FEM Modeling on Scratch Behavior of Micro-Patterned Polymer Surface

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Abstract

Polymers are inherently scratch-sensitive due to their low resistance to deformation. Surface patterning is a viable strategy to achieve better scratch performance. In this paper, we model the scratch behavior of micro-patterned surfaces using FEM simulation by employing the powerful coupled Eulerian-Lagrangian approach. The effect of two different pattern types on the scratch behavior of polycarbonate was studied and validated with available experimental results. Results support the use of patterned surfaces in improving scratch performance..

1. Introduction

Polymeric systems are commonly used as the skin layer of most consumer products due to their low cost, ease of processing, and esthetics. The rising concern over the scratch performance of polymers has come about with its extensive usage in the electronic, optics, and automotive applications. The scratch phenomenon involves a tribological contact between two surfaces sliding against each other under load, which poses significant challenges to the material and mechanics research community.

Using the combination of the ASTM/ISO scratch test and three-dimensional (3-D) FEM modeling, the present study investigates how the surface patterning affects the scratch behavior of polymers. Scratch tests were performed on micro-patterned polycarbonate (PC) sheets. Three-dimensional FEM modeling with the powerful coupled Eulerian-Lagrangian technique to avoid excessive distortion error of fine surface features was employed to evaluate the scratch performance in terms of scratch depth. The coupled Eulerian-Lagrangian approach is a powerful technique in modeling extreme deformations inherent to simulation of fine surface features. The scratch performance observed experimentally is well correlated with the numerical modeling results.

2. Results

Scratch tests of the patterned PC sheets were fixed with vacuum fixture and PC plaque backing and then carried out according to ASTM D7027-13 / ISO 19252:08. Three scratches were done for each system. A 1 mm diameter spherical steel tip with a linearly increasing load of 1-30 N over a distance of 50 mm at 1 mm/sec speed were used. Analysis of scratch-induced damage mechanisms was carried out using Keyence® VK9700 violet laser scanning confocal microscope (VLSCM).

Experimental results show that the "Holes" pattern can delay onset of scratch groove formation than "Pillars" and "flat" surfaces as well as a lower scratch depth (Fig.1A & Fig. 1B). The Holes surface pattern improves the scratch resistance. Micro-imprinted holes reduce area of contact. In addition, air entrapped in the holes results in decreased frictional force during scratching.

To tackle the extreme deformations of fine surface features, the coupled Eulerian-Lagrangian analysis was utilized with tip being a rigid Lagrangian part and the PC thin sheet as the Eulerian part. Holes and Pillars are modeled 10 times the actual size with around 125 holes and pillars of 100×100 μm lateral size and 20 μm in depth and height, respectively (Fig.1C). A 2 mm hemispherical tip was used for the scratch simulation to increase area of contact. Scratch distance was 3 mm with the same linearly increasing load in all cases.

Each model was meshed by around 6 million reduced integration EC38DR elements with extremely fine mesh at the scratch surface with an element size of 2.5×2.5×2.5 μm. As observed in the experimental study, holes perform better than pillars in terms of scratch depth for the same loading, Fig.1D shows the relative difference in scratch depth (pillar system scratch depth – hole system scratch depth) along the scratch path.

The scratch depth in the system with pillars takes over holes after scratch distance of 1.5 mm. This transition happens when the first row of micro-imprint feature is completely covered by the scratch tip, indicating the importance of surface topology.

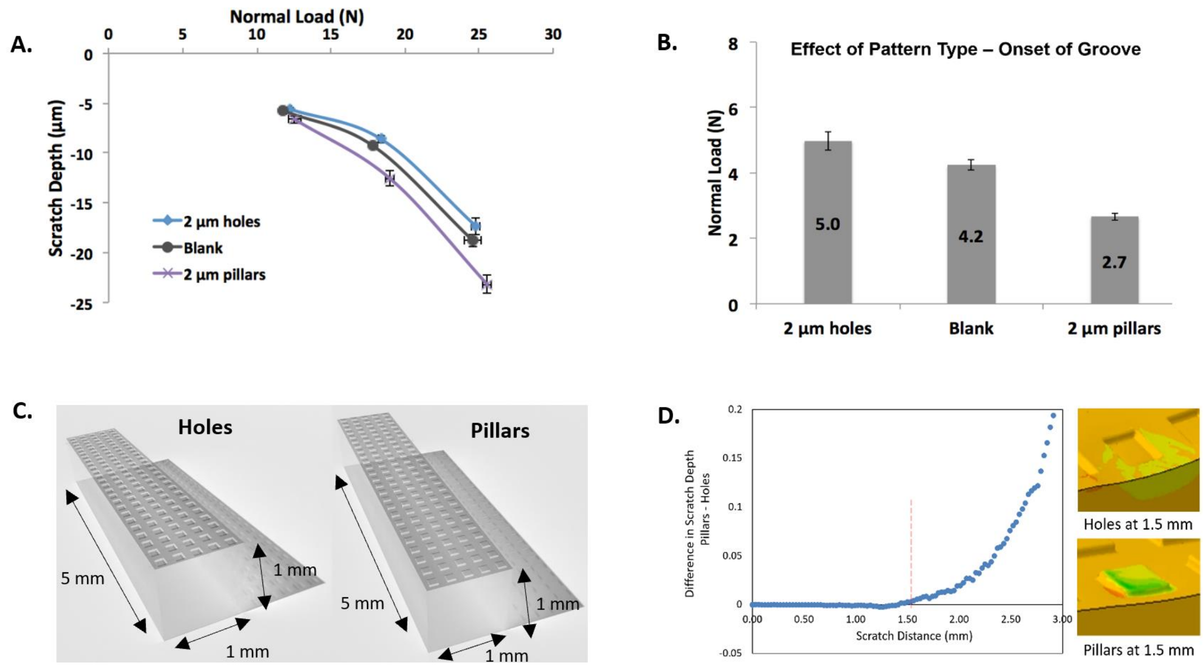

Fig1. **A.** The experimental scratch depth of both hole and pillar system compared to the blank (flat surface). **B.** The critical normal load at the onset of scratch groove for different pattern types which directly corresponds to scratch visibility. **C**. 3D rendering of the Scratch FEM models for both the hole and pillar systems. **D.** The relative improvement in scratch performance in terms of scratch depth between pillars and holes.

This simulation can be improved even further by inclusion of realistic polymer constitutive models and inclusion of polymer damage modeling. A parametric study will be pursued by considering optimal combination of shape, size and spacing to achieve desirable scratch performance.

3. Conclusions

The scratch behavior of micro-imprinted PC surfaces was investigated. The imprinted hole structure improves scratch resistance. FEM simulation corroborates that the surface topology plays an important role in indentation and scratch performance with holes performing better than pillars as observed in experiments. Including air cushion effect further showcases the importance of fluid-structure interaction in the hole system.

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