EFFECTS OF STRESS-TRIAXIALITY AND SURFACE FRICTION ON POLYMER SCRATCH BEHAVIORS

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Summary This paper discusses the effects of stress triaxiality and surface friction on scratch behaviors of polymeric materials. FE (Finite Element) simulation results, as well the experimental findings, illustrate that the location and mechanism of possible scratch damage modes are quit different for materials with various sensitivity to the stress triaxiality. The surface friction affects not only the residual scratch depth, but also the possible damage modes which can alter the onset of visible scratch.

INTRODUCTION

While the long-term aesthetics is one of the most important concerns for their application on electronic, optical, household, and automotive industry, polymers are vulnerable to surface scratch, even under low contact loads. Various damage modes have been experimentally observed for polymer scratch[1-3], in which the test rate, tip geometry, substrate thickness, surface characteristics, as well as material properties themselves all show significant effects on the scratch performance.

While the behaviors of polymeric material depend heavily on rate and temperature, many experimental investigations show the remarkable influence of the triaxiality of the stress state. The stress-triaxiality is critical to crack opening, fracture propagation, void growth, craze initiation, etc. During the scratch process, the stress and strain states experienced by the substrate are extremely complex. As shown experimentally and numerically [1-5], rose in front of the scratch tip, the material beneath the front portion of the scratch tip always experiences a compression, while the noticeable tensile region exists behind the tip. With the rapid movement of scratch tip, the substrate material quickly transits from a tensile condition to a compressive one, and then back to tension. Inherently, the initiation of possible damage will be influenced by the stress state, in other words, the stress-triaxiality experienced by the material.

It is intuitively evident that surface characteristics such as surface friction can have significant effect on polymer. It has been shown that the smaller the friction coefficient, the larger the average critical load for the onset of visible scratch (observed experimentally [4]), the deeper the residual scratch depth (numerically found [6]).

In this paper, FE (Finite Element) simulation, as well the experimental findings, illustrate that the possible location and mechanism of damage are quite different for materials with various sensitivity to the stress triaxiality, and the surface friction affects not only the residual scratch depth, but also the possible damage modes.

METHOD AND SIMULATIONS

Experimental Setup

Following the ASTM and ISO testing standard for polymer scratch [7, 8], a stainless steel spherical tip with 1 mm in diameter was utilized to perform the scratch tests at ambient condition. The scratch length was set at 100 mm. A linearly increasing normal load (1N-30N) was imposed on the scratch tip at a scratch velocity of 100 mm/s.

A PP (polypropylene) material (System 1) without additives which barely shows stress-triaxiality sensitivity, i.e., with similar ductile damage criterion for either uni-axial tension or compression, was scratched as the control set. A PP (System 2) with good ductility under compression but relatively brittle under tension, showing significant sensitivity to the effect of stress-triaxiality on damage initiation, was chosen. Meanwhile, adding surface slip agent to System 1, a PP material (System 3) was scratched to study how the surface friction influences the possible scratch damage mechanisms.

FE Simulation

To understand the observed various scratch damage modes [1-5], 3D FE simulation was performed to study the extremely complex stress and strain states experienced by the polymer substrate during the scratch process using ABAQUS/Explicit [9]. A phenomenological model for predicting the onset of ductile fracture damage assumes that the critical equivalent plastic strain is a function of stress triaxiality and strain rate as $\boldsymbol{\varepsilon_D}^{\boldsymbol{pl}}(-\boldsymbol{p}/\boldsymbol{q},\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{pl}})$. The criterion for damage initiation is met when the following condition is satisfied [9]:

$$\int \frac{d\boldsymbol{\varepsilon}^{pl}}{\boldsymbol{\varepsilon_D}^{pl}(-\boldsymbol{p}/\boldsymbol{q},\dot{\boldsymbol{\varepsilon}}^{pl})} = \mathbf{1}$$

where –p/q is the stress triaxiality, p is the pressure stress, and q is the Mises equivalent stress. The stress triaxiality factor is 0.33 and -0.33 for uni-axial tension and compression, respectively.

The scratch tip was modelled as an analytical rigid surface. A fine FE mesh was adopted with 512 elements over the scratch path. Eight-node tri-linear elements were chosen with a typical size of 0.05 mm by 0.05 mm by 0.05 mm.

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Corresponding boundary conditions were applied. A small normal load of 0.05 N was applied at the beginning to maintain substantial contact between the tip and substrate, followed by a linear increasing normal load up to 30 N. A 3D dynamic and plastic stress analysis mode was executed.

A typical ductile PP was chosen for System 1 for which a piecewise linear stress–strain curve was constructed [5]. The coefficient of friction between the tip and substrate was taken to be 0.3. For System 2 with little tolerance for any uniaxial tensile plastic deformation, its critical equivalent strain for damage initiation is very sensitive to stress state. The material parameters were correspondingly defined in the simulation routine. While the real friction coefficient is ~0.06 for system 3, a frictionless case was utilized to explore the extreme scenery. It should be noted that, no crack formation, i.e., no nodes or elements separation or removal after damage was considered. While the simulation is valid only up to the onset of damage formation, the qualitative trends for the initiation of possible scratch damage still stands.

RESULTS AND DISCUSSION

Effect of stress triaxiality

One focus of this work is the influence of stress-triaxiality on the scratch damage initiation. For System 1, the numerical results clearly show the compressive region under tip. While the tensile region behind the tip appears even at early stage, i.e. under small load level, the damage is not easy to happen because of material's lacking of sensitivity to stress-triaxiality. The magnitude of tensile stress will develop with the increasing of normal load and can finally lead to severe tensile type of damage at the normal load of 22N. For System 2 with poor tensile properties, or highly sensitive to stress-triaxiality, the substrate material undergoes tensile failure in the tensile region behind the scratch indenter at a much lower load level (~12N). Similar phenomena was experimentally observed where the PP with worse tensile properties than compressive ones showed much poorer scratch resistance than the material with less sensitivity to stress-triaxiality but similar other material parameters.

Effect of surface friction

In addition to the known fact that smaller friction coefficient, the less the scratch tangential force and residual depth[], the numerical results of scratch process on frictionless System 3 also illustrated that the tensile region evolution is much slower than the System 1 with surface friction. While the magnitude of tensile stress behind the tip reaches 20MPa under normal load of 12N, this level of tensile stress does not develop at the same region for System 1 until the normal load increases toward 20N. Different from System 1 in which the large magnitude of tensile stress locates at the middle line of scratch path, that of System 3 moves outward to the region close to scratch side groove.

By altering the surface friction, one not only affect the residual scratch depth, but also the possible modes and location of damage. Generously speaking, the smaller surface friction coefficient, the higher normal load is required to induce possible tensile type of damage, thus, the later onset of scratch visibility.

CONCLUDING REMARKS

Both FE simulation and experimental findings illustrate the effects of stress triaxiality and the surface friction on possible scratch damage modes and mechanism. Substrate with higher sensitivity to stress triaxiality or larger surface friction coefficient is shown to possess poor scratch resistance, i.e. lower critical load of onset scratch visibility. These two parameters can be important for material scientists to improve the scratch performance of polymeric materials.

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