Tribology International 90 (2015) 491–501

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Observation and understanding of scratch behaviors of glass fiber reinforced polycarbonate plates with various packing pressures during the injection molding process

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
20 April 2015
Accepted 8 May 2015
Available online 22 May 2015

Keywords:
Scratch
Polycarbonate
Glass fibers
Injection molding.

ABSTRACT

In this paper, the scratch resistance of injection molded, glass fiber reinforced polycarbonate (PC), constructed with different packing pressures and fiber compositions, was evaluated using the progressive normal load scratch test. The quantitative evaluation of scratch resistance of the samples was based on the onset of visibility and morphological transition points of the scratch for two fiber orientations and various scratch speeds. This study reveals that glass fiber reinforcement exerts a beneficial influence on scratch visibility; however, it has an adverse effect on morphological damage. Anisotropy and heterogeneity of glass fiber reinforced PC also plays a role in scratch resistance. The relationship between the onset of scratch visibility and damage transition points is also discussed.

1. Introduction

In recent years, polymeric materials have received considerable attention owing to their light weight, cost effectiveness, and high productivity. However, in general, polymeric materials have lower stiffness and strength compared with other engineered materials such as metals or ceramics [1]. Hence, the utilization of polymers is focused on the nonstructural components, such as decorative parts of automobiles, home appliances, and especially coatings of electronic goods. Moreover, consumer requirements of esthetic properties have risen uninterruptedly. Therefore, the surface properties of polymeric materials have drawn considerable research attention.

Among the surface damages, scratch and wear are the most representative damage features that occur with the use of diverse polymeric products. Scratch and wear damage are both caused by surface sliding. While wear damage is caused by a repeated sliding motion between surfaces, scratches are induced by a single sliding event between a tip and surface, and both should be fully studied using different approaches.

Resistance to wear damage can be estimated quantitatively by the wear rate, or volume loss per unit sliding distance, and research on the wear damage resistance of various types of polymers have been conducted, particularly fiber reinforced polymers [2,3]. Previously, however, evaluation methods of scratch resistance of polymeric coatings and materials were only able to make qualitative comparisons of materials. Examples of these evaluation methods include the following: the Pencil hardness test [4,5], the knife test [6], the tape test [7], and the Ford five-finger test [8,9]. Endeavors to address the limitations of the listed methods include the newly developed scratch test methods by Wong et al. [10,11]. The scratch resistance of polymeric materials has been evaluated with this method in previous studies [12–16]. In addition, studies to uncover which experimental or material parameters could affect scratch resistance have been conducted previously in the literature. Xiang et al. [17] endeavored to experimentally determine the mechanical properties that affect scratch resistance through the use of various types of polymers. Chivatanasoontorn et al. [18] studied the effects of scratch speed on neat polypropylene (PP) with different molecular weights. Jiang et al. [19] and Hossain et al. [20] conducted the parametric studies of material properties on scratch resistance using finite element methods (FEM), which commonly revealed that the yield strength and stiffness have a major impact on scratch resistance of a polymer substance.

Generally, in the progressive load scratch test of common polymer substances, scratched morphologies show three distinct damage modes. The first stage, generally called mar mode, is characterized by nonvisible surface damage or slightly visible plowing features. The second stage, whitening mode, shows visible regular damage, which appear as fish scales for ductile polymers and parabolic cracks for brittle polymers. The third stage, cutting mode, shows severe, irregular damage with material removal occurring in this last stage [21]. The damage transition

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http://dx.doi.org/10.1016/j.triboint.2015.05.009
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points between the three stages are called the 1st and 2nd critical points, respectively. Almost all polymeric substances show similar damage features in the first and last stages, the mar and the cutting mode, respectively. Whitening mode, however, is characterized by different damage morphologies from material to material. In other words, damage features in whitening mode could be used as a measure of material character. For instance, Jiang et al. [21] studied the distinct features of various polymers in the whitening mode. In their research, typical thermoplastic polyolefins (TPOs) and weak and ductile polymers such as PP show fish scales in the whitening mode. In contrast, strong and ductile polycarbonate (PC) and strong and brittle epoxy show parabolic cracks in this mode. An et al. [22] intensively studied the damage morphologies of poly(methyl methacrylate) (PMMA), which experiences parabolic cracks during the whitening mode. Lee et al. [23] also revealed the scratch properties of glass fiber reinforced PC (GFRP). However, this research only shows the trends of the 2nd critical points.

Besides the abovementioned studies with regard to morphology transition, the onset of scratch visibility also attracts the concerns of researchers. Some studies accepted that if the brightness difference between virgin and deformed surfaces is greater than a threshold of approximately 3%, the unaided human eye was capable of capturing the distinction [18,24,25]. This concept to determine the onset of scratch visibility can be used objectively with the aid of a flat-bed scanner and the application of the threshold function in the Image J software.

Although many previous studies have been conducted, to the best of our knowledge, there lacks a study on the scratch properties of polymers with varying processing conditions, such as injection pressure, melt flow rate, injection speed, and packing pressure, which are all manufacturing parameters in injection molding. Therefore, well designed parametric studies on the various manufacturing conditions must be conducted. Further, studies on more practical approaches are needed. In reality, in order to overcome the relatively low stiffness and strength of neat polymers, ceramic particles or carbon and glass fibers are often embedded in the polymer matrix, creating composite materials. It is evident that GFRP has less energy absorption during an impact test, higher yield, higher tensile strength, higher stiffness, and less failure strain in the tensile test, that is, becoming more brittle than neat polymer macroscopically [26,27]. However, this tendency is only a bulk phenomenon, and it has not been fully proven in the scratch test. Thus, the scratch properties of these types of materials must be fundamentally studied.

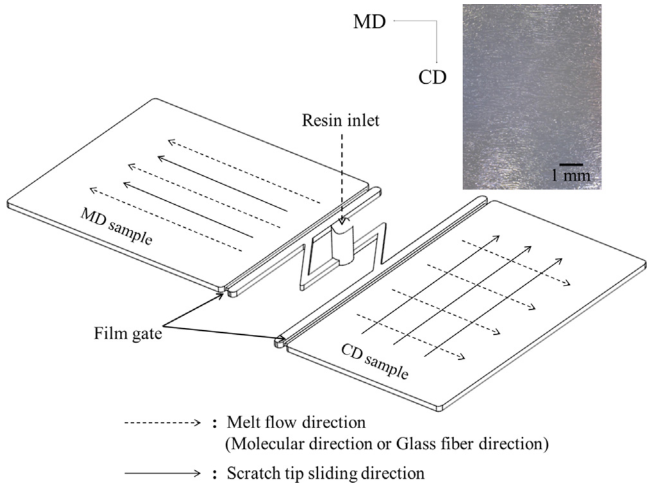

Fig. 1. Geometric details of test samples.

In this paper, the quantitative scratch resistance tests of PC plates, made with different packing pressures and different glass fiber weight fractions, were conducted using a progressive load scratch test. The effect of scratch speeds and melt flow direction on each sample was investigated. That is, a study on the scratch anisotropy and inhomogeneity was conducted, providing a basic understanding about the scratch mechanisms. In addition, scratch-induced damage morphologies of samples were also presented and discussed.

2. Materials and methods

2.1. Materials

In this study, various injection molded GFRP plates made with different packing pressures and different weight fractions of chopped glass fiber were used. First, the packing pressures for neat PC were chosen to be 65 bar, 50 bar, and 80 bar for the normal injection molding condition, deficient condition, and excessive condition, respectively. Second, the chopped glass fiber weight fractions were chosen to be 10% and 20% for modified PC. Lastly, as illustrated in Fig. 1, each sample had two different melting flow directions using of a custom-made molding cavity. Thus, the effect of molecular directions can be discussed. The overall details of the samples are shown in Table 1. In addition, specific process conditions of the samples are given in Table 2.

2.2. Scratch test

The custom built scratch machine following the American Society for Testing and Materials (ASTM) standard was utilized in this study [11]. The apparatus records normal load and tangential load, as well as scratch distance during the test. A stainless steel scratch tip with a diameter of 1 mm was employed, and scratch speeds were chosen for 10, 50, 100, and 150 mm/s with a constant length of 100 mm. For a progressive load test, the normal scratch load increased linearly from 1 N to 60 N. At least three tests were performed to ensure reproducibility for each test condition. To compensate for the time-dependent recovery of deformed polymeric materials, observations were conducted at least 24 h after the scratch tests.

2.3. Characterizations of scratch damages

After the scratch tests were conducted, samples were scanned in perpendicular directions to the scan light motion with a Canon MF 4140 scanner with a resolution of 300 × 300 dpi. To find the onset point of scratch visibility objectively, a 3% brightness criterion was applied to the scanned images (Fig. 2) as mentioned earlier. Then, the damaged samples were observed by optical microscopy (OM) to determine the relative macroscopic damage mechanisms and the damage transition points. Then, in order to

Table 1
Processing conditions in injection molding.

Composition (wt%)	Injection speed (mm/s)	Mold temperature (°C)	Barrel temperature (°C) (NH–H1–H2–H3)	Cooling time (s)	Packing pressure (bar)
PC 100%	32	90–50	245–250–230–230	20	50–60–80
PC 90%+ GF 10%	80	80	285–290–280–270	20	600
PC 80%+ GF 20%					750