



Understanding the scratch behaviour of polymeric materials with surface texture

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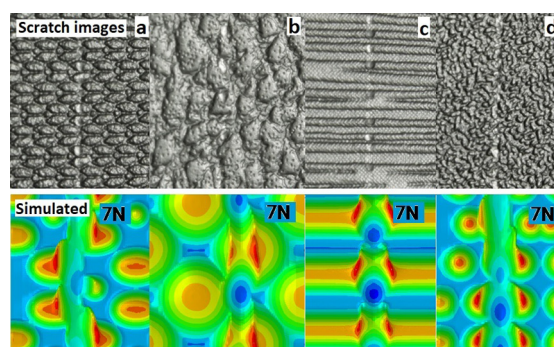
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HIGHLIGHTS

- Scratching on polymeric components with surface textures is investigated with finite element method and scratch testing.
- A classification of scratches is proposed.
- Three parameters are developed for evaluating the irregular geometry of scratches on a surface texture.
- A new methodology for characterizing patterns and grains on polymeric materials is developed.

GRAPHICAL ABSTRACT



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ABSTRACT

The surface texture of a polymeric product plays an important role in enhancing the product appearance and improving its resistance to scratch. The design and selection of texture features in the polymeric materials require an understanding of (i) the relationship between scratch/mar behaviour and the material property, (ii) the influence of surface texture on scratch resistance. This work simulates scratching processes on five different texture patterns at a number of scratch loads by using the coupled Eulerian-Lagrangian approach with the finite element method. To create texture pattern models for the simulations, a new methodology for characterizing the pattern and grain of textures was presented. To scale the scratch degree, three parameters were developed for the irregular geometry of scratches. The simulation results were compared with scratch experiments and a very good agreement between them was found. The analysis of the simulated scratches and the variation features of the three parameters led to a classification of scratches, which are *bruise spots*, *creeping scratches* and *pattern damage*, depending on the scratch load.

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1. Introduction

Surface scratch/mar of polymeric materials has been a quality problem. It greatly affects the integrity, durability and the aesthetics of the consumer products. Understanding the scratch/mar behaviour of relatively soft materials has long been of interest to both academia and industry [1,2]. The scratch/mar of the materials is a complicated

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mechanical process due to the complexity of material varieties [3,4], the dependence on the geometry of scratching object (indenter), and the surface interaction between the indenter and materials [2]. Polymeric materials generally show different mechanical properties (stiffness, flexural strength, modulus etc.) depending on their microstructure and molecular weight [5]. They may be ductile or brittle. Fillers and reinforcements, such as talc [6–10], glass beads [9], glass fiber [10], rubber [10], flax [11] and minerals in the form of micro-particles [12–14] are generally added into polymeric materials to improve their mechanical properties. Hence, the properties of the polymeric materials are more complex and the material response to scratch is greatly different from each other. As a result, the scratch behaviour is difficult to predict. The geometry of the scratching indenter also significantly affects scratch resistance of polymer materials [2,15]. Sharp indenters create deeper scratches and cause more brittle failure. The type and size of indenters vary and are in a wide range. In practice the geometry of indenters sometimes is difficult to be characterized.

Surface texturing is used extensively in polymeric products for the sake of functionality and/or aesthetics, gaining its importance together with material improvement over the last few decades. Surface textures not only enhance the look and feel of consumer products [16–18] but also conceal some surface damages to a certain extent and retain the visual appearance of the product largely unaffected [2,17,18]. Some textures also alter the material ability to resist scratch damage compared to smooth surfaces [2,19]. It was reported that the friction associated with a barrel tip on textured surfaces showed significantly less fluctuation compared to their smooth-surfaced counterpart [19,20]. The contact area of an indenter with textured surfaces under load is greatly lower than that with smooth surfaces and the friction is reduced. The function of surface texturing on enhancing scratch resistance greatly depends on the characteristics of the textures. Surface textures can be patterned or random and the grains can be in any shape and size, from several microns to several millimeters. They could show different ability to resist scratch damage. Understanding how surface texture influences scratch resistance is therefore of great interest to manufactures who aspire to improve the texture of polymeric materials and enhance product quality.

One effective method to delve into the scratch/mar mechanism of polymeric materials is the computational modelling of the scratch process, as it can provide insight into the material behaviour and the response to the external force. Modelling also allows to examine the underlying material science and physics involved in fundamental studies. The computational modelling can include all important factors in a high level of complexity involved in the scratching process and examine their inter-relationships. Unlike its application on traditional materials, such as metals, alloys and ceramics, that enjoy a longer research history [21,22], using an established computational modelling method to study the scratch of polymers is still in its early stages [23–25]. The simulation of scratching of polymers is difficult due to several inherent issues [26]. First the scratching process of polymers includes several physics (mechanics) events, i.e., tribology, material deformation and damage, indenter statics and dynamics. Hence, a robust model capable of modelling these events simultaneously is required. Secondly the scratched surface generally shows textured patterns, such as ‘fish scale’ [3], cracks and crazes [3,27]. These surface textures may greatly enhance the visual and tactile sense of the scratch. Accurately modelling the formation of scratch surface texture is still a challenge for current simulation techniques. Thirdly there is a lack of standardized test methods and equipment to provide sufficient data for building constitutive models that are capable of capturing the characteristics of very large strain, large deformation, failure, and strain rate dependence for polymeric materials. In the present work, the scratch imposed via a blunt indenter on five talc-filled polypropylene (PP) panels with different surface textures is computationally simulated by the Coupled Eulerian-Lagrangian (CEL) approach of finite element method (FEM). The mechanism of the scratch and behaviour of the polymer as well as

the influence of surface texture on scratch resistance are analysed. A geometrical analysis method is proposed to characterize the features of surface textures. Three parameters are developed to evaluate the degree of scratches. The FEM simulation results are also compared with scratch experiment values.

2. Texture characterization

Five different textures, tessellated, coarse bump, wood grain, shallow bump and fine stipple texture patterns, as shown in Fig. 1, were analysed. The features of each texture have been described in our previous work [17]. In the present work, the characterization of the texture was focused on the geometric features of the constitutive grains and their arrangement. Scratch of polymers depends on the local scratch stress field in the material, which associates with both the indenter geometry and the grain features. The indentation of grains that would affect the scratch performance should be based on the shape and size of the indenter used. The grains that have similar size to that of the indenter would significantly influence the scratches, while the grains and pits with much smaller size than the indenter can be neglected and treated as the area of rough surface. Here, we focus on the scratches created by blunt indenters, which have been proved to produce scratches closer to that are seen in practice [15]. In this work, an indenter with a 1 mm diameter spherical scratch tip is used. Therefore small grains and small pits of less than about 0.06 mm in size are not considered as significant texture pattern, because at such low ratio of surface feature spacing to indenter tip radius the indenter moves on as per a smooth surface [2]. For example, the tessellated texture pattern (Fig. 1a) consists of a repeating group with three shapes like a pair of lungs and a small bead on the left, whereas the small grains and pits over the lung-like surface are not accounted. The coarse bump pattern (Fig. 1b) is characterized by much larger and taller islands, whereas the random craters over their surface are not distinguished as a characteristic. The wood grain pattern (Fig. 1c) is described as numerous ridges aligned in a single direction, however the thick network on the surface is not marked.

For the geometry of characteristic grains, a methodology was developed to quantitatively determine their shape and size, as shown in Fig. 2. The analysis was based on the digital data (in stereolithography file format) of the texture image. A MATLAB program was developed for the purpose, which consists of the functions of data transformation, statistical analysis of grain profile, export and print of 3D, contour and X-Y figures. The texture data were first transformed to the Cartesian coordinate system, where the coordinate origin, O, locates at the waist of the grain and changes around the grain, so that there are a series of origins, $O(\theta)$, and a series of hr -coordinates, where θ is the angle to the initial reference direction, as shown in Fig. 2. In the present work θ increased from 0° to 355° at a radius angle increment of 5° . A series of corresponding data transform is then performed and the grain profile on each hr -coordinate plane is calculated. The method can produce a two-direction ($-r$ and $+r$) radial height function ($+/-rRHF$) for the grain. The $+r$ region describes the valley between the grain and its neighbours and the distribution of all grains around the grain, while the $-r$ region gives a statistical profile of the upper half of the grain. One of the important merits of this method is that the results come from all radial directions and all neighbouring grains.

A statistical result for a specified grain was achieved from all profile data around the grain. The area within about $2b$ (b is the max spacing between grains) distance from the grain was used to obtain its geometry. For example, the profile of a lung-like grain on the tessellated texture is shown in Fig. 3b, which is statistical result around the grain. The two-direction ($-r$ and $+r$) radial height function clearly shows the grain profile and the distribution of other grains around the grain concerned. The statistical profile parameters are also reported in the figure. The data close to $r = 0$ show the gradient of the grain, which is nearly linear for the lung-like grain. The point of the first valley at $r >$

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