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Combined puncture/cutting of elastomer membranes by pointed blades: An alternative approach of fracture energy

Ennouri Triki*

Département de génie mécanique, École de Technologie Supérieure (ÉTS), 1100 Rue Notre-Dame Ouest, Montréal, QC H3C 1K3, Canada

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ABSTRACT

Resistance to combined puncture and cutting is controlled by two energies, one is the fracture energy or the intrinsic strength of the material, the other reflects the friction energy between a pointed blade and the material. The purpose of this study is to propose an alternative approach derived from the fracture mechanics theory to calculate the fracture energy associated to the puncture/cutting of neoprene rubber by pointed blades. The proposed approach is also based on the application of a sample pre-strained during the puncture/cutting test in order to remove the contribution of friction. It was validated with two different pointed blade angles of 22.5° and 35°. Results show that for an applied pre-strain energy (or tearing energy) of high value, the friction between pointed blade and material is completely removed. Without friction, the total fracture energy is constant. In that case, the crack growth contribution of the applied pre-strain energy is marginal. Growth of the crack is thus completely caused by the puncture/cutting by a pointed blade. Finally, results suggest that the value of the fracture energy corresponding to puncture/cutting by pointed blades is obtained at a frictional contribution of zero, but not at tearing energy value of zero. The value obtained is three times higher than the cutting energy corresponding to a cut by razor blade and also larger than that obtained from puncture by medical needles.

1. Introduction

The combined puncture and cutting behaviors of protective materials are a major component of their resistance to the combined mechanical aggressors. In particular, in the case of protective gloves used in workplaces exposed to metal sharps, glass splinters or knife tips. For example, in the meat processing industrial, laceration of knifes causes 30% of all hand injuries (Caple, 2000). According to CSST (2014), the lacerations of cut and puncture types cause about 50% of hand injuries. Wearing appropriate protective gloves to resist against puncture and cutting can reduce the risks of hand injuries about 70% (Sorock et al., 2004). The development of resistance materials to these hazard types requires various investigations of puncture and cutting mechanisms. Indeed, Triki et al. (2015) reported that the combined puncture and cutting of protective materials, especially an elastomer membrane, by a pointed blade required two crack growth mechanisms. The first was the fracture of the material, which is the intrinsic property of said material. The other was the mechanism reflecting the friction between a pointed blade and the material.

The characterization of the previous mechanisms and the evaluation of the puncture/cutting resistance also demand a fundamental method. However, the measurements for the intrinsic material parameters controlling crack propagation by combined puncture and cutting are still unknown, but fewer efforts have been devoted to understanding the puncture/cutting process of elastomer membranes by pointed blades (Triki et al., 2015).

* Tel.: +1 15146558510.
E-mail address: ennouri.triki.1@ens.etsmtl.ca, triki.nouri@gmail.com

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Nomenclature

U_t	total energy stored before the pre-crack is made
U	total energy stored after the pre-crack is made
c	length of the pre-crack
t	thickness of the test piece
S_e	stored-energy density
λ	extension ratio
$\beta(\lambda)$	numerical factor
G	fracture energy
∂U	change of applied work
∂A	change of fracture surface
G_{Total}	total puncture/cutting or fracture energy
$G_{Fracture}$	fracture energy
$G_{Friction}$	friction energy
G_{Blade}	fracture energy of the pointed blade
T	tearing or pre-strain energy
d	crack depth
$2c$	puncture/cutting length
C_1, C_2	Mooney–Rivlin coefficients
F_t	force of the sample without pre-crack
F_i	force on the sample in the presence of pre-crack
l_0	initial length of the tensile sample
A	fracture surface

Puncture/cutting resistance has therefore been characterized according to ASTM standards for puncture by medical needles (Triki et al., 2015; ASTM, 2005, 2010). These normalized methods suggest that puncture resistance can be obtained through the measurement of force of penetration, which equals the maximal value of the curve force. The global fracture energy and the global friction energy were also calculated in order to characterize the contribution of friction (Triki et al., 2015). In this recent research, it has been shown that crack growth propagation is subject to either the puncture-process or the cutting-process, according to the geometry of the tip angle blade. The synergy between the puncture and the cutting processes generated two fracture modes: Mode I and Mode III.

However, the methods of characterization of the fracture energy corresponds to the crack propagation in the material by pointed blades are not yet available up to now. Crack growth is usually expressed in terms of the strain energy release rate available from the applied deformations. This mechanical property is independent from the fracture mode of crack propagation. Rivlin and Thomas (Rivlin and Thomas, 1953) proposed a new method to calculate the fracture energy of rubbers. In their work, Rivlin and Thomas proposed changes in the total energy stored in the test piece stretched in simple extension by:

$$U_t - U = \beta(\lambda)c^2 t S_e \tag{1}$$

where U_t and U are the total energies stored before and after the pre-crack is made; c is the length of the pre-crack; t is the thickness of the test piece measured in its un-deformed state; S_e is the stored-energy density corresponding to extension ratio λ in the simple extension region; and $\beta(\lambda)$ is a numerical factor related to λ.

The energy formula corresponding to a unit increase in the fracture surface was used by various authors to describe the fracture process in the material. It is thus proposed to calculate the fracture behavior of materials by way of the tearing energy (Rivlin and Thomas, 1953; Triki et al., 2011; Felbeck and Atkins, 1996), the cutting energy (Lake and Yeoh, 1978; Vu Thi et al., 2005), the puncture energy (Nguyen et al., 2009b) and the puncture/cutting energy (Triki et al., 2016) based on the fracture mechanics theory (Griffth, 1920). In this approach, fracture energy G, which is related to the change of applied work ∂U expanded to increase the surface of a crack by quantity ∂A can be readily calculated from:

$$G = -\left(\frac{\partial U}{\partial A}\right) \tag{2}$$

In addition, the fracture energies associated to the cutting by razor blade and the puncture by medical needles were calculated by using the principles of Lake and Yeoh (1978). A pre-strain technique was proposed to remove the friction between razor blade and material. According to these principles, the fracture energy value corresponding to puncture/cutting by pointed blades has also been calculated by subtracting the friction energy from the applied total fracture energy (Triki et al., 2016). The fracture energy of neoprene rubber was thusly estimated at 2.15 kJ/m^2. In that case, the frictional contribution was completely removed by quantifying the friction energy.

In this paper, however, we propose an alternative method of calculating the exact value of the fracture energy corresponding to the puncture/cutting of neoprene rubber by pointed blades. This method is based on the application of a pre-strain technique during puncture/cutting testing, as proposed by Lake and Yeoh (1978). A formulation of the proposed approach for calculating the fracture energy is also derived from the Rivlin and Thomas theory (Rivlin and Thomas, 1953). The proposed method was also validated with two pointed blade angles of 22.5° and 35°. The fracture energy value obtained was then compared with those estimated for other hazard types.

2. Material and experimental methods

2.1. Material and pointed blades

A 1.6 mm-thick neoprene rubber membrane was used in this study. This material is often used for manufacturing protective gloves (McMaster Carr).

Two models of pointed blades with different configurations have been used and their characteristics are shown in Fig. 1. Blade #11 is a fine blade with a 22.5° angle tip (X-Acto, Model X211). Blade #24 is a medium blade with a 35° angle tip (X-Acto, Model X224).

2.2. Puncture/cutting by a pointed blade

The puncture/cutting by pointed blades tests were performed according to standard testing ASTMF1342 (ASTM, 2005). The sample holder setup was positioned in