DEFORMATION AND FRICTION DURING SCRATCHING OF POLYMERIC SURFACES

B.J.Briscoe*, E.Pelillo* and S.K.Sinha*

A scratch deformation procedure is described which has been adopted in order to characterise the surface mechanical damage mechanisms of two polymers; a poly(methylmethacrylate) (PMMA) and an ultra high molecular weight poly(ethylene) (UHMWPE) under dry and lubricated conditions. The variation of the evaluated friction coefficient under a range of experimental conditions, such as the scratching velocity, the imposed strain of the deformation and the state of the interfacial lubrication is described. The results show a marked dependence of the friction coefficient upon the computed contact strain for both materials. The dependence of the friction upon the velocity was found to be evident at the lower velocities when the contact is realised in dry conditions and using the sharper indenters. A subjective assessment of the surface damage was also made for the PMMA system using SEM imaging.

INTRODUCTION

The scratching technique is widely adopted to study the surface mechanical properties of engineering materials, especially metals, and the adhesive strength of coatings. Recently, scratching was found to be a convenient means to investigate the scratch hardness and the scratch resistance of organic polymers (Briscoe et al. (1)), although the method has been long recognised as having value in this context (Bernhardt (2) and Boor et al. (3)). By this route, information about the strain and strain rate dependence of the material deformation may be obtained and deformation maps, constructed from the observation of the surface damage and failure, may be produced (Briscoe et al. (5)).

This paper presents an account of results obtained from the scratching of a PMMA and an UHMWPE. The study is focused upon the interrelationships between the friction and the deformation during the scratching process and the dependence of both upon the contact strain and the contact time. The contact strain was varied by changing the cone angle of the indenter tip, a series of cones, and the

* Chemical Engineering Department, Imperial College, London, U.K.

contact time was varied by using a range of scratching velocities (Briscoe et al. (1) and Johnson (4)). The influence of the interfacial shear stress of the contact has also been studied by performing the scratching under lubricated and unlubricated
conditions.

EXPERIMENTAL APPROACH

Scratch deformations were performed by drawing a loaded conical indenter along the specimen surfaces for a range of scratching velocities (0.0026 to 0.31 mm/s) and conical tip angles (45° to 120°). The rigid indenters used were manufactured from a tool steel and the surface roughness of 2μm c.l.a. for all of the indenters. SEM imaging was used to evaluate the true geometry of the indenter tips and they were found to be slightly rounded. The tip defect of all the indenters was evaluated to be of ca. 5μm radius. Cast poly(methylmethacrylate) (ICI) and an ultra high molecular weight poly(ethylene) (Goodfellow) were studied in unlubricated contacts and lubricated with a commercial silicone fluid (kinematic viscosity ν=0.001 m^2 / s, Dow Corning).

RESULTS AND DISCUSSION

Figure 1 shows the variation of the friction coefficient as a function of the applied normal load for PMMA. Data are shown for both the lubricated and unlubricated (dry) cases, for the indenter of a 60° included angle. The friction data indicate that there is little change in the coefficient of friction when a lubricant is used. This may be due to two possible effects; either that the lubrication is not effective or that the adhesive strength of the contact is small compared to the deformation component. The friction coefficient shows a decreasing trend for the lower loads and the value stabilises at ca. 1.1 (lubricated case) and ca. 1.2 (unlubricated case) beyond a normal load of 2N. An increase in the brittle fracture of the material during scratching is noted as the normal load is increased. The increase of the brittle component increases the friction. This was also noted in a previous study where deformation maps were constructed for different applied normal loads (5). A first order estimate of the friction coefficient for simple ploughing by a cone is given by $\mu = (2/\pi)\tan\theta$, where θ is the angle between the slope of the cone and the sample surface (attack angle) (Bowden and Tabor (6)). Thus, the predicted value (see Table 1), μ=1.102, is near to the experimental value and the friction coefficient is dependent upon the geometry of the contact. The state of lubrication regulates the contact adhesion which presumably has little influence. An explanation for the increasing trend of the friction coefficient at the lower loads is

TABLE 1- Theoretical values of friction coefficient for conical geometry calculated according to Bowden and Tabor (6).

Cone Angle	Attack Angle θ	$\mu = (2/\pi)\tan\theta$
45°	67.5°	1.536
60°	60°	1.102
90°	45°	0.636
120°	30°	0.366

that, below the value of ca. 2N for the applied normal load, the scratch depth values were comparable to the size of the pseudo-spherical indenter tip defect. Therefore, the prevailing different contact geometry gave rise to lower friction coefficients and a more ductile deformation is encountered.

The effects of the scratch velocity and the included angle of the conical indenter upon the friction coefficient for PMMA are given in Figure 2. The data shown are for two interfacial conditions; lubricated and dry. In this Figure there is a general trend of a decreasing coefficient of friction as the scratch velocity is increased from 0.002 mm/s to 0.31 mm/s. This trend is similar for all angles of the indenters. However, for the largest cone angle used (120°), the friction coefficient does not show much change as the scratching velocity is increased. The data obtained from the experiments show a good agreement with the predicted values (see Table 1), calculated according to the equation $\mu = (2/\pi)\tan\theta$ (6), only for the lower velocities and under the unlubricated conditions, except for the 120° cone angle. Therefore, at the higher sliding velocities, the friction coefficient values are found to be no longer dependent exclusively upon the geometry of the contact. In the case of 120° cone angle, the experimental data of friction coefficient are lower than the predicted values for the whole range of velocities. This may be explained by the different damage mechanism occurring for this contact geometry, where a large visco-elastic recovery is noted. The decrease in the friction coefficient from the theoretical values, with the increase of the scratch velocity, is associated with two phenomena at the interfacial contact. An increase of the deformation rate, due to the higher velocity, could possibly generate a thermal heating effect. This has been noted previously for other organic polymers (5) and also in the present study it was found that the interfacial heating may cause a change in the deformation mechanism towards ductile flow suppressing the brittle failure. The other effect is a decrease in the depth of the scratches and hence in the contact area at the high scratch velocity. This is caused by the dynamics of the scratching process and may be interpreted as an effective decrease in the load; see Figure 1.

At the lower velocities, the effect of the lubrication is more pronounced. This suggests that the lower contact velocities allow a greater time for the flow of the lubricant towards the interface between the indenter and the polymer. This effect is greater when the indenter angle is smaller (45° and 60°). This is due to the larger area of contact for the lower angles, owing to the greater scratch force encountered under these conditions. A reduction in the friction coefficient also indicates a change in the mechanism of the deformation from brittle to ductile flow; this is presented in Figure 3. This figure shows a deformation map for PMMA under lubricated and dry interfacial conditions. The map shows that the material tends to deform in a more ductile manner when the present lubricant is utilised. The map also shows the effects of the scratch velocity upon the deformation mechanisms of PMMA. For PMMA, a higher velocity reduces the extent of the brittle fracture. This result correlates with a decrease in the friction coefficient at the higher velocities; as shown in Figure 2.

Figure 4 provides the results of the scratching for an ultra high molecular weight poly(ethylene) (UHMWPE) under dry and lubricated conditions. The scratch experiments were performed for the same range of velocities (0.0026 to 0.31 mm/s) and for a range of conical indenters (45° to 120°) under a normal applied load of 1.3 N. An evident dependence of the friction coefficient values upon the cone angles is observed. Like the case of the PMMA, the friction coefficient increases as the cone angle decreases. Although Figure 4 shows a decrease in the evaluated friction coefficient for the lower cone angles, the experimental data are lower than those obtained from the theoretical prediction (see Table 1). Furthermore, no significant dependence of the friction coefficient upon the scratching velocity is noticed for both states of interfacial lubrication except for the 45° indenter at the lower velocities. This may be explained by the absence of any severe brittle fracture for all range of cones and a general more visco-elastic and highly strain softening behaviour for the UHMWPE compared to the PMMA. For this range of velocities the influence of the lubricant is minimal.

CONCLUSIONS

The friction coefficient which was evaluated from the scratching of a PMMA and an UHMWPE, depends upon the geometry of the contact under both dry and lubricated conditions. At constant applied normal load, the values of the friction coefficient increase as the strain increases (lower cone angles). This trend is detected for both the dry and lubricated cases and for both of the materials tested. The friction coefficient decreases as the scratch velocity is increased in the case of dry PMMA, whilst no relevant dependence was noted for the UHMWPE. A reduction in the friction coefficient under lubricated conditions was found for the sharper cone angles (45° and 60°) for both the PMMA and the UHMWPE, especially at the lower velocities. This may be explained as being due to a more effective lubricating mechanism and the higher values of scratch depth at the lower velocities. Surface brittle failure was detected for the scratches performed with the lower tip included angles (45° and 60°) in the case of the PMMA, undei both dry and lubricated conditions and a regular cracking mechanism was found for the UHMWPE when subjected to scratching under dry conditions with a 45° indenter. A ductile ploughing deformation was prevalent in the case of the scratches performed by the blunter cones (>90°) for both the materials and in any state of lubrication at the imposed normal load. The effect of a reduced interfacial shear stress obtained by using a commercial lubricant was reported and an increase of the ductile deformation for both the materials was seen and with the partial suppression of the brittle surface failure in the case of the PMMA. The brittle mechanism of failure was more severe in the case of the slowest sliding velocities and under dry conditions.Thus, whilst the models based upon ductile ploughing provide a reasonable first order prediction of the friction coefficient, they do not account for the many subtle trends observed for these two polymers as the sliding velocity, load and state of interfacial lubrication are varied.

SYMBOLS USED

μ = coefficient of friction

θ = attack angle

REFERENCES

(1) Briscoe, B.J., Evans, P.D., Biswas, S.K. and Sinha, S.K., "The hardness of poly(methylmethacrylate)", Trib.Int., Jan 1996.

(2) Bernhardt, E.C., Modern Plast., Vol. 26, Oct. 1948, pp. 123-186.

(3) Boor, L., Ryan, J.D., Marks, M.E. and Bartoe, W.F., ASTM Bull., Vol. 145, 1947, pp. 68-73.

(4) Johnson, K.L., “Contact Mechanics”, Cambridge University Press, Cambridge, UK, 1985.

(5) Briscoe, B.J., Pelillo, E. and Sinha, S.K., "Scratch Hardness and Deformation Maps for Polymers", sub. to Pol.Eng.Sci., Jan 1996.

(6) Bowden, F.P. and Tabor, D., "The Friction and Lubrication of Solids", Clarendon Press, Oxford, UK, 1950.

(7) S.C.Lim and M.F.Asby, Acta Metall., Vol. 35, No. 1, 1987, pp.1-24.

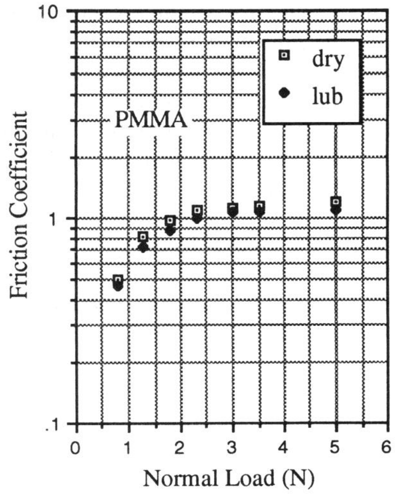

Fig.1 Friction coeff. against load (dry and lubr. contacts; v=0.1mm/s; 60deg cone).

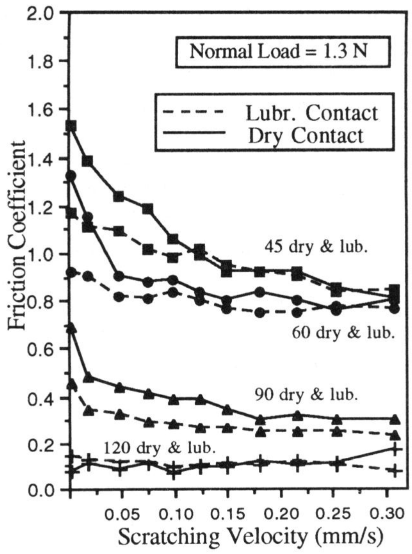

Fig. 2 Friction coeff. vs. scratch velocity for PMMA (various cones; dry/lubr.)

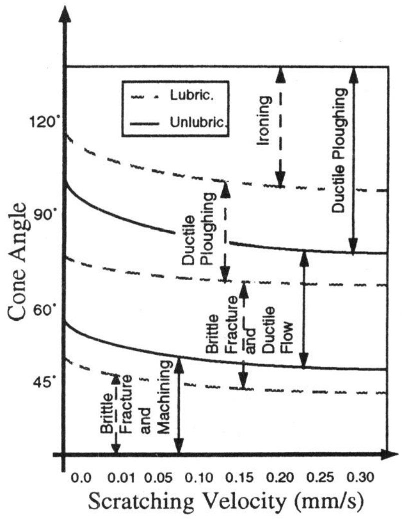

Fig. 3 Deformation Map for PMMA. The normal load is kept at 1.3 N.

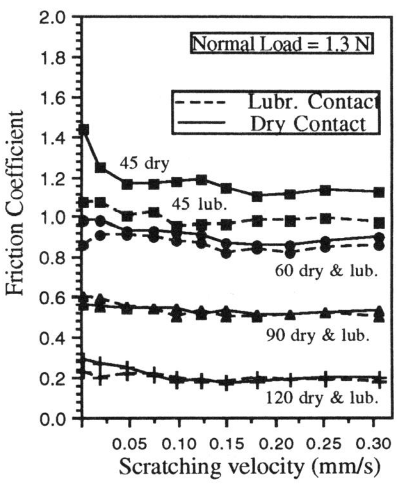

Fig.4 Friction coeff. vs scratch velocity for UHMWPE (various cones;dry/lubr.)