THE VISCOELASTIC VISCOPLASTIC BEHAVIOUR OF A SCRATCH ON A POLYMERIC SURFACE

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SUMMARY
This paper presents experimental results for a body scratched by a single tip and an analysis of the viscoelastic viscoplastic response. The material was a commercial grade of cast polymethylmethacrylate (PMMA) and the experimental data were obtained with a scratch apparatus allowing analysis of the contact area and the groove left on the surface. Transitions from viscoplastic scratching to elastic sliding were observed and temperature, strain and strain rate were found to be important parameters controlling the type of scratching. The approaches used by Hertz to analyse the elastic contact and by Johnson to analyse the indentation pressure are transposed to examine the contact pressure during tangential contact. Strain – stress curves are plotted to determine the evolution of this contact pressure with the mean strain in the contact area. The definition of the mean strain given by Tabor for indentation of a strain hardening material can be used to explore the nature of the strain during tangential contact. As this definition would seem to overestimate the strain in the case of sliding contact, a correction is proposed which takes into account the asymmetry of the contact area, i.e., the ratio of the frontal and rear contact areas.

Keywords: polymer, scratch, recovery, viscoelasticity, viscoplasticity

1 INTRODUCTION

There are several ways of removing matter from a surface with a moving tip: by cutting, grooving, fracture or fatigue damage. Using the same normal load applied to the same tip, the response of metallic materials is a plastic groove (low yield stress compared to the elastic modulus), that of ceramic materials is a fracture with small plastic deformation (low toughness compared to the yield stress), while the response of polymeric materials may be elastic, viscoelastic or viscoplastic. The surfaces of the majority of polymeric materials are highly sensitive to scratches and mechanical models are required to investigate how the surface is damaged, models in which a moving hard tip makes a groove on the viscoelastic viscoplastic material. Most existing scratch models take into account forces acting at the interface between the material and a grooving tip, but do not consider the stress and strain properties of the material beneath or ahead of the tip. In the case of a perfectly plastic material and a grooving tip, the volume of matter removed by plasticity was first calculated by Rabinowicz [1]. The basic assumption of this model is that all matter in the path of the moving tip is removed from the surface. The energy consumed to displace this volume was first estimated by Lamy [2], who introduced a geometrical factor to account for the plastic wave. On the surface of highly viscoelastic viscoplastic materials, the matter "removed" is in fact not removed but rather pushed in front of the tip, creating a wave ahead and on both sides. The wave dimensions depend on the geometry and speed of the tip. There are however no scratch models which take into account the viscoelastic viscoplastic behaviour of the material. Briscoe and Thomas [3] and Gauthier and Schirrer [4] have shown that an analysis of the viscoplastic response of the surface of a material requires an estimate of the strain and strain rate during contact. Generally, the average value of the far field moderate rate \( \dot{\varepsilon} \) may be simply estimated as the tip speed divided by the groove width:

\[
\dot{\varepsilon} = \frac{V_{tp}}{L_g}
\]

(1)

where \( V_{tp} \) is the velocity of the moving tip and \( L_g \) the width of the groove. The mean strain is proportional to the ratio of the radius of the surface contact area to the radius of the tip. In the case of normal indentation, Tabor [5] has shown that the constant ratio of hardness to yield stress for a perfectly plastic solid may be applied with good approximation to a solid hardening under strain, provided the yield stress is replaced by the flow stress measured under simple compression at a representative strain \( \varepsilon_r \).

\[
\varepsilon_r = 0.2 \tan \beta
\]

(2)

for a conical tip, where \( \beta \) is the angle between the tip and the surface, while for a spherical tip:

\[
\varepsilon_r = 0.2 a / R
\]

(3)

where \( R \) is the radius of the tip and \( a \) the radius of the surface contact area. The mechanical properties of polymeric materials are usually stress and temperature activated and follow an Arrhenius process at temperatures below the glass transition. Therefore, the mechanism may be described by an equation based on concepts similar to those used by Eyring, relating the strain rate and temperature to the material properties:

\[
\dot{\varepsilon} = A e^{\frac{E_a}{kT}} e^{\frac{V_a}{kT}}
\]

(4)

where \( A \) is a constant, \( E_a \) the activation energy, \( T \) the temperature, \( V_a \) the activation volume, \( k \) the Boltzmann constant and \( \sigma \) a material property. The slope of \( \sigma \) vs ln(\( \dot{\varepsilon} \)) at constant temperature gives the
value of $\nu^v$, while experiments at variable temperature provide $E_a$. Once the activation volume and energy are known, experiments performed at any temperature and strain rate may be plotted on a single master curve at 20°C. If the mean strain is sufficient to induce a viscoplastic response of the material, i.e., the edges of the groove left on the surface stay parallel, then the dynamic scratch hardness, defined as the ratio of the applied load to the contact area between the tip and the surface, obeys an Eyring’s law:

$$p_{	ext{sw}} = C \frac{E_a + k T \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}}{v_o}$$

(5)

where $C$ is a coefficient depending on the strain in the contact area, while the yield stress may be expressed by:

$$\sigma_{\text{sw}} = \frac{E_a + k T \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}}{v_o}$$

(6)

As a polymeric material has a yield strain of some ten percent, this analysis [4] which assumes full plasticity around the tip must be generalised in the case of a viscoelastic or viscoelastic viscoplastic response of the surface. The aims of the present study were to obtain experimental results for a body scratched by a single tip and to analyse the viscoelastic viscoplastic response. Experimental data describing the contact pressure during tangential contact were obtained with a scratch apparatus allowing analysis of the contact area and the groove left on the surface. Results are compared with the approach of Hertz to examine the elastic contact and with that of Johnson to analyse the indentation pressure. A strain – stress curve is plotted to depict the evolution of this contact pressure with the mean strain in the contact area.

2 EXPERIMENTAL DETAILS

The main innovative features of the scratch apparatus [4] are the capacity to scratch over a wide range of speeds (1 µm/s to 10^6 µm/s) and within a temperature range covering the $\alpha$ and $\beta$ transitions of common polymers (-70 to +120°C) and that it allows in situ control and analysis of the groove left on the surface. In the present experiments, the load applied to the moving tip was varied from 0.1 to 1.5 N to induce scratch transitions and the temperature from +20°C to +100°C. The moving tip was a diamond or steel ball with a radius of 100, 200, 790 or 1500 µm.

3 RESULTS

Temperature, load and radius of the grooving tip were adjusted to scan a wide range of the ratio of contact radius to tip radius. To obtain a transition from viscoplastic scratching to viscoelastic sliding (figure 1), the mean strain was adjusted to a few percent by varying the normal load on the tip and hence the radius of the contact area. Since the material was viscoelastic and viscoplastic and the normal load constant, an increase in tip speed decreased the contact radius and also the mean strain. On the other hand, an increase in tip speed increased the strain rate and provided the initial mean strain was no more than a few percent, a transition from viscoplastic scratching to viscoelastic grooving took place. As the material properties were time and temperature dependent, the same transition could be obtained at a lower temperature by adjusting the strain and strain rate.

![Figure 1: A typical viscoplastic scratch to viscoelastic groove transition, in situ photograph. In this experiment, the normal load was 0.5N and the temperature 100°C.](image1)

![Figure 2: Evolution of the ratio of the true contact area to the full disc contact with the ratio of the contact radius to tip radius (normal load 0.1 to 1.5 N, temperature +20°C to +100°C, sliding speed 1E-4mm/s to 15 mm/s).](image2)

The geometry of the true contact area, which at high strain and low strain rate is the front half of a disc, is modified as the sliding speed of the tip increases. In addition, plastic flow around the tip can generate a pad and the edges of the groove do not generate a pad and the edges of the groove left on the surface do not lie parallel. The groove relaxes within a time lapse comparable to the contact time of the tip. At higher sliding speeds, the deformation of the surface recovers almost instantaneously and the contact area becomes quasi-symmetric. A geometrical parameter $\alpha$ can be defined, which is the ratio of the true contact area to the full disc contact and provides an index of the elastic ($\alpha=1$) or plastic ($\alpha=0.5$) response of the surface. The evolution of this parameter is shown in figure 2. The contact pressure is the ratio of the normal
load to the true contact area, which is the sum of the front and rear areas, while the yield stress can be estimated in the same temperature and velocity range from results previously obtained using a conical tip [4]. Figure 3 depicts the mean contact pressure normalised to the yield stress as a function of the strain as defined by Tabor.

Figure 3: Contact pressure normalised to the yield stress versus the strain as defined by Tabor.

In elastic static contact, yield occurs when the ratio of the mean contact pressure to the yield stress is equal to 1.1 [6]. When the sliding of elastics bodies has a low value of the friction coefficient, this relationship can be used to estimate the limit of the elastic response domain, which exists until 2% mean strain. At the onset of plasticity of the response, the maximum contact pressure is 1.5 times the mean strain. The yield strain is by assumption related to the mean strain, equal to the maximum pressure at the beginning of plasticity, as follows:

\[ \varepsilon_{\text{mean}} = 0.2 \frac{a}{R} \]  
(7)

Applying this assumption and Tabor’s definition of the strain, full plasticity appears for strains of over 6%. Three domains of strain response can then be identified: elastic, elastic plastic and plastic. The mean strain as defined by Tabor seems to separate with good agreement the regimes of plastic and elastic deformation around the tip and hence appears to give a good approximation of the different domains of response.

4 DISCUSSION

The scratch hardness, like other mechanical properties, follows an Eyring’s law. When the mean contact strain is normalised to the yield stress, the time and temperature dependency are masked and this ratio depends only on the strain in the contact area. A previous model developed for an elastic plastic material [6] may be used to analyse the response of viscoelastic viscoplastic materials.

Although indentation or scratch tests permit easy measurement of a mean contact pressure, interpretation of the stress-strain curves is often difficult. In elastic static normal contact, the solution of the normalised contact pressure for a spherical tip is:

\[ p_{\text{mean}} = \frac{4}{\pi} \frac{R}{(1-v^2)E \sigma_{\text{yield}}} \]  
(8)

There exists, between the onset of plasticity and the appearance of full plasticity around the tip or under the contact area, a regime where superposition of the plastic contribution on the elastic plastic response influences the deformation and contact pressure. When plasticity occurs, Tabor has shown that the ratio of the hardness to the yield stress is a constant which depends on the geometry of the tip:

\[ \frac{p_{m}}{\sigma_{\text{yield}}} = c \]  
(9)

Applying the analysis of Hill [7] to different materials and wedges of different apex angle, Hirst and Howse [8] showed that the hardness (plastic indentation pressure) normalised to the yield stress increases with the logarithm of the ratio of the elastic modulus to the yield stress. Johnson [6] correlated the indentation process with the expansion of a half plastic core in an elastic plastic material by extending the theory of Hill. In the case of an elastic plastic response and conical tip, the model gives:

\[ \frac{p_{\text{yield}}}{\sigma_{\text{yield}}} = \frac{2}{3} \left( 1 + \ln \left( \frac{E \tan \beta + 2(1-\nu)}{\sigma_{\text{yield}}(1-\nu)} \right) \right) \]  
(10)

while for a spherical tip with full plasticity around the tip, it takes the form:

\[ \frac{p_{\text{yield}}}{\sigma_{\text{yield}}} = \frac{2}{3} \left( 1 + \ln \left( \frac{E \sigma_{\text{yield}}}{\sigma_{\text{yield}} R} \right) \right) \]  
(11)

Figure 4: Normalised mean contact pressure versus normalised mean strain. There is good correlation between the normal static contact laws and tangential experimental data in the case of plasticity.

Scratching may be defined as tangential indentation and the radial elastic plastic expansion of a half core transposed to the tangential expansion of a quarter plastic core. Figure 4 shows the normalised contact pressure during scratching as a function of the ratio of the strain imposed by the tip to the yield strain of the material, \[ \frac{E a}{\sigma_{\text{yield}} R} \], defined as the normalised mean strain. There is good correlation between model and experiment when full plasticity exists, i.e., when the normalised mean contact pressure exceeds 1.65, as can
be illustrated by in situ photography. On the contrary, in the case of an elastic or elastic plastic response, the normalised mean strain seems to be overestimated by a factor of 2. During the transition from elastic sliding to plastic scratching, the normalised mean contact pressure increases from 1.1 to 1.65, while at the same time the geometry of the contact area decreases from a full disc to close to a half disc. Hence we propose to take into account this variation of the geometry, in order to correct the estimation of the normalised mean strain during sliding contact:

\[
\lambda_{\text{sliding}} = \frac{1}{2 \alpha} \frac{E}{\sigma_{\text{yield}}} \frac{a}{R}
\]  

(12)

The normalised mean strain in static contact remains:

\[
\lambda_{\text{static}} = \frac{E}{\sigma_{\text{yield}}} \frac{a}{R}
\]

(13)

One observes good correlation between the normal static laws and tangential experimental data (figure 5) provided the normalised elastic and plastic mean stresses are expressed respectively as:

\[
P_{\text{mean}} = \frac{4}{3 \pi} \lambda
\]

(14)

\[
P_{\text{yield}} = \frac{2}{3} \left[ 1 + \ln \frac{\lambda}{3} \right]
\]

(15)

Figure 5: Contact pressure normalised to the yield stress versus normalised strain.

Figure 6: Contact pressure normalised to the yield stress versus Tabor’s generalised mean strain.

Tabor gives a definition of the mean strain for the case of full plasticity in indentation and plastic or viscoplastic scratching may be regarded as half contact tangential indentation. However, when the contact is elastic plastic or elastic, it is clear that this definition overestimates the true mean strain. Once again, the definition may be corrected by means of a parameter describing the geometry of the contact:

\[
\epsilon_{\text{mean, cor}} = \frac{0.2 a}{2 \alpha R}
\]

(16)

It must be noted that for a perfectly plastic response, the mean strain in scratching is still equal to that in indentation. As shown in figure 6, if the normalised mean stress is plotted against the corrected mean strain, the end of the elastic domain may be estimated to lie at about 1% strain, which is in good agreement with experimental results obtained in a compressive test.

5 CONCLUSION

Transitions from viscoplastic scratching to elastic sliding have been investigated and temperature, strain and strain rate found to be important parameters to control and predict the type of scratching on viscoelastic viscoplastic materials like polymers. The definition of the mean strain given by Tabor for a strain hardening material can be used to describe and predict the nature of the strain during sliding contact, provided this definition is generalised by taking into account the geometry of the true contact area. Experimental data for the contact pressure on a viscoelastic viscoplastic material are easily plotted as a function of the mean strain when the pressure is normalised to the yield stress.

6 REFERENCES