Proceedings of WTC2005
World Tribology Congress III
September 12-16, 2005, Washington, D.C., USA

WTC2005-63582

MECHANICAL ANALYSIS OF THE DAMAGE OF A THIN POLYMERIC COATING DURING SCRATCHING

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ABSTRACT

Coating is a common way of improving the scratch behaviour of polymeric glasses. A thin coating will prevent the micro-scratches created by the roughness of a diamond tip at the surface of the macro-groove left on the substrate and allow recovery of the groove. The ratio of the thickness of the coating to the roughness of the tip is a critical parameter, which enables one to increase the scratch resistance in the case of a thin coating. A single value of the critical load cannot describe the damage behaviour of a coating on a polymeric material. It is generally assumed that cracking appears at the rear edge of the contact area and is related to the tensile stress, whereas we observed that cracking of the coating appears within the contact area. The mechanical behaviour of a coating on a viscoelastic material should be analysed in terms of the shape of the stress field, modified by the effect of the local friction between a scratching tip and the coat, where this local friction will depend on the roughness of the tip. Some numerical simulations were performed to attempt to elucidate the cracking mechanism.

1. INTRODUCTION

If coating is a common way of improving the scratch behaviour of polymeric glasses, a thin polymeric coating deposited on a polymeric substrate will not modify the global mechanical response to an indenter. Hence the scratch resistance conferred by the thin coating cannot be investigated on the macroscopic scale of the contact [1]. The limiting factor of this improved resistance is the cracking of the coating. Most of the existing models describing the wear behaviour of such coatings use the concept of the critical load [2-7]. These models always predict that the first damage will appear behind or in front of the contact area and one may note that in most cases the normal load was connected to the crack energy, sometimes also taking into account the strain energy of the substrate. More recently, Bertand-Lambotte et al. [8] have proposed that the transition from ductile to brittle scratching of a coating is dependent on a double condition: a fracture energy criterion and a size criterion. Since the mechanical properties of polymers are time and temperature dependent, a single value of the critical load cannot describe the overall mechanical behaviour.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

The material was an amorphous thermoset polymer (diethylene glycol bis(allyl carbonate)) called CR39 and the coating was a spin coating of a nano-composite material, a thermoset matrix filled to about 20% of its volume with sub-micron silica particles (about 10 nm in diameter). Coats of different thicknesses in the range 0.4 to 5 µm were tested and scratches were made with spherical and conical diamond tips, using a previously described scratch apparatus. In the case of a transparent polymer, the scratch may be viewed with a microscope during the scratching procedure [9]. The radii of the tips ranged from 110 to 240 µm and their roughness Rt from 0.3 to 2.5 µm.

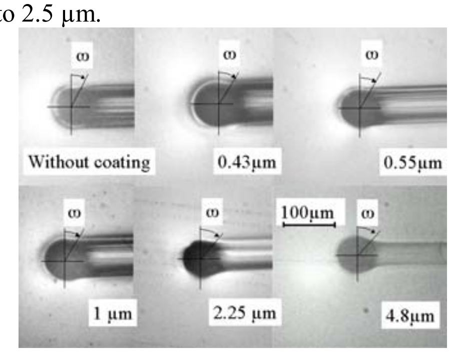

Figure 1: Contact area and groove left on the surface for different thicknesses of the coating (2.5 µm total roughness of the tip).

3. RESULTS AND DISCUSSION

Thickness versus roughness

As seen in the in-situ photographs of figure 1, when the thickness of the coat exceeds the total roughness of the sliding tip, there are no micro-scratches along the macro-groove and the groove can relax easily. The coating prevents the roughness of the diamond tip from creating micro-scratches at the surface of the macro-groove and hence the groove can recover. Figure 2 compares the groove left on the surface of the substrate by a smooth tip having a maximum roughness Rt of 0.6 µm (right) with the groove left on a 4.4 µm thick coating by a rough tip having a maximum roughness Rt of 2.5 µm (left). These in-situ observations confirm that the action of the thin solid coating is to prevent the roughness of the tip from generating micro-scratches along the macro-groove left on the surface.

Cracking of the coating

Experiments were performed at various normal loads, tip speeds and temperatures. After setting the experimental conditions, a first scratch was made to find a normal load which triggered cracking of the coating. In subsequent tests, the moving tip was started at 1µm/s and its speed was increased stepwise up to 10mm/s. Since the mechanical properties of the substrate are time and temperature dependent, the width of the contact area decreased as the sliding speed increased. Cracking disappeared at a critical sliding speed (figure 3) and this critical speed depended on the normal load applied to the tip for given values of the temperature and tip radius. A cracking transition was always observed at the same contact width for a given tip radius, whatever the normal load. Hence the mechanical behaviour of a coating on a viscoelastic material should not be analysed in terms of the critical load or contact pressure, but in terms of the shape of the strain field which is dependent on the ratio between the contact radius and the tip radius and of the true friction between the moving tip and the coat. The in-situ photograph of figure 4 shows that cracking appears in the rear half of the contact with two branches in the frontal part of the contact area.

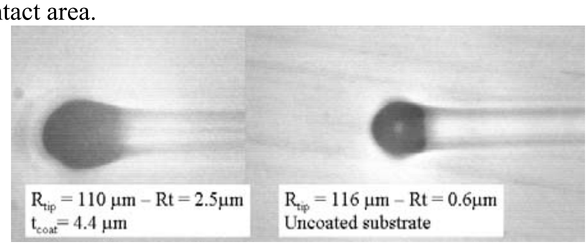

Figure 2: On the left, a rough tip scratches a 4.4 µm coating. On the right, a smooth tip scratches the uncoated material.

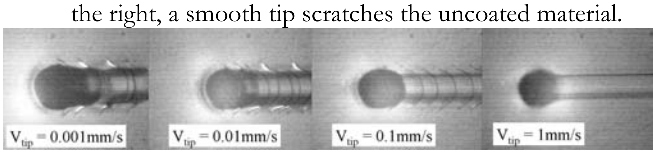

Figure 3: Transition from cracking to smooth grooving with increasing sliding speed at a constant normal load.

Numerical simulations

Some numerical simulations were performed using a finite element method and CAST3M© software to attempt to elucidate the cracking mechanism. The external loading was imposed as a stress field acting on a circular contact. The domain elements were three-dimensional meshes with ten-node tetrahedra and the mesh was refined under the contact area. Elliptical and constant pressure distributions were used to define the real form of the contact pressure. The mean contact pressure determined from a knowledge of the true contact area and the local friction coefficient estimated using a previous model [10] were introduced as variables, while the flow stress accounting for the elastic-plastic behaviour of the substrate and the coating was described by a simplified G'sell-Jonas law [11]. As a general remark, the form of the pressure distribution had very little influence on the numerical results. Figure 5 shows that only the maximum value of the principal strain was found to lie at a position in good agreement with the experimental observations.

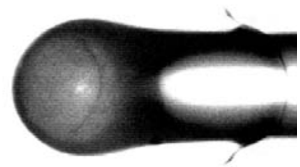

Figure 4: A crack appears in the contact area.

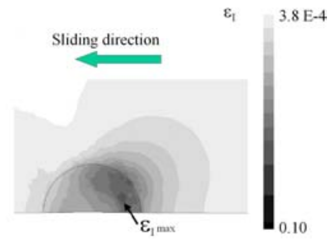

Figure 5: Principal strain under the contact area.

CONCLUSIONS

It was observed that cracking of a coating on a polymeric material appeared within the contact area. On thin solid films, the ratio of the contact radius to the radius of the scratching tip proved to be a pertinent parameter to predict the damage and did not depend on the scratching velocity or temperature. The ratio of the thickness of the coating to the roughness of the tip was another critical parameter, which enabled one to increase the scratch resistance in the case of a thin coating. The mechanical behaviour of a coating on a viscoelastic material should not be analysed in terms of the critical load, but in terms of the shape of the stress field, modified by the effect of the local friction between a scratching tip and the coat, where this local friction will depend on the roughness of the tip.

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