a soft solid is placed on a hard flat, under a normal load W. Plastic flow occurs at the entire area of real contact A_0. In (b) a tangential force F is applied along the x-axis; this causes further yielding and the area of real contact increases to A [9]. $P_0 = W/A_0$; $P = W/A$.

different geometries were used and in all of them a significant amount of junction growth took place.

2. Experimental details

2.1. Materials

Spheres of PTFE and nylon, diameter 3.14 mm, and 2.98 mm diameter aluminium spheres were obtained from Insley Industrial Ltd, UK. Cones of included angles 30°, 45°, 60°, 90°, 120°, 150° and 170° were machined carefully from as-received 6.35 mm diameter rods of copper (C102) so that the tips obtained were as fine as possible. Most tip diameters were in the range 10 to 25 μm, though some were less than 5 μm. PTFE cones of included angles in the range of 60° to 170° were machined from as-received 6.35 mm diameter rods and two nylon 66 cones of

TABLE I Vickers hardness (indentor load: 50 gf) of the various materials used in this work and their relevant elastic constants.

Material	Vickers hardness (GPa)	Young's modulus (GPa)	Poisson ratio
Copper (as-received rods)	1.32 ± 0.03	120	0.37
Aluminium spheres	0.44 ± 0.01	70	0.34
PTFE (as-received rods)	0.023 ± 0.001	0.36	0.4
PTFE (as-received spheres)	0.043 ± 0.003	–	0.4
Soda-lime glass	5.60	69	0.25

included angles 60° and 120° were machined from a 6.35 mm diameter as-received rod. All cones had a base height of at least 6.35 mm. In this work the spheres and cones were used as model test asperities.

Before use, all spheres and cones were thoroughly cleaned with ethanol and dried.

The Vickers hardness values of the various materials along with some relevant elastic constants are given in Table I. Stress–strain curves of the PTFE and copper were obtained by compressing small cylinders, 6 mm diameter and 6 to 8 mm long, of these materials between flat smooth anvils. The curves are shown in Figs 2a and b. It will be seen that whereas the PTFE shows a considerable amount of strain-hardening, the copper work-hardens only very slightly.

2.2. Apparatus

A schematic diagram of the experimental arrangement used for studying the junction growth of individual asperities is shown in Fig. 3. The test asperity was mounted on one end of an aluminium rod T, of 8 mm diameter and 15 mm long. On the other end of T was a horizontal platform, on which selected dead loads

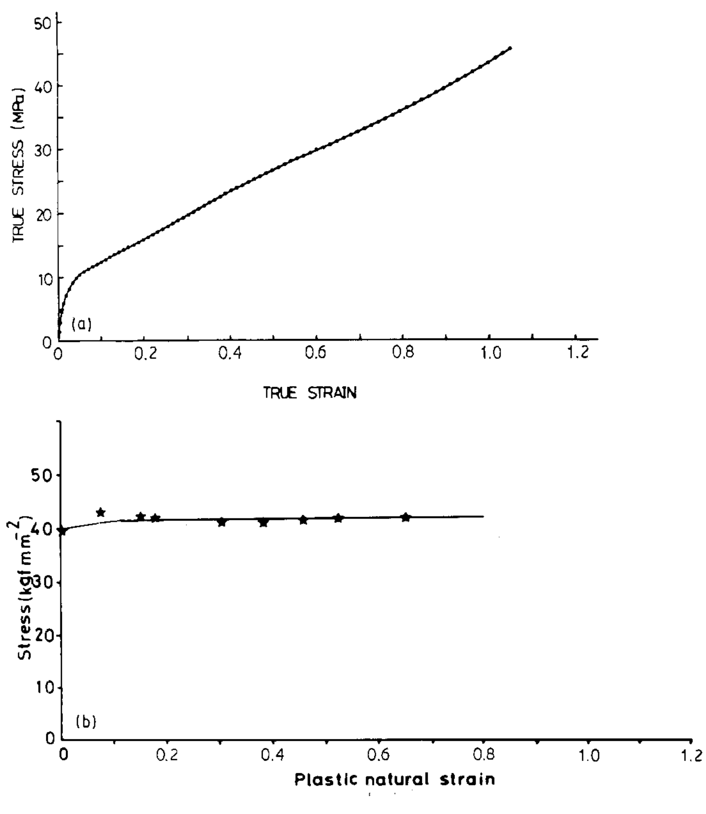

Figure 2 Stress-strain behaviour of (a) as-received PTFE and (b) the work-hardened copper in compression.

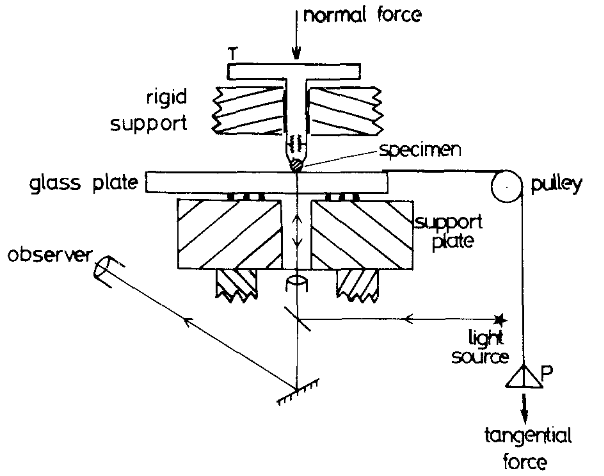

Figure 3 Schematic diagram of the experimental arrangement used for studying the junction growth optically.

were placed. This rod was kept vertically upright with the help of linear bearings, and it was capable of sliding freely along the vertical.

The test asperity could be normally loaded on to a clean and optically smooth 3 mm thick soda-lime glass plate, which in turn was firmly held in a mild steel frame. With the help of roller bearings (see Fig. 3), the frame could freely slide horizontally on a thick support plate of steel.

A force in a horizontal direction could be applied to the glass plate by adding small lead spheres, 2 mm diameter, to the pan P, which was connected to the glass plate with a piece of cotton thread passing over a pulley, as shown in Fig. 3.

The area of contact between the test asperity and the glass plate was viewed through a microscope using reflected light. When desired, the contact area could be photographed.

2.3. Experimental procedure

First, a chosen normal load in the range 0.2 to 2.5 kgf was applied to the test asperity, which was sufficient to cause plastic flow at the contact. A photograph of the contact area was then taken. Then lead spheres were gradually and gently added to the pan P (Fig. 3). The contact area was constantly observed through the microscope and it was photographed at regular increments of the tangential load, which could be measured to an accuracy of 0.1 gf. The latter was increased until the glass plate began to slide continuously with respect to the asperity; the sliding was eventually arrested by means of a mechanical stop built in the apparatus.

In the case of the metallic asperities, the real contact area was brighter than the background, whereas it was the reverse for the polymer asperities. The size of the contact area at different stages of loading was measured graphically from the photographs; in these measurements, an account was made of the smaller non-contact areas existing within the larger size areas of contact. The resolution attained through the microscope was 2 μm.

The experiments were carried out in the laboratory atmosphere at a temperature of about 20° C. Each asperity was used only for a single normal load. Similarly, a fresh glass plate, thoroughly cleaned in ethanol and dried, was employed in every experiment.

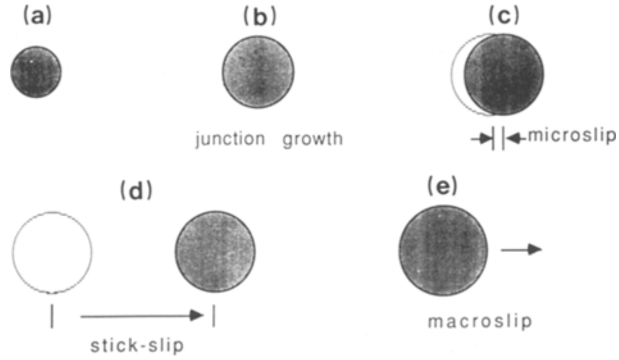

Figure 4 Different stages in the slipping of an axisymmetric asperity against a glass plate. At (a) the asperity is under purely normal loading, W, which causes a plastically deformed circular contact of area A_0. At (b) a tangential force, F, has been gradually applied to the contact while W was retained as in (a). The contact area, A, has increased (junction growth) under the combined stresses, retaining the same centre. Further increase of the tangential force brings a stage when, besides growing in size, the contact area shifts abruptly a few tens of micrometres in the direction of the applied tangential stress (see at c). The broken line represents the position of the previous contact; we define the process as microslip. As F continues to increase, further junction growth occurs, without any relative displacement between the asperity and the glass plate, until at a high enough tangential force the contact area is displaced abruptly by several millimetres (see at d). We call this the "stick–slip" stage. As before, the dotted and solid circles represent the contact before and after the occurrence of the "stick–slip", respectively. With increasing tangential force, and after further junction growth, a particular value of F is reached when the contact begins to move continuously over the glass plate (see e). We call this macroslip.

After completing a sliding experiment with an asperity, it and the glass plate on which it slid were examined under another optical microscope working at a higher magnification than that used in the apparatus shown in Fig. 3. Further investigations of the glass plates for any grooves and transferred material were made in a scanning electron microscope (Cambridge Stereoscan 250 mk2), which incorporated a Link system X-ray energy analysis facility. In some of the glass plates, grooves were formed due to the sliding of asperities. The profiles of these grooves were recorded with a Talysurf 4 (Taylor and Hobson).

3. Observations and results

The test asperities deformed plastically under all the normal loads used in these experiments. The real contact area between the test asperity and the flat glass plate was clearly visible through the microscope and was roughly circular in shape.

When the tangential force on the glass plate, against which the test asperity was pressed under a normal load, was gradually increased from zero, in all cases the real area of contact was found to increase, maintaining its shape and retaining its centre at the same position as when the applied tangential force was zero.

During the gradual increase of the tangential force, several stages of the slipping process at the asperity/glass plate interface were noted. These are shown schematically in Fig. 4. At (a) the asperity is pressed against the glass plate under a normal load, W. The

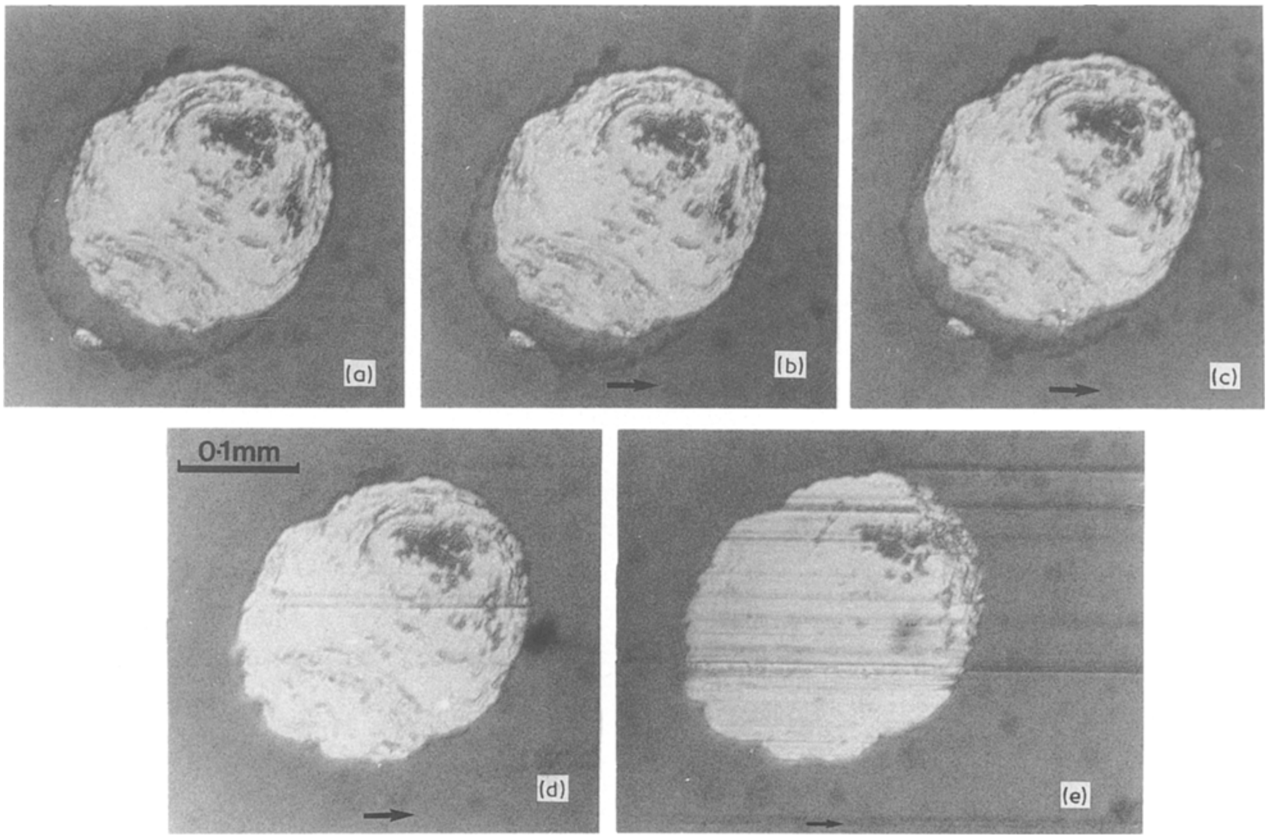

Figure 5 Junction growth in a conical asperity of included angle 45° of the work-hardened copper. In (a) the asperity is pressed against the glass plate under a purely normal load of 2 kgf. The brighter area represents the true contact. In (b) and (c) the tangential forces are 70 and 89 gf, respectively; the arrow at the bottom of each frame indicates the direction of the tangential force and the sliding. Note that the size of the contact area has increased, but without there being any relative displacement between the solids. In (d) the tangential force is 127 gf, which is sufficient to cause microslip; this gives rise to grooving of the copper as well as of the glass plate. The grooves, about 5 μm deep both in the glass and copper, form straight lines along the sliding direction. The degree of grooving increases when macroslip occurs at a tangential force of 141 gf (see e).

tangential force, F, is zero and the real contact is roughly circular. With the application of a tangential force, F, the radius of the contact circle increases, (see at b) with no relative displacement between the glass plate and the asperity. The contact area continues to increase with increasing tangential force, but when the latter reaches a critical value, which is different for different asperities, there is a rather sudden relative displacement, defined as microslip, of about a few tens of micrometres, between the asperity and the glass plate (see at c). This is accompanied by a discontinuous increase in the contact area. If the tangential force is not increased further, there is no more relative displacement of the glass plate. That this was so was checked for a time of up to 80 sec. This type of microdisplacement between metallic solids has also been investigated by Courtney-Pratt and Eisner [5]. However, our observations contrast with theirs: they did not observe any discontinuous relative displacements. A possible reason for this difference is given in Section 5.

In some cases more than one microslip phase occurred at different values of the tangential force.

As the tangential force continues to increase, another stage is reached at which the glass plate slips abruptly with respect to the asperity by about 1 to 10 mm and again causes a discontinuous increase in the contact area (see at d). At this tangential force, this relatively large-scale slip occurs just once at the end of which the relative velocity becomes zero once again. We call this stage the "stick–slip" phase.

Again, as before, if a higher tangential force is applied, the contact area increases correspondingly. But with a further increase of the former, another stage is reached at which the glass plate begins to slide continuously against the asperity and continues to do so until it is stopped by the mechanical stop (see at e). We call this macroslip and denote the critical tangential force which caused it by F_c.

It may be added that in any particular experimental run, either or both of the microslip and stick–slip stages could be absent.

3.1. Evidence of junction growth

Junction growth occurred in all types of asperity used in this work. Typical examples from each material will be presented separately.

3.1.1. Copper cones

The variation of the area of contact in a copper cone of included angle of 45° due to the application of different magnitudes of the tangential force is shown in Fig. 5. In (a) the normal load on the asperity is 2 kgf with the tangential force being zero; the brighter area represents the true contact, whereas the darker zones within it are regions of non-contact. In (b) the applied

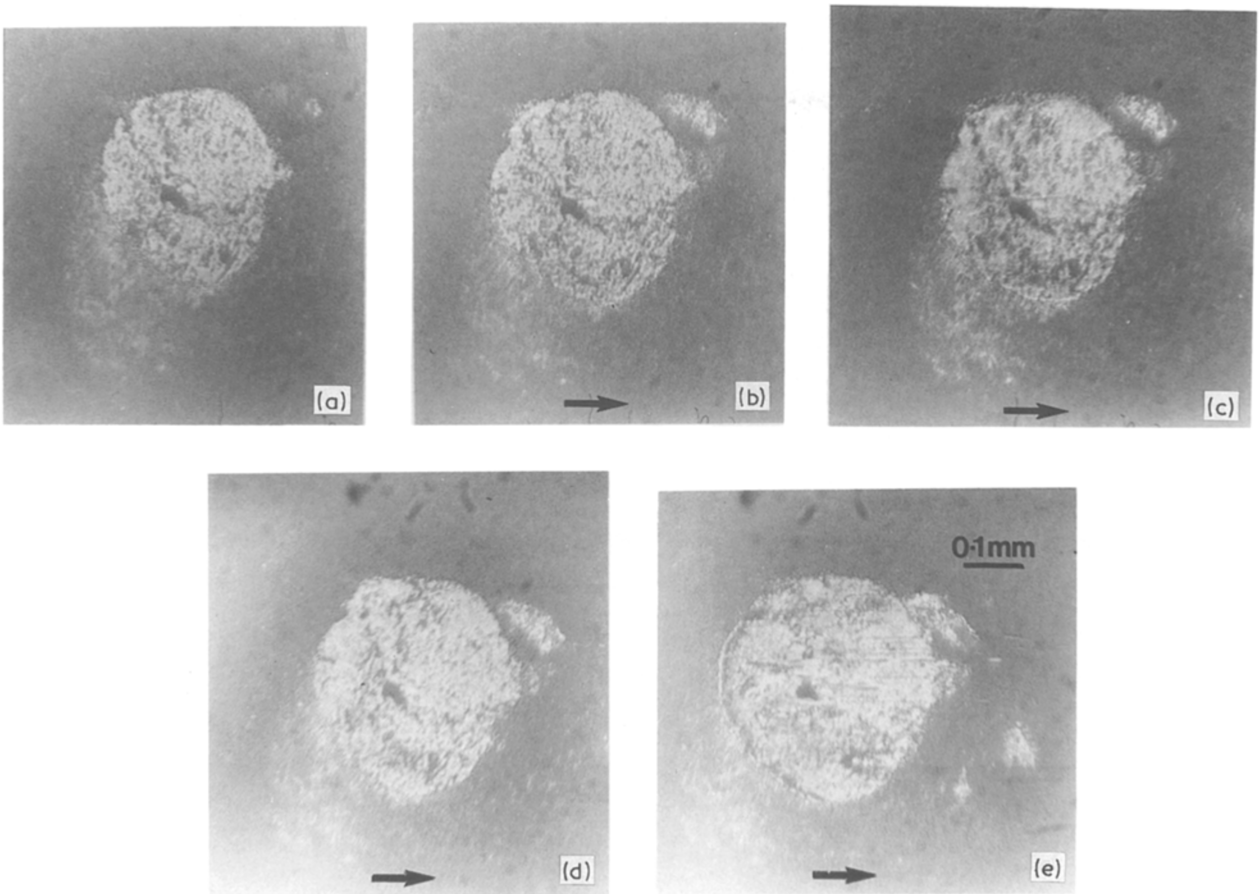

Figure 6 Junction growth in a 3 mm diameter aluminium sphere pressed against a glass plate and subjected to combined normal and tangential stresses. The normal load in all frames is 1750 gf, whereas the tangential loads are as follows: (a) $F = 0$ gf; (b) $F = 222$ gf; (c) $F = 229$ gf; (d) $F = 252$ gf; (e) $F = 369$ gf. The arrows indicate the direction of the tangential force and sliding of the glass plate. Note some non-contact regions (i.e. darker) within the contact (i.e. lighter) area.

tangential force has been increased to 70 gf and as yet no relative displacement between the glass plate and the asperity has taken place. The true area of contact is larger in (b) than in (a); this has happened by an increase in the average radius of contact and also by a reduction in the total area of the darker zones within it. In (c) the tangential force has been increased to 89 gf, but still there is no relative displacement between the asperity and the plate. However, the true area of contact has increased further. As the tangential force is increased to 127 gf, "stick-slip" occurs along with a further increase in the contact area (see Fig. 5d). It may also be noted that in this experimental run the microslip stage was not observed. With further increase of the tangential force to 141 gf, the glass plate slid continuously, until its movement was arrested by the mechanical stop. In (e) the glass plate has come to a halt after having slid for some distance. Note that there are a number of straight lines in the sliding direction right across the contact area; these lines also extend on to the glass plate. On further examination at a higher magnification, the lines were found to be due to grooves both on the copper and on the glass plate. Typical groove depths were $\sim 5\,\mu$m in the glass and copper.

It was also observed that the continuous sliding process left smears of the copper on the glass plate. This transferred copper was found to adhere firmly to the glass.

3.1.2. Aluminium spheres

Fig. 6 shows the process of junction growth in the case of an aluminium sphere pressed normally against a glass plate. In (a) the normal load is 1750 gf, and there is no tangential force. As for the copper cones, the true area of contact appears bright and within this bright zone, dark areas, corresponding to non-contact, can also be seen. The true contact area grows with the application of an increasing tangential force, as shown in (b), (c) and (d) for which the tangential forces are 222, 229 and 252 gf, respectively. Continuous sliding occurs when the tangential force reaches a value of 369 gf. In (e) the continuous displacement of the glass plate has been arrested. Note that there are a number of grooves on the glass plate, all aligned along the direction of sliding. Some of these grooves appear to originate at the dark spots, corresponding to regions of non-contact, within the larger contact zone. The mean normal pressure at the contact at this stage is 207 MPa, which is only about 1/27th of the Vickers hardness value of the glass. The dark regions on the surface of the deformed aluminium sphere and within the contact zone were examined in the scanning electron microscope using the Link System energy dispersive X-ray analyser. Apart from a minute trace of sodium, no other impurities were detected. However, we could not ascertain whether there was any aluminium oxide on the aluminium sphere.

The grooves on the glass plate were also examined

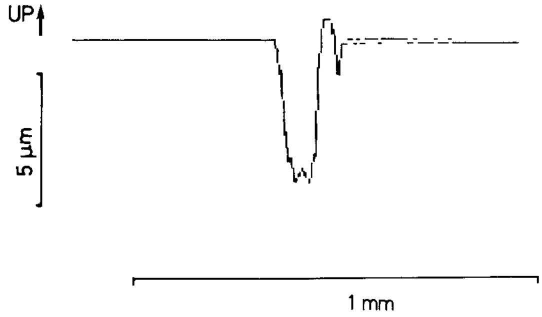

Figure 7 The surface profile of a groove on a glass plate formed due to the sliding of an aluminium sphere on it, under a normal load of 1500 gf.

with the surface profilometer. A profile of a groove formed by a single traversal of an aluminium sphere under a normal load of 1500 gf and F_c = 315 gf is shown in Fig. 7; its maximum depth is ~ 5 μm and it is ~ 100 μm wide. These dimensions are typical of the grooves on the glass. We did not observe any chipping of the glass from around the grooves, probably suggesting that there was not enough stored elastic energy in the glass.

During the sliding under combined normal and tangential forces, some aluminium was transferred from the sphere on to the glass plate. An example is shown in Fig. 8. Here an aluminium sphere was first pressed against the glass plate under a normal load of 1750 gf; then the tangential force was gradually increased. Continuous sliding of the glass plate with respect to the sphere commenced when the tangential force reached a value of 409 gf. In Fig. 8a the sliding has been arrested. A piece of the aluminium, P, has been transferred from the sphere on to the glass, leaving a dark region almost equal to the size of the detached piece within the contact area (see at D). Because the original normal load on the sphere still exists, the freshly created dark zone fills up with newly deformed metal in order to bring back the mean normal pressure to the same value which existed before the aluminium piece detached from the sphere (see Fig. 8b).

3.1.3. PTFE cones and spheres

Fig. 9a shows the contact area between a PTFE cone of included angle 90° and a glass plate pressed together by a normal force of 1000 gf. As a tangential force of 56 gf is applied (Fig. 9b) to the junction, the radius of the contact increases significantly. In (c) and (d) the tangential forces are 66 and 74 gf, respectively; the contact area in (d) is ~ 1.3 times that in (a). As for the metallic asperities, continuous displacement of the glass plate with respect to the conical asperity causes the transfer of the PTFE material on to the glass. In the case of a PTFE sphere, the variation of the real area of contact under a varying tangential force is shown in Fig. 10. The values of the normal load and the tangential force are given in the caption to the figure. The glass surface was not examined for any transferred layer of the PTFE, which probably took place. In fact, the transfer occurred under the action of a normal force alone. An example is shown in Fig. 11; the loading conditions are given in the caption to the figure.

3.1.4. Nylon cones and spheres

The junction growth behaviour of the nylon cones and spheres was similar to that of the PTFE cones and spheres. Fig. 12a shows the area of contact between a 120° nylon cone and a glass plate under a normal load of 2 kgf; here the tangential force is zero. In (b) the tangential force is 98 gf, which gives rise to an enlarged area of contact. In (c) the tangential force is 142 gf, which causes a further increase in the size of the contact. Continuous displacement of the glass plate with respect to the asperity occurs in (d) when the tangential force is 172 gf. Transfer of the nylon on to the glass plate during the sliding also occurs. It is interesting that for all stages of the tangential force, the true area of contact remains fairly circular (with contact occurring at all points within the contact circle) with junction growth taking place radially outwards with equal amounts in all directions.

In the case of the nylon spheres, the contact was rather discontinuous; this was due to the fact that the original surface of the as-received nylon spheres was relatively rough. A sequence of photographs of the contact area of a sphere pressed against a glass plate with a normal load of 1250 gf and for different values of the tangential force is shown in Fig. 13. In (a) the tangential force is zero; the contact area increases significantly as the tangential force increases to 322 gf in (c). An effect of the tangential force on the contact

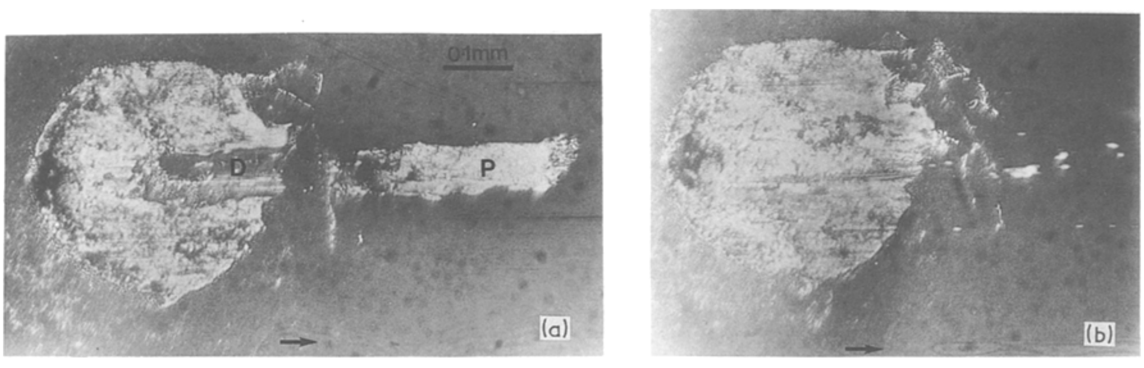

Figure 8 Transfer of aluminium from a 3 mm diameter sphere on to the glass plate during sliding, when the loading conditions were W = 1750 gf, F = 409 gf. In (a) the transferred piece P leaves a region D of non-contact between the sphere and glass. With increasing time, and continued sliding, plastic flow of the aluminium, in (b), increases the contact area to a value equal to that before P had detached. The arrows at the bottom indicate the direction of the tangential force and sliding.

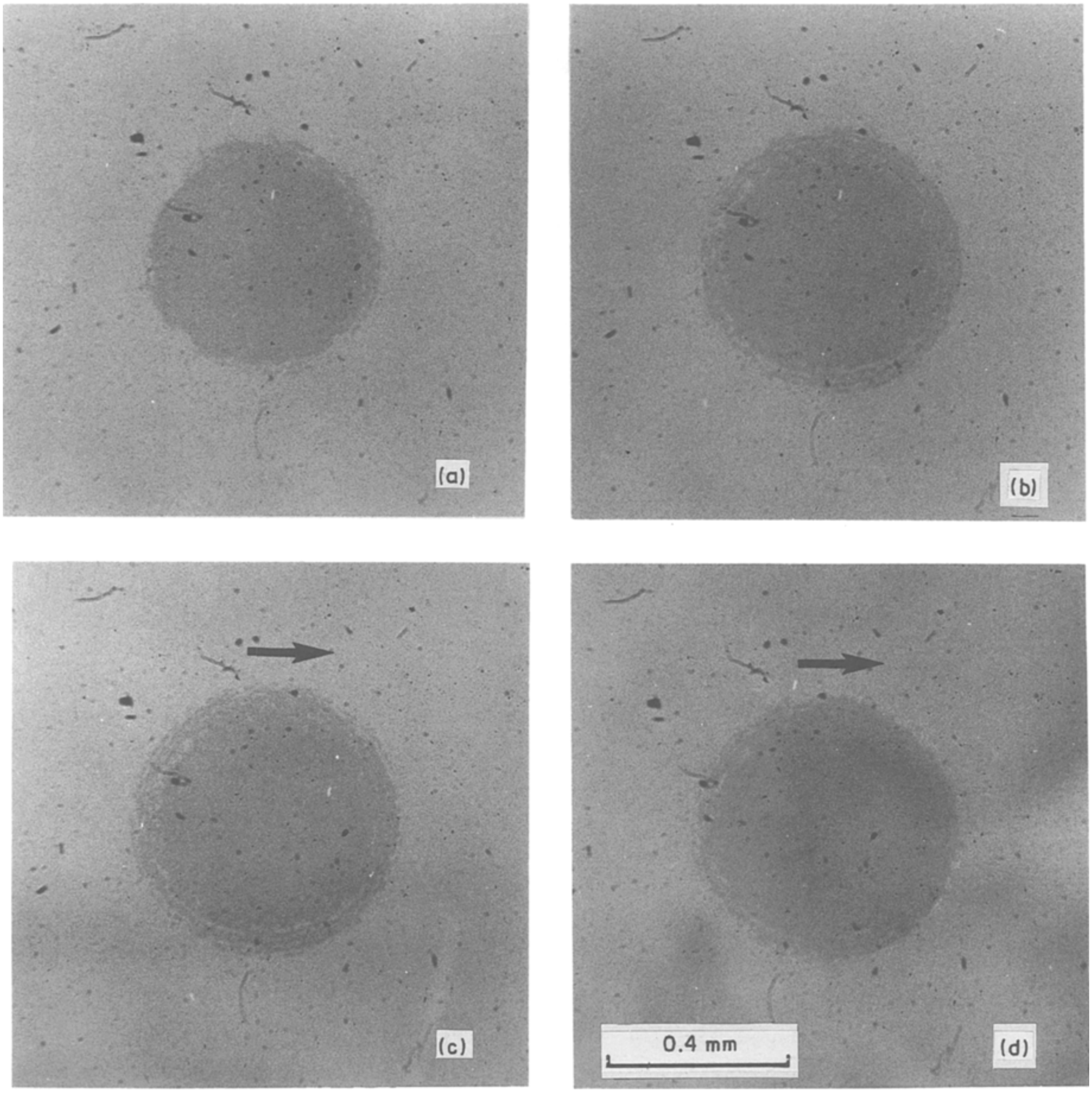

Figure 9 Junction growth in a 90° (included angle) cone of PTFE due to combined normal and tangential forces. The normal force in all frames is 1000 gf. The values of the tangential force are (a) 0 gf; (b) 56 gf; (c) 66 gf; (d) 74 gf. The arrows indicate the direction of the tangential force. No relative displacement has yet occurred. The darker area represents the true contact. Note non-contact areas (i.e. lighter) within the larger contact (i.e. darker) zone.

area is to make it more continuous. Fig. 13d shows the contact area after slip has occurred at $F_c = 352$ gf. For both the cones and spheres, nylon is transferred to the glass plate as the latter slides with respect to the former.

3.2. Contact area variation due to tangential stress

Figs 14a to f show typical relative variations of the true area of contact for asperities of different materials and various geometries due to the applied tangential stress. In Fig. 14a different regions of the tangential stress corresponding to the different slipping processes have been indicated with digits 1 to 5; in the rest of the frames these zones have not been marked. (This zone division corresponds to that shown in Fig. 4.) In zones 1 and 3 only the junction growth occurs, while in zones 2, 4 and 5 junction growth along with microslip, stick–slip and macroslip (i.e. continuous sliding) take place, respectively. It is interesting to note that both for the metals and polymers the size of the true area of contact at the moment of the continuous sliding due to the application of a tangential force, F_c can be up to 40% higher than that in the absence of the tangential force. Moreover, for a given applied tangential stress the relative increase of the contact area appears to be significantly larger in the conical asperities of small included angles than in the spherical ones (compare Figs 14b with e, and c with f). Although this may be partly due to any differences in the mechanical properties of the materials from which the conical and spherical asperities are made, their geometry also appears to be important.

4. Data analysis

From the measurements described in the previous section, the following quantities are obtained: (i) the behaviour of the mean normal contact pressure of cones and spheres with varying included angle and

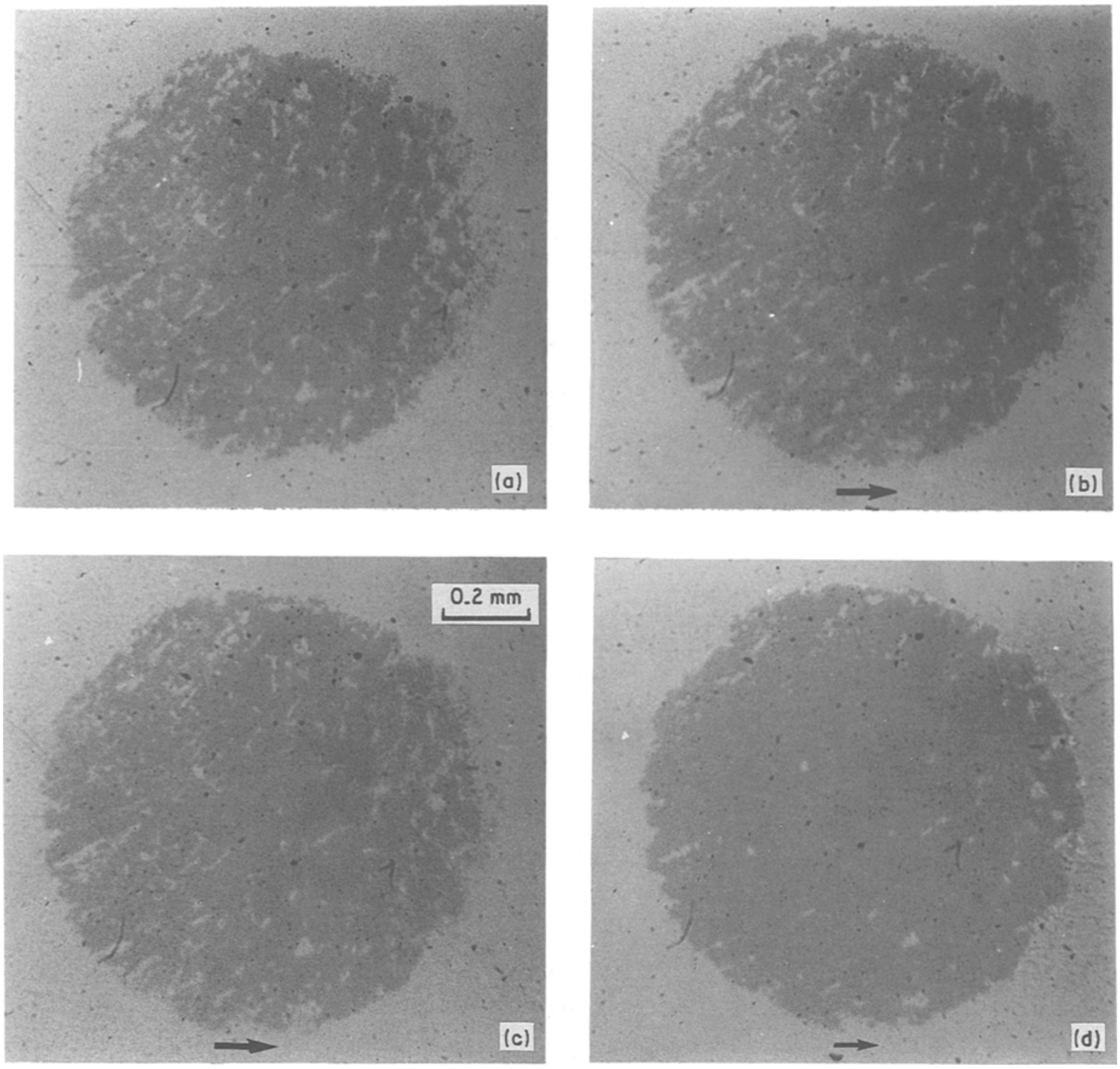

Figure 10 Junction growth in a 3 mm diameter PTFE sphere due to combined normal and tangential forces. The normal force in all frames is 1750 gf, whereas the tangential force is different in different frames: (a) 0 gf; (b) 180 gf; (c) 199 gf; (d) 264 gf. The arrows indicate the directions of the tangential force and sliding. The darker area in each frame represents the true contact.

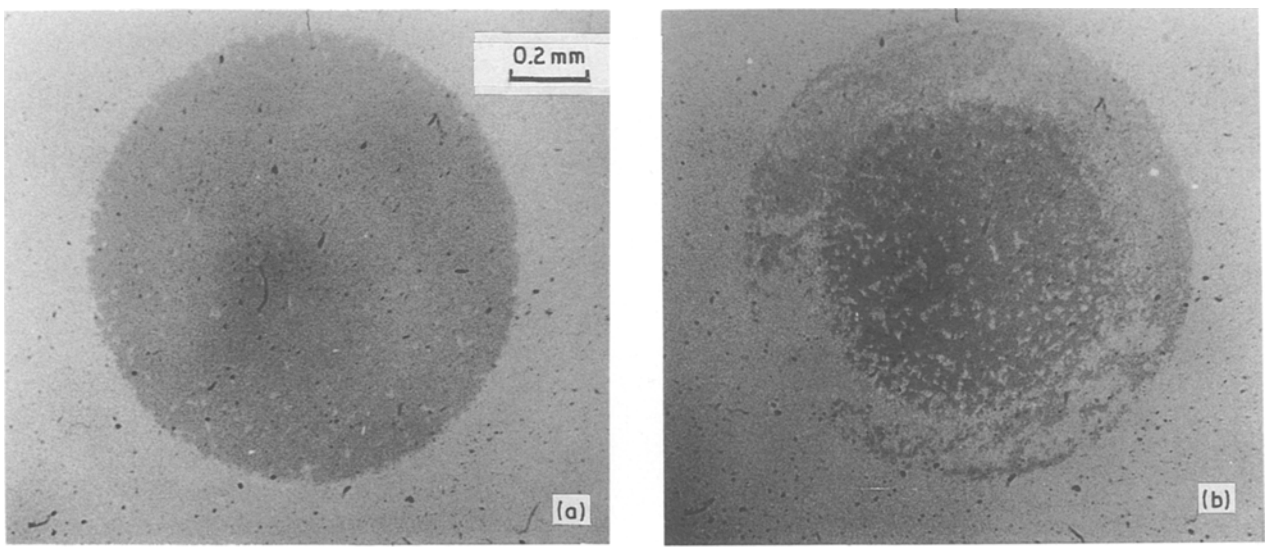

Figure 11 Transfer of PTFE to a glass plate due to normal loading alone. In (a) a 3 mm diameter PTFE sphere is pressed against a glass plate under a normal load of 3430 gf. In (b) the load has been gradually decreased to 510 gf; the central darker circular disc represents the true contact, whereas the fainter outer annulus consists of the PTFE that has transferred to the glass plate.

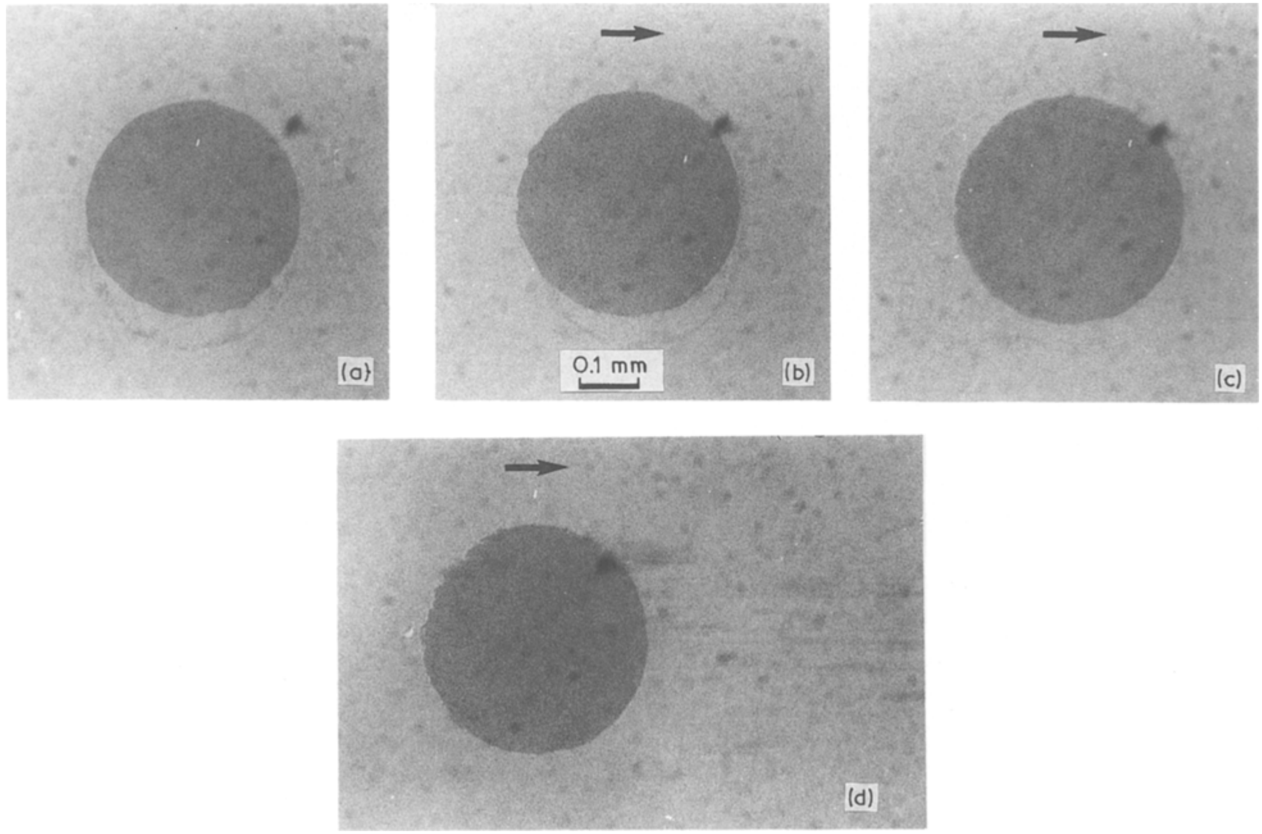

Figure 12 Junction grown in a nylon 66 cone of included angle 120°, which is subjected to combined normal and tangential forces. In all frames the normal load is 2000 gf. The tangential force in the various frames is: (a) 0 gf; (b) 98 gf; (c) 142 gf; (d) 172 gf. The arrows indicate the direction of the tangential force and sliding. Note that in (d) the tangential force is high enough to have caused continuous sliding of the glass plate over the deformed cone. The true contact area is represented by the darker area. There is some indication that the nylon has transferred to the glass plate.

varying a/R, respectively, measured in the presence or absence of a tangential force; and (ii) the magnitude of the asperity/glass interfacial shear strength, S_i.

Using the values of the deformation pressures thus obtained, the validity of the junction growth Equations 1 and 2 was also examined (see Section 5).

4.1. Mean normal contact pressure

Since the application of a tangential force to the plastically deformed contact of an asperity loaded normally causes an increase in the size of the contact area, the mean normal pressure is smaller in the presence of the tangential force than when there is none. In order to present the data, we compare the mean normal pressure values when the tangential force is (a) zero, (b) just sufficient to cause the microslip, and (c) just sufficient to cause a continuous displacement (i.e. macroslip) of the glass plate with respect to the asperity. We refer to the latter two forces as F_μ and F_c, respectively.

The variation of the mean normal pressure of the copper cones with varying included angle for the three different applied tangential forces is shown in Fig. 15a. It is interesting to note that even in the presence of a tangential force, the mean normal pressure increases linearly with increasing cone angle. The behaviour of the PTFE cones (see Fig. 15b) is quite opposite to that of the copper cones. This difference has been related to work-hardening characteristics of the cone materials [12].

The behaviour of the aluminium spheres is shown in Fig. 15c; the pressure variation with varying a/R in the absence of a tangential force is in agreement with the previously published data [11]. Although the application of a tangential force gives rise to a decrease in the normal contact pressure values, the data show a considerable amount of scatter. This may be partly due to a relatively large amount of material transfer and grooving of the glass plate that occurs with the aluminium spheres. In the case of the PTFE and nylon spheres the variation of the normal pressure for different a/R values, as shown in Figs 15d and 16e respectively, is more systematic.

4.2. Interfacial shear strength, S_i

From a knowledge of the true contact area, A, of an asperity corresponding to an applied tangential force, F_c, the value of S_i was determined using the relationship $S_i = F_c/A$. Even for a single material, S_i was found to vary for asperities of different geometries. A comparison of our experimentally determined S_i values and the bulk shear strength, S_b, values of the various materials has been given in Table II.

5. Discussion

The experiments reported here have yielded a number of important observations. First of all, it has been established that if an axi-symmetric asperity of copper, aluminium, PTFE or nylon is first pressed against a hard smooth flat surface, such as glass, by a normal load sufficient to cause plastic flow at the contact region, the area of the contact grows when, in

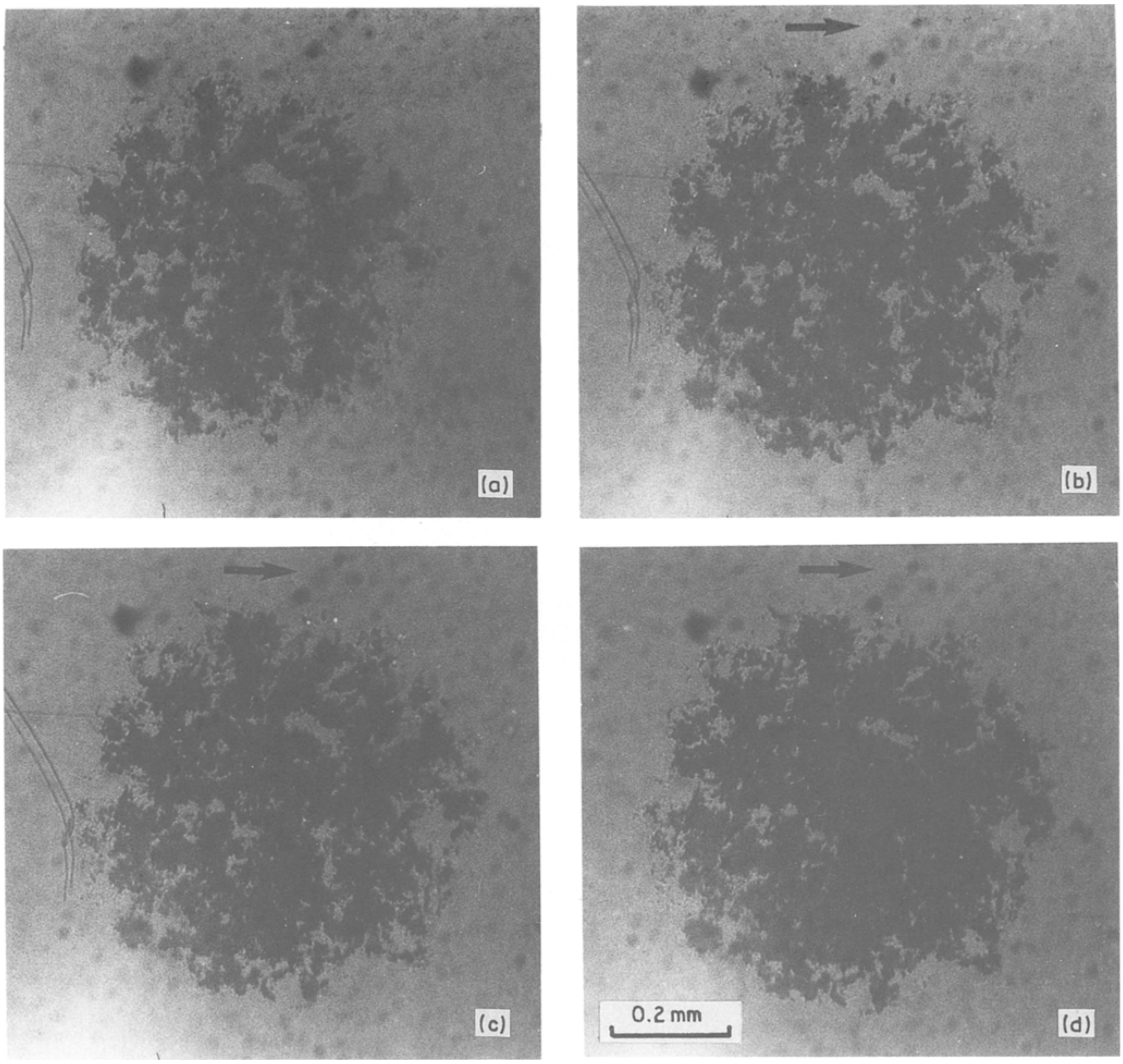

Figure 13 Junction growth in a 3 mm diameter nylon sphere under combined normal and tangential forces. The former is kept constant at 1250 gf, while the latter is varied. The tangential force in the different frames is: (a) 0 gf; (b) 268 gf; (c) 322 gf; (d) 352 gf. The darker area represents the true contact and the direction of the tangential force and the sliding is represented by the arrows. Note the relatively large areas of non-contact (i.e. lighter) within the larger contact (i.e. darker) zone.

the presence of the normal load, a tangential force is applied to the contact. In other words "junction growth" occurs for both metals and polymers. In the case of the latter such observations have not been reported before [6].

During the application of an increasing tangential force, the contact region goes through a number of stages. For low values of the tangential force, the size of the true area of contact increases without there being any relative displacement between the deformed zone on the asperity and the hard flat against which it is pressed. This observation appears to be similar to that made by Courtney-Pratt and Eisner [5]. It will be seen from their Fig. 8 that if the elastic component of the observed displacement within the experimental system is taken into account, then for a tangential force of up to 15% of the normal force, the relative displacement between the slider and the flat is negligibly small. Bowden and Tabor [7] (see Fig. 30, p. 63) suggest that for such low tangential stresses, the two solids sink into each other along the normal load axis. This suggestion is supported by our experiments. For higher tangential forces, we observed discontinuous movements of the slider relative to the flat. On the other hand, Courtney-Pratt and Eisner [5] do not

TABLE II Comparison of the bulk shear strength and the interfacial shear strength of the various materials

Material	Interfacial shear strength, S_i (MPa)		Bulk shear strength, S_b (MPa)	Ratio S_b/S_i	
	Cones	spheres		Cones	spheres
Copper	26–133	–	206 [12]	7.9–1.55	–
Aluminium	–	10–47*	73.3†	–	7.3–1.56
PTFE	1.0–3.5	2.4–5.3	22.8 [13]	22.8–6.5	9.5–4.3
Nylon	5–13	7–15	22 [17]	4.4–1.69	3.14–1.47

*Measured at the point of microslip.
†Taken as (Vickers hardness)/6.

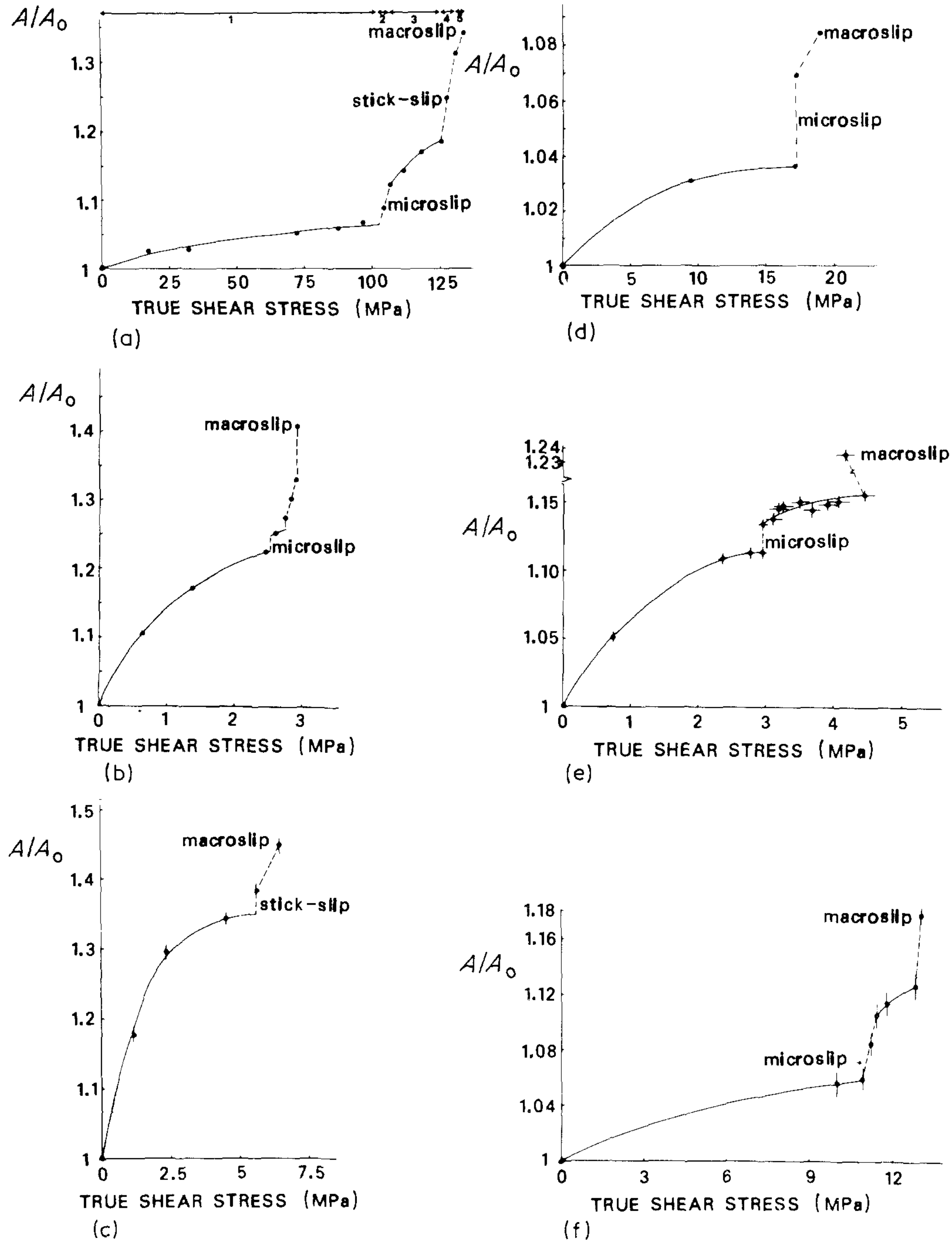

Figure 14 The variation of the true area of contact, A, measured in the presence of the normal and tangential forces, relative to the contact area, A_0, in the absence of the tangential force, for asperities of different geometries and of different materials. Solid lines represent the gradual increase of the contact area without there being any relative displacement between the test asperity and the glass plate, whereas the dashed lines represent the rather abrupt increase of the contact area which occurs along with some relative displacement, as indicated, between the two solids. The asperities and the corresponding normal forces are: (a) 120° copper cone, $W = 2$ kgf; (b) 60° PTFE cone, $W = 3$ kgf; (c) 60° nylon 66 cone, $W = 2$ kgf; (d) 3 mm diameter aluminium sphere, $W = 1.25$ kgf; (e) 3 mm diameter PTFE sphere, $W = 1.5$ kgf; (f) 3 mm diameter nylon sphere, $W = 1.2$ kgf. All angles are included cone angles.

report such discontinuities. A possible reason for the difference may be the nature of the contacting surfaces. In our experiments a soft asperity slides on a hard flat, whereas, Courtney-Pratt and Eisner [5] had both the slider and the flat of the same metal. In the latter, both contacting surfaces may have suffered gross plastic deformation, possibly inhibiting any discontinuous displacements.

During the second slipping stage (i.e. microslip), the size of the contact zone increases rather abruptly and this is accompanied by a definite displacement of a few micrometres of the slider with respect to the flat. Assuming that the interfacial shear strength remains constant, we can understand why the displacement of the slider stops after only a few micrometres' displacement. At the beginning of the microslip, the applied tangential force $F_a = A_a S_i$, where A_a is the contact area at this stage and S_i the shear strength of the interface. During the microslip, as the area suddenly increases from A_a to A_b, the tangential force required to cause further sliding will be $F_b = A_b S_i$; because $F_b > F_a$, the sliding will stop.

The same type of argument may also be applicable during the stick–slip stage. What is not clear at present is the detailed mechanism of the rather abrupt increase of the contact area during each of these stages.

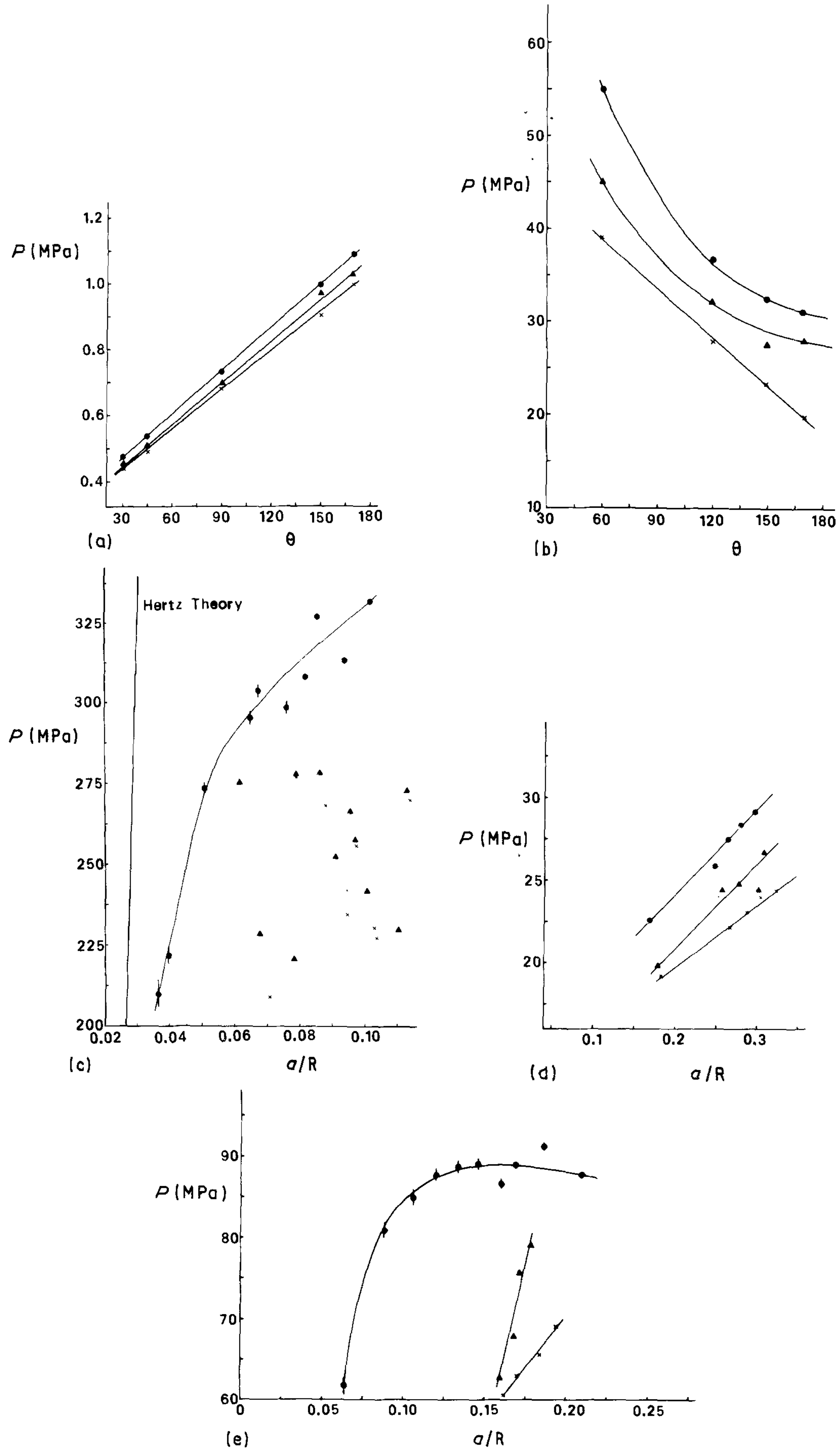

Figure 15 The normal plastic deformation pressure, P, of different asperities due to the action of a normal force alone (●), the normal force and a tangential force, F_{μ}, sufficient to cause the microslip (▲), and the normal force and a tangential force, F_c, sufficient to cause the macroslip (x) between the asperity and the glass plate. In the case of the conical asperities, the variation of P has been plotted against their included angles, whereas for spherical asperities the variation of P has been shown against a/R, where a is the radius of the flat on the deformed sphere whose original radius was R. (a) cones of work-hardened copper; (b) cones of PTFE; (c) 3 mm diameter aluminium spheres; (d) 3 mm diameter PTFE spheres; (e) 3 mm diameter nylon spheres. Note that in all cases the normal pressure in the presence of the combined forces is smaller than that when there is no tangential force.

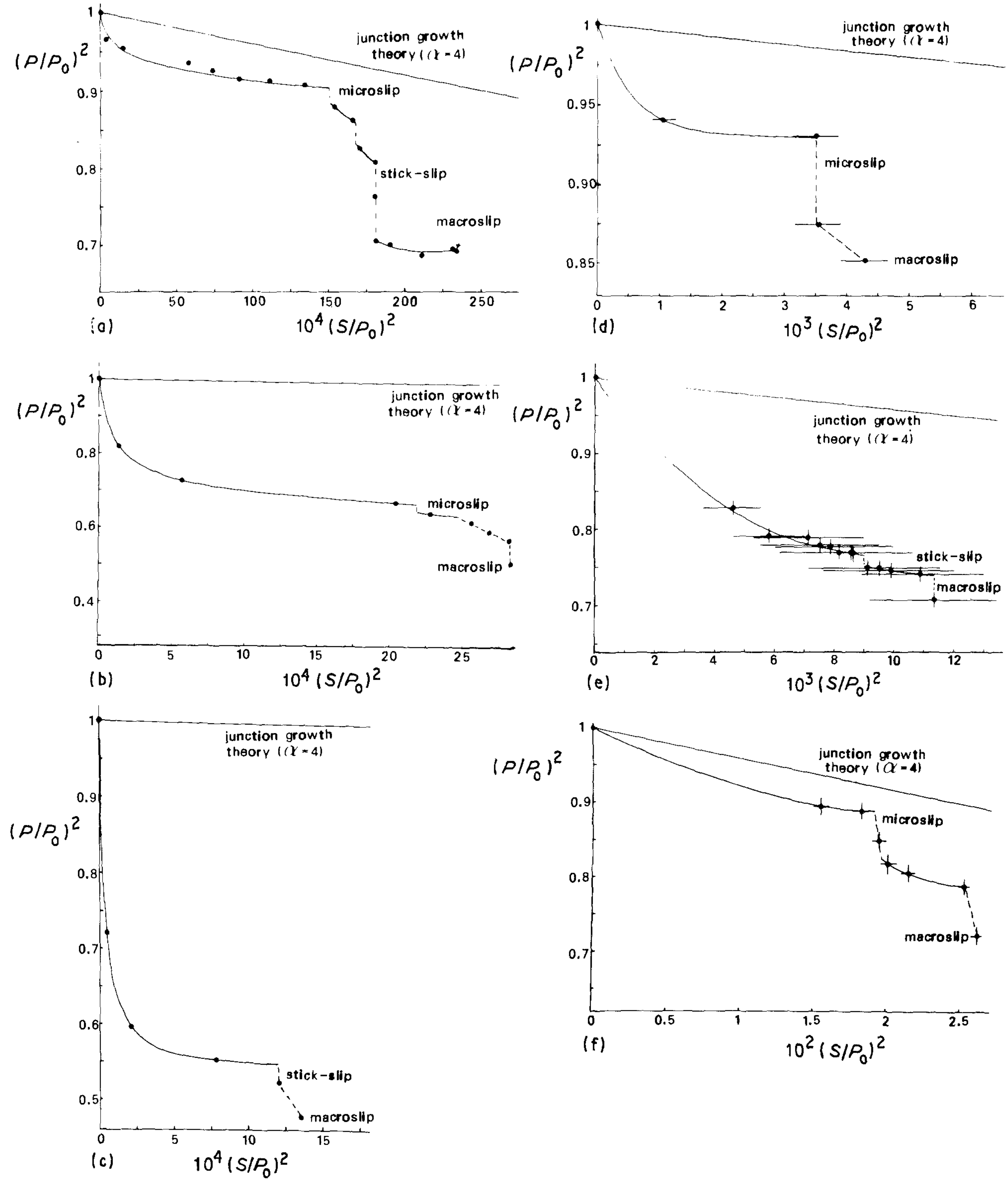

Figure 16 Comparison of the experimental data from different asperities with the junction growth Equation 2. In every curve the solid line represents the effect of the gradual increase of the area of contact with increasing tangential stress, S, whereas the dashed line represents the regions of microslip, stick–slip and macroslip, as indicated. The asperities and the corresponding normal forces are: (a) 60° (included angle) copper cone, $W = 2$ kgf; (b) 60° PTFE cone, $W = 2$ kgf; (c) 60° nylon 66 cone, $W =$ (f)2 kgf; (d) 3 mm diameter aluminium sphere, $W = 1.5$ kgf; (e) 3 mm diameter PTFE sphere, $W = 0.5$ kgf; (f) 3 mm diameter nylon sphere under a normal load of 1.25 kg.

During the macroslip (i.e. continuous sliding), the contact area increases as well. In our experiments it was not possible to see whether the contact area increased abruptly; we could only measure the final area of contact after the relative movement had been stopped by the mechanical stop built in the machine.

The ratios of the bulk shear strength, S_b, and the interfacial shear strength, S_i, as measured from our sliding experiments, have been found to lie within a relatively wide range (see Table II). It also appears that the asperity geometry also controls the value of this ratio to some extent. For example, in the case of the PTFE spheres, the ratio varies from 4.3 to 9.5, whereas, the range is 6.5 to 22.8 for the conical asperities. For a spherical PTFE slider rubbing on glass, Pooley and Tabor [13] give a value of 3.8 for the ratio in their high-friction regime, which is in reasonable agreement with our lower end of the range value of 4.3.

Some of the higher values of the ratio correspond to a regime in which the coefficient of static friction is low, that is less than 0.1. It is interesting that in our experiments low values of the coefficient of static friction were obtained at the instance of the very first macroslip of a PTFE asperity on a clean glass plate. Pooley and Tabor [13] report that for a PTFE hemisphere sliding on soda-lime glass the coefficient of static friction was as high as ~ 0.2. However, if the slider was first allowed to slide ~ 20 to 30 mm on the glass and then, keeping the same orientation of the slider, if a second traverse was made on a fresh part of the glass, the coefficient of static friction was never greater than ~ 0.07. A detailed account of our friction results will be reported separately.

In the case of the asperities of copper, aluminium, and nylon, the values of the ratio S_b/S_i at the lower ends of the ranges are close to 1.5; this is consistent with the observations that material transfer on to the glass occurred for asperities of all the various materials used in the present work.

It is quite possible that the interfacial bonding at the metal asperity/glass plate interface is not uniform and that is why the transfer of the asperity material to the glass plate occurs in patches. In the case of the polymer asperity/glass plate interface, the interfacial bonding appears more uniform. This is also supported by our experiments in which it is observed that the transfer of the polymers to the glass plate occurs quite uniformly. We may add that there was no experimental evidence of the transfer of the glass to any of the asperities [14].

As regards the magnitude of the junction growth, a comparison of the experimental data and theory (see Equation 2) has been provided in Figs 16a to f). The closest agreement appears to be in the case of the copper cone of included angle of 60° and for tangential stress values in the range 0 to $S_{\mu slip}$, where $S_{\mu slip}$, is the shear stress at the moment of microslip. If the tangential force is higher, the departure from the theory becomes greater. As stated in Section 1, for an axi-symmetric asperity such as those in these experiments, we should expect an agreement between experiment and theory only for conical asperities of small enough included angles, so that the normal pressure in the absence of a tangential force is $\sim Y$. This condition is satisfied only for the 30° (included angle) cones of work-hardened copper. Therefore, for a cone of included angle of 60°, we do not expect to observe a perfect agreement.

Finally, we briefly discuss the formation of grooves on the surface of the glass when normally loaded spheres of aluminium and cones of copper were slid on it under the influence of a tangential force. We may emphasize that we were unable to detect any impurity particles on the asperities. In our sliding experiments the normal pressures for the aluminium and copper asperities were in the range 200 to 300 and 500 to 1000 MPa, respectively. We suggest that the grooving of the glass occurs due to the combined action of sufficiently high normal and tangential stresses even though the values of the former may be considerably smaller than the minimum normal pressure values of 3 GPa at which indentation plasticity of soda-lime glass by small WC spheres has been observed [15]. It seems likely that a similar argument will apply in the case of the plasticity of hard MgO crystals by softer conical sliders as observed by Brookes *et al.* [16].

6. Conclusions

The experiments described in this paper have clearly shown that the "junction growth" occurs in copper, aluminium, PTFE and nylon. The experimental results from conical and spherical asperities have shown that the closest agreement between the expression derived by Chaudhri [9] and experiment is for the 60° conical asperities of the copper and for small spheres of nylon. It has also been shown that a relatively hard surface of soda-lime glass can be grooved by sliding on it asperities of copper and aluminium.

After the submission of the paper, Guo, Ross and Pollock [18] have reported the observation of junction growth in the case of a tungsten tip of 0.5 μm in diameter pressed against a gold flat down to zero externally applied loads. However, they determined a rather low value of 0.2 of the constant α (see Equation 1).

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