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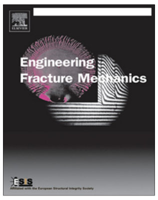

On the toughness measurement for ductile polymers by orthogonal cutting

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ABSTRACT

The fracture toughness, G_c, of three commercial polymers (HDPE, PP and PEEK) has been determined using a cutting test method. The traditional linear elastic fracture mechanics tests were conducted for comparison. The results showed that the cutting analysis is capable of giving valid fracture data for ductile polymers. However, when the cut depth is small, e.g. less than 100 μm, an inverse size effect on G_c was observed in cutting, i.e. the measured toughness of the polymers tends to decrease with the decrease of the cutting depth. Possible mechanisms for such a scale effect on fracture energy are discussed.

1. Introduction

Orthogonal cutting is a plane strain material removal process using a tool which has a plane face and a single cutting edge. During the cutting, the tool edge is perpendicular to the direction of cut and parallel with the cutting plane of the workpiece. As one of the basic material removal or machining processes, the mechanics of orthogonal cutting has received considerable attention over the past few decades. Originally, the main purpose was to predict cutting forces, chip behaviour and surface finish for various machining operations. Accordingly, early studies of the cutting process were focused on the shear yielding of the material and friction during tool-chip contact [1,2]. The energy required for new surface formation was thought to be the surface free energy and thus very small, and was ignored in the analysis of the cutting process [3]. Later there were assumptions assuming chip formation by deformation and fracture caused by tensile stresses in front of the tool cutting edge [4]. It has also been argued that the material separation in cutting was mainly caused by plastic flow due to an inevitable "ploughing" between the finite tool tip radius and the work material [5].

More recently, the issues involved in orthogonal cutting have been reviewed by Atkins [6]. It was pointed out that energy is required to separate the material and that it can be as significant as plastic shearing and friction in the cutting process. Further, the chip removal in cutting is actually equivalent to a fracture process where a crack is propagating ahead of the tip of the cutting tool. The energy required for material separation (G_c) should be the sum of the surface energy for the fresh surfaces formed ($2\gamma_s$) and the plastic deformation energy around the advancing crack tip (G_p), according to fracture mechanics [7],

$$G_c = 2\gamma_s + G_p \tag{1}$$

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Nomenclature

Greek alphabet

α	rake angle
γ	equivalent strain
γ_s	surface energy
ε	engineering strain
σ_s	critical shear stress
σ_Y	yield stress
φ	angle of shear plane

English alphabet

b	width of cutting specimen
du_s	shear displacement
dx	tool movement
dx_c	distance moved by friction S
E	Young's modulus
F_c	cutting force
F_n	normal force on the shear plane
F_s	shear force on the shear plane
F_t	thrust force
G	fracture toughness at 5% increase of compliance load point in SENB test
G_c	fracture toughness
G_p	plasticity dissipation per unit area of crack growth
G_q	reduced fracture toughness due to limited depths of cut
h	depth of cut
h_c	chip thickness
N	normal force on the tool chip interface
R^2	coefficient of determination
r_p	plane strain crack-tip plastic zone size
S	friction force on the tool chip interface

With this in mind, it was suggested that cutting could be a possible way to establish fracture toughness of materials [8]. The notion has been pursued by Williams et al. [9,10] and a method has been developed to experimentally determine the fracture toughness of ductile and tough polymeric materials. The toughness of such polymers is notoriously difficult to measure using conventional LEFM testing methods because the fracture process is always accompanied by blunting or crazing at the crack-tip. Cutting is expected to be able to overcome the problem as the external work done on the materials can be concentrated at the tip of the tool.

In the present work, the cutting theory proposed in [10] is adopted to determine the fracture toughness of HDPE, PP and PEEK. According to the theory, the friction work and plastic energies are proportional to the cut depth whereas the fracture energy would remain unchanged. This leads to the conclusion that plots of total cutting energy versus depth of cut would show a positive intercept on the force axis at zero depth of cut, which gives the value of fracture energy, i.e. fracture toughness. The experiments were carried out with different cut-depths from 10 to 250 μm, by using the tools with different rake angles ranging from 0° to 30°. The experimental data confirmed the linear plots predicted by the cutting analysis. Also, the measured fracture toughness was independent of the rake angle, suggesting that it is a fundamental property of the material. However, an inverse size effect was observed at smaller cut depths, i.e. the measured fracture toughness decreases with the decrease of the cut depth. The new results reveal a possible scale effect on fracture energy in the cutting process, which cannot be fully explained by the current cutting model. It is worth mentioning that the results are also different from the ploughing phenomenon in metal-cutting. The latter tends to give a larger intercept at a smaller cut depth [11]. Based on the mechanics analysis and experimental data, possible mechanisms for such a scale effect in cutting will be discussed.

2. Mechanics analysis

The theory of orthogonal cutting for determining the fracture toughness of materials, and polymers in particular, has not been widely discussed in the literature. However, some workers have been active in the field [8,10]. The analysis adopted in this work follows that of [10].

A schematic view of orthogonal cutting with continuous chip formation is illustrated in Fig. 1, in which the shear force F_s on the shear plane and the friction S on the tool chip interface are constructed in the same way as in the single shear plane

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