Polymer Testing 49 (2016) 38–45

Contents lists available at ScienceDirect

Polymer Testing

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

Steady-state scratch testing of polymers

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ARTICLE INFO

Article history:
Received 25 September 2015
Accepted 1 November 2015
Available online 9 November 2015

Keywords:
Steady-state scratching
Orthogonal cutting
Fracture toughness
Friction
Micro-cracking
Damage

ABSTRACT

The paper extends the notion of steady-state cutting of polymers with a sharp tool to scratching. The analysis assumes there is separation at the tool tip (fracture) and the removed layer undergoes plastic shear. Results are presented for three polymers: PMMA, PC and PBT. For the tougher polymer, PC, smooth scratches were obtained and the modified cutting analysis works well provided that the wear on the initially sharp tip is accounted for. For the more brittle polymers, PMMA and PBT, rougher scratches were obtained and this is consistent with the notion that the polymers exhibited micro-cracking ahead of the tool tip, which led to rough surfaces being generated. The results demonstrate that the fracture toughness and the yield stress are controlling parameters in the scratching process and that a sufficiently high value of crack opening displacement COD (greater than about 10 μm) ensures that smooth scratches are obtained, as was the case for PC.

1. Introduction

Thermoplastic polymers are increasingly finding application in a wide range of uses including automotive parts, consumer products and medical devices. In many demanding applications the fracture toughness and yield strength are important properties and a particular challenge has been to develop a toughness test for polymers which possess a high toughness and a low yield strength as these materials are difficult to characterise with conventional tests. Such materials often violate the conditions of linear elastic fracture mechanics (LEFM) and an alternative approach is required. Previous research has focussed on the development of an orthogonal cutting test for polymers [1,2] and this method has been shown to work well for tough polymers exhibiting high ductility. The analysis for orthogonal cutting involved the extension of conventional machining modelling [3] to include the toughness term as advocated by Atkins [4]. The method has proved successful and a standard test is under development [5].

There are also a significant number of applications where the scratch resistance of the polymer is also important. Examples include the use of polymer layers in automotive clear coats (protecting the paint layers) and in touch screens for mobile devices. There is therefore the requirement to develop scratch tests and analyses for polymers which can measure scratch performance and allow the inter-relationship between scratch resistance and other key mechanical properties to be better understood. In the research reported here the main objectives have been to extend the experimental approach and analysis adopted for the cutting of polymers to scratching. In the tests, a groove is formed on the surface of the flat specimen using a sharp scratching tool with a 90° angle. Such a test has been proposed for the determination of toughness [6] using initiation rather than steady-state scratching. It is not advocated here as a test for toughness measurement because of difficulties in defining the tool profile and the occurrence of micro-cracking, which have been observed to occur. However, the scratch data can be analysed in a similar way to orthogonal cutting data to obtain the toughness and yield strength, albeit to a lower accuracy. The objective has been to demonstrate that the scratching behaviour of polymers is controlled by the properties of toughness and yield strength and this allows the possibility to control their scratch behaviour by the careful selection and manipulation of these material properties.

2. Analysis

The analysis of scratching used here is an extension of that used for steady-state orthogonal cutting using a sharp tool. In that

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http://dx.doi.org/10.1016/j.polymertesting.2015.11.002

process there is separation at the tool tip (fracture) and the removed layer undergoes plastic shear along a shear plane resulting in the off-cut chip [1,2]. Fig. 1(a and b) show the details of the scratching process with a tool of rake angle α and a profile giving a projected area A and a perimeter p. Resolving the forces on the shear plane on which there is a shear stress $\sigma_Y/2$ at an angle ϕ from the horizontal, gives: See Fig. 1b.

$$(F_c - pG_c)\cos\phi - F_t\sin\phi = \frac{\sigma_Y A}{2\sin\phi}$$
$$\text{i.e. } \frac{F_c}{p} - \tan\phi\frac{F_t}{p} = \frac{\sigma_Y}{2}\frac{A}{p}\left(\tan\phi + \frac{1}{\tan\phi}\right) + G_c \tag{1}$$

(Here pG_c may be treated as a force because of the steady-state with the loads moving with the crack and is equivalent to an energy balance.)

The two material properties of yield strength, σ_Y, and fracture toughness, G_c, may be found by performing a series of tests in which the cut depth h is varied, thus changing A and p and then measuring the cutting force F_c and the transverse reaction F_t. In addition, ϕ is required and this may be determined directly from the chip height, h_c, see Fig. 2, from,

$$\tan\phi = \frac{\cos\alpha}{{}^{h_c}/_{h} - \sin\alpha} \tag{2}$$

In orthogonal cutting, a surface layer of width b and thickness h is removed so that $p = b$ and $A = b{\cdot}h$ giving:

$$\frac{F_c}{b} - \tan\phi\frac{F_t}{b} = \frac{\sigma_Y}{2}h\left(\tan\phi + \frac{1}{\tan\phi}\right) + G_c \tag{3}$$

and if h_c is measured on the offcut chip, tan ϕ can be determined using equation (2) and hence σ_Y and G_c are determined from the slope and Y-intercept of the linear plot of $((F_c/b) - \tan\phi(F_t/b))$ versus $(h/2(\tan\phi - (1/\tan\phi)))$. This is known as 'Method 2' in the proposed standard for finding G_c from cutting tests [5].

In scratching tests the dimensions of the chips are difficult to measure accurately, particularly at small h values, and so recourse is made here to what is known as 'Method 1' from Refs. [1,2] in which ϕ is determined by minimizing the forces, i.e. the Merchant method [7] i.e.

$$\frac{dF_c}{d\tan\phi} = \frac{dF_t}{d\tan\phi} = 0$$

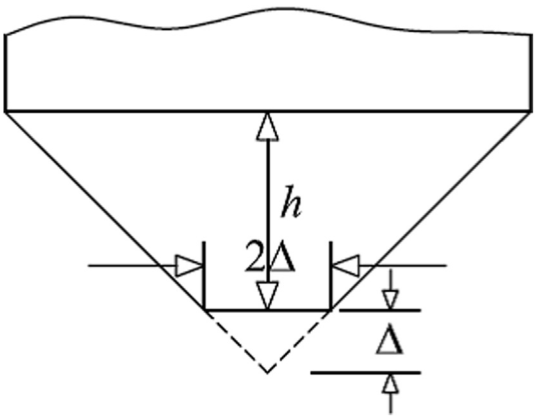

Fig. 2. Geometry of the worn tool (for corrected analysis): Former tool angle 90°, worn tip approximated as flat.

and from equation (1)

$$-\frac{F_t}{p} = \frac{\sigma_Y}{2}\frac{A}{p}\left(1 - \cot^2\phi\right), \quad \text{and} \quad \frac{F_c}{p} = \sigma_Y\frac{A}{p}\cot\phi + G_C \tag{4}$$

i.e.

$$\cot\phi = \left(1 + \frac{2}{\sigma_Y}\left(\frac{p}{A}\right)\frac{F_t}{p}\right)^{\frac{1}{2}}$$

and

$$\frac{F_c}{p} = \sigma_Y\frac{A}{p}\left(1 + \frac{2}{\sigma_Y}\left(\frac{p}{A}\right)\frac{F_t}{p}\right)^{0.5} + G_c \tag{5}$$

Thus if a set of F_c and F_t values are measured for a range of h and hence A and p values, σ_Y and G_c may be determined numerically to minimize the standard deviations.

The geometry of the scratching tool used here is shown in Fig 2. It is a 90° angled sharp point but in most cases the initially sharp point wore away quickly to leave a flat tip of width 2Δ with a length Δ having been worn away. The length Δ can be measured from the tool directly or from sectioning the resulting groove and measuring the profile. The geometric parameters are:

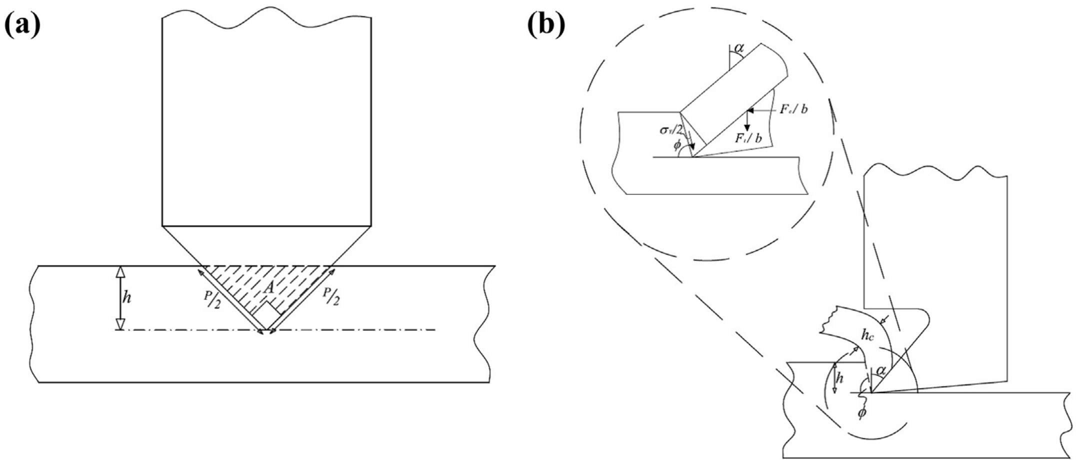

Fig. 1. Scratch tool geometry (a) View in scratch direction and (b) side view.