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Short Communication: Material Properties

Fracture toughness of gamma irradiated polycarbonate sheet using the essential work of fracture

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A B S T R A C T

Polycarbonate (PC), a ductile polymer, has been found by both linear elastic fracture mechanics and impact tests to present a ductile-brittle transition, which depends on notched specimen thickness, test speed and gamma irradiation. Owing to large amounts of plastic deformation, fracture toughness measurements by these test methods are not precise. In the present communication, a better method, the Essential Work of Fracture (EWF), to assess the fracture characteristics in plane state of stress was for the first time used to evaluate the fracture toughness of PC sheets subjected to gamma irradiation dose. Three-points bend tests of sharp pre-cracked specimens with different ligament lengths were 340 kGy gamma irradiated. EWF results showed that the total fracture work increased linearly with length for both non-irradiated and gamma irradiated conditions. A significant decrease in EWF fracture toughness was associated with brittleness promoted by gamma irradiation. This brittleness was also confirmed by macro and microscopy (SEM) evidence.

1. Introduction

Polycarbonate (PC) is a thermoplastic ductile polymer, which might display brittle rupture when subjected to conditions such as notched specimen [1–3], low thickness [1,4], high speed [5] and gamma radiation [6,7]. Moreover, works on two types of PC, Makrolon [4] and Lexan [5,7] revealed by impact tests (IT) and linear elastic fracture mechanics (LEFM), respectively, a ductile-brittle transition. These works recognize, however, that due to the relative high amount of developed plastic deformation, measurements of fracture toughness by either IT of LEFM are not precise. In particular, Melo et al. [7] found that a ductile Lexan polycarbonate sheet (90–120% tensile elongation at break) exhibited a ductile-to-brittle transition on exposure to gamma radiation doses in the range from 50 to 125 kGy. Since their sheet thickness did not allow the determination of a valid fracture toughness K_{IC}, an apparent K_{app} was calculated only for comparative purpose. Nevertheless, the increasing applications of PC subjected to gamma irradiation, such as in nuclear engineering (dielectric, insulator and track detector) [8–14] as well as sterilized medical instrumental and devices [15–17] require a precise determination of its fracture toughness.

A better approach to investigate the fracture toughness of ductile materials is the Essential Work of Fracture (EWF) method [18–20]. It assumes that the region around the crack tip can be divided into two different zones, the inner fracture process zone and the outer plastic deformation zone. In this way, the total fracture work (W_t) can also be separated into two parts, the essential fracture work (W_e) associated with two newly created fracture surfaces, and the non-essential fracture work (W_p), related to plastic deformation. The value $W_t = W_e + W_p$ from bending tests of sharp pre-cracked specimens with different ligament lengths (L) can be obtained by integrating the area under the force-elongation curve. The value of W_e, a material property for a given sheet thickness, is then determined by the interception at zero length of the best fit of W_f versus L plot [21,22].

The EWF, in principle, could provide a more precise and quantitative evaluation of the influence of gamma irradiation on the fracture toughness of a PC sheet. The effect of gamma irradiation on the hardness [23] and optical properties [24] of PC has been disclosed for relatively higher doses (800 kGy). However, as aforementioned, a more reliable gamma irradiation effect on the PC

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fracture toughness is yet to be evaluated, particularly for doses above 125 kGy [7]. As a practical example, this effect is of importance for assessing the impact behavior of ballistic armors with PC components exposed to environmental conditions associated with gamma radiation [6]. Additionally, an investigation of the possible mechanisms responsible for changes in the fracture toughness might contribute to understand the role played by gamma irradiation in PC behavior. Therefore, the present communication applied the EWF method to characterize the fracture behavior of a Brazilian made PC sheet in both conditions: non-irradiated and subjected to 340 kGy dose of gamma irradiation. Moreover, comparison between the gel content, viscosimetry and hardness for the two conditions permitted proposal of a related mechanism.

2. Experimental procedure

The investigated PC was Brazilian made, with technical denomination of PC Light, fabricated by Policarbonatos do Brasil firm and supplied as 8 mm thick extruded sheets. Samples extracted from these PC sheets were room temperature (RT) gamma irradiated in air with a ^{137}Cs source at a dose rate of 2.0 kGy/h, with an accuracy of ±2%. The total accumulated radiation dose, 340 kGy (34 Mrad), was selected by considering that a PC sheet should become brittle after this relatively high gamma irradiated dose [7]. According to the operational parameters, the uncertainty in the absorbed dose was estimated to be about ±5%.

Physicochemical and mechanical properties of PC were determined before and after exposure to radiation in order to investigate possible embrittlement mechanisms. The fracture surfaces of the specimens were observed, after being sputtered with gold, by scanning electron microscopy (SEM) in a model JSM 5800LV JEOL microscope operating with secondary electrons at 30 kV.

The gel content was determined, before and after irradiation, by extracting the soluble fraction of polycarbonate with chloroform for 24 h in a Soxhlet extractor as per ASTM D2765 [25]. The viscosimetric molecular weights were determined before and after irradiation by intrinsic (η) viscosity using an Ubbelhode capillary viscometer at 25 °C. Molecular weights were measured in chloroform by solution viscometry using the Kuhn–Mark–Houwink–Sakurada relationship:

$$[\eta] = KM^a \tag{1}$$

where K and a depend on the test conditions. For the test conditions of the present work, $K = 12 \times 10^{-3}$ mL/g and $a = 0.82$ [26].

Rockwell hardness tests were performed on the front face of stacked specimens as per ASTM Standard D785 [27] in a Model RBS Pantec hardness tester (Brazil) using the M scale (60 kg and 0.5 in steel ball). Tension tests were carried out at RT as per ASTM D638 [28] in a model DL2000 EMIC universal testing machine (Brazil) with a crosshead speed of 10 mm/min. Three-points flexure fracture toughness tests, based on the ESIS EWF test protocol [29], were performed at RT in the same machine as used for tensile tests. Notched specimens with dimensions of 70.6 mm × 16.0 mm × 8.0 mm and gage length of 50 mm were tested with a crosshead speed of 10 mm/min. The 0.3 mm notch was made with a diamond disk in a Struers, model Accertom-2 cutting machine. A sharp pre-crack was cut through the specimen using a fresh 0.15 mm wide razor blade to produce specimens with initial crack length $\boldsymbol{a}$ varying between 2.43 mm and 9.8 mm. Fig. 1 shows a schematic representation of the specimen before fracture. Different ligament lengths with $L = (16.0 - 0.3 - \boldsymbol{a})$ mm were then considered by subtracting the notch and the initial crack length from the specimen width. Load-displacement curves were recorded and the total fracture work was determined as a function of ligament length.

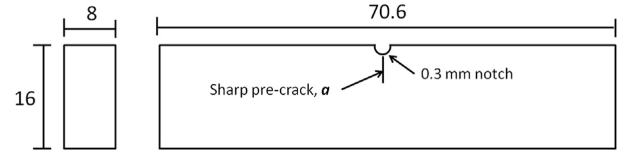

Fig. 1. Schematic of a fracture toughness test specimen (dimensions in mm).

Fractographic evaluation was carried out by direct macro-observation of the fractured surface topography and SEM.

3. Results and discussion

Table 1 shows the results of gel content, viscosimetric molecular weight and basic mechanical properties of both non-irradiated and 340 kGy gamma-irradiated PC samples. In this table, the absence of gel content after gamma-irradiation suggests that, apparently, no cross-linking was produced in the investigated PC. On the other hand, the significant reduction (~60%) in molecular weight clearly indicates an effective scission mechanism occurring in the molecular chain backbone of the PC. In fact, a substantial reduction in molecular weight of a polymer can only be attributed to chain scission [30].

The results of hardness and tensile properties in Table 1 show a significant decrease in values after gamma irradiation. This might also be assigned to scission of molecular chains in PC. Indeed, the higher radiation dose was associated with a comparative increase in the amount of shorter chains, which facilitates the chains disentanglement and favors the process of polymeric rupture [7]. The marked decrease (~19%) in tensile elongation at break, Table 1,

Table 1
Gel content, viscosimetric molecular weight, harness, ultimate strength and elongation at break for the PC Light polycarbonate.

Property	Non-Irradiated	Gamma Irradiated (340 kGy)
Gel Content (%)	Zero	Zero
Viscosimetric Molecular Weight (g/mol)	34,000	14,000
Rockwell Hardness M	55 ± 2.28	37 ± 0.97
Ultimate Strength (MPa)	64 ± 0.94	56 ± 0.08
Elongation at Break (%)	77 ± 0.04	55 ± 0.11

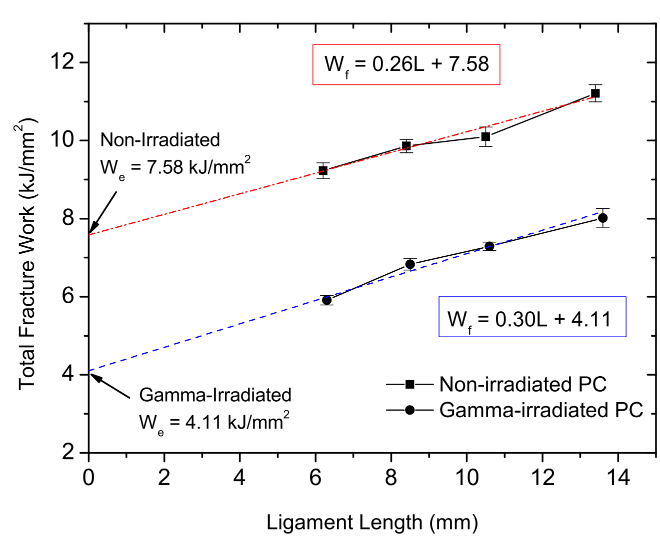

Fig. 2. Dependence of total fracture work on ligament length before and after gamma irradiation.