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The influence of strain hardening of polymers on the piling-up phenomenon in scratch tests: Experiments and numerical modelling

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Abstract

The aim of this study was to relate the scratching behaviour of polymers to their mechanical properties. A thermosetting resin (CR39) and a thermoplastic polymer (PMMA) were studied using a microscratch tester allowing in situ observation of the contact area. These two polymers exhibit different elastic and viscoplastic properties, the main difference being the large ability of CR39 to strain harden, whereas PMMA softens. A spherical indenter was used to vary the level of deformation imposed on the samples. The response was initially elastic, then viscoelastic and finally mainly viscoplastic with increasing penetration of the indenter into the material. The two polymers displayed the same response for small levels of deformation, while at larger strains PMMA showed more pronounced plastic behaviour. The origin of this difference in behaviour was investigated by means of a three dimensional finite element analysis. The rheology of PMMA and CR39 was simplified and modelled by assuming linear elastic behaviour and a viscoplastic law taking into account their strain hardening capacity at high strains. Strain hardening was found to be a key factor to correctly model the material flow around the indenter. The response of the polymers was governed by the ratio between the plastic and elastic strains involved in the deformation in the contact region. In first approximation, the representative strain was imposed mainly by the geometry of the indenter, while the elastic deformation was controlled by the mechanical properties of the material, a larger strain hardening leading to a greater elastic deformation and a lower plastic strain thus a better scratch resistance of the specimen.

Keywords: Scratch resistance; Contact area; Strain hardening; Numerical modelling; Micro visio scratch tester; Compression tests

1. Introduction

Transparent polymers are widely used in many industrial applications such as ophthalmology and the automobile industry and are often preferred to glass because of their lower density and lower brittleness. However, their relatively low hardness makes their surface susceptible to damage. Thus, scratches alter their optical, aesthetic and mechanical properties and hard varnishes are deposited on the surface to avoid the occurrence of such alterations. The industrial and academic communities are both interested in developing new materials having a better scratch resistance, which passes through a better understanding of the mechanics of the scratch test (Fig. 1).

According to Briscoe et al. [1], the deformation modes of polymers during a scratch test may be classified in three main categories: quasi-elastic behaviour, ductile ploughing and severe damage. In the first regime, there is no significant residual groove due to the large viscoelastic recovery at the rear of the indenter. In the second mode, the material flows plastically around the indenter and this ductile ploughing is

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Nomenclature

a	radius of the contact area
a_{T}	thermal coefficient
e_{p}	thickness of the push pad
E	Young's modulus
F_{t}	tangential load necessary to generate the relative motion
h	depth of the contact
h_{g}	strain hardening coefficient
K	consistency
m	sensitivity to the strain rate
R	radius of the scratching tip
W	applied normal load

Greek symbols

α, β	relaxation peaks of polymers
ε	total strain
$\mathrm{d}\varepsilon/\mathrm{d}t$	strain rate
ε_{e}	elastic strain
$\varepsilon_{\mathrm{vp}}$	viscoplastic strain
$\dot{\varepsilon}_{\mathrm{vp}}$	generalised viscoplastic strain rate
μ_0	apparent friction coefficient
ν	Poisson's ratio
σ_{y}	compression yield stress
σ	stress
ω	angle describing the recovery of the groove and the symmetry of the contact area

accompanied by piling-up at the sides of the groove. The last regime is reached for severe conditions of deformation where cracks develop at the edge or within the groove [2]. In some cases, machining or chip formation may also be observed. The behaviour of the material and the appearance of one of these three deformation modes depend on several factors including the friction [3], temperature [4], indenter speed [5] and level of deformation imposed on the specimen [6,7]. The latter parameter is controlled by the shape of the indenter and scratching mode maps relating the strain the temperature, normal load . . . to the kind of deformation and damage modes have been established [1]. In the case of scratching with spheres, Gauthier et al. [8] have shown that the level of deformation ε is governed by the relation proposed by Tabor for indentation of metals [9]:

$$\varepsilon = 0.2\frac{a}{R} \tag{1}$$

where R is the radius of the scratching tip and a, the radius of the contact area (Fig. 1). The deformations under the indenter tip are not homogeneous and this relation gives an average value of the deformation. As this equation was established for scratch tests on materials having a very small elastic strain at yielding:

$$\varepsilon_{\mathrm{ey}} = \frac{\sigma_{\mathrm{y}}}{E} \tag{2}$$

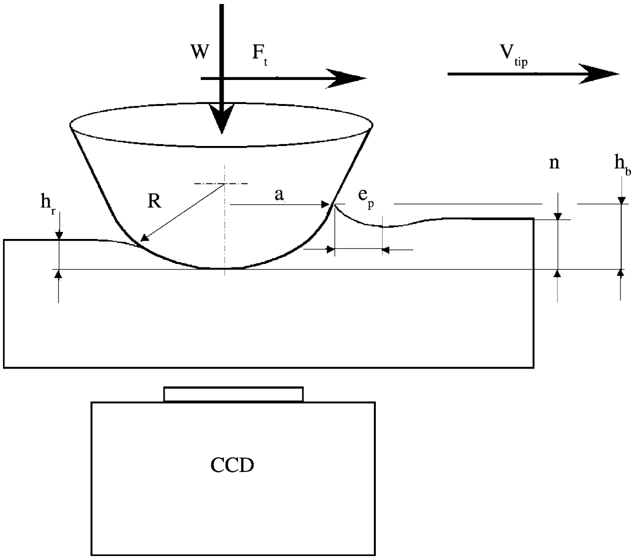

Fig. 1. Principle of the scratch test and in situ observation device. The main geometrical parameters are defined on the schema.

where E and σ_{y} are, respectively, Young's modulus and the yield stress, the coefficient 0.2 does not hold for polymers which have large elastic strains [10]. Nevertheless, for spherical indenters, the deformation remains proportional to the ratio a/R, which is termed the representative strain in the following discussion.

Over the last few years, efforts have been made to gain a fundamental understanding of the scratch test on polymers in order to relate the deformation modes to the mechanical properties of the materials [8,11–13]. Using a finite element analysis, Bucaille et al. [12] were able to link the contact pressure, contact geometry and the elastic recovery at the rear of the indenter to the elastoplastic properties of the material. Despite the fact that the rheological model employed in this study is a very rough description of the real rheology of polymers, as it introduced only E and σ_{y}, it gives valuable information concerning the material flow around the indenter. Bucaille et al. [14] recently introduced a more complex rheological model and showed that the strain hardening of polymers and the ratio between the elastic and plastic strains are key points to explain the scratch resistance. In this context, the present work deals with the transition between the quasi-elastic and ductile ploughing regimes. Microscratching tests were carried out on two polymers at small and large strains. Pile formation and the extent of elastic recovery were observed in situ and related to the material behaviour measured under compression. These tests were then modelled using three dimensional finite element modelling. The aim of the numerical simulation was to show, by using a simplified modelling of the polymer rheology, that there is a strong link between the strain hardening of polymer and the material flow around the indenter during scratching.