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Fracture toughness characterization of polymers-based composites using essential work of fracture method

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Abstract. Fracture toughness of polymer-based composites in plane stress condition has been successfully evaluated using latest method namely essential work of fracture (EWF). This method has been extensively performed in order to assess the performance of two parameters in fracture, i.e. essential work of fracture (w_e) and non-essential work (βw_p) ones. The use of EWF method is widespread due to the preparation of uncomplicated specimens, easy examination and easy data processing procedures but accurate in data analysis. This review is focused on the EWF application for the characterization of fracture toughness of polymer-based composites in which the fracture occurs in plane stress state. The EWF testing procedure is in accordance with the recommendations of the ESIS protocol TC-4. Literature reviewed includes all the major areas of testing and simplification of associated data for both quasi-static and dynamic condition. The latter is an EWF application classified by the type of load applied.

1. Introduction

A polymer is made of large molecules composed of many repeated subunits that are connected by covalent bonds. Polymer have many advantages such as light weight, good corrosion resistance and low cost, and have become the important commercial material such as construction, automotive, biomedical, household appliances, etc. An important parameter in evaluating the materials is fracture toughness. This parameter is very important to know especially for materials that are subjected to impact load in its application. In the case of biomaterials for load bearing implant application such as skull bone implant, it is important to examine the various fracture parameters with the consideration that they protect a critical part of human brain.

Since the wide use of polymers, their mechanical properties such as fractures are very importance. Fracture behavior, i.e. brittle or ductile, is categorized by the amount of deformation that occurs during the fracture process. Brittle fractures are characterized by very limited or no plastic deformation involved. As for the ductile fracture, the polymer undergoes plastic deformation prior to and during the fracture occurred. The fracture toughness behavior of materials can be evaluated using fracture mechanics methods [1-4]. In order to analyze the material fracture, a linear elastic fracture mechanics (LEFM) approach widely used to assess the fracture mechanics of material under plane-strain condition that mostly occurs in extremely thick specimens and satisfy small-scale yield conditions [5, 6]. The LEFM is particularly suitable to be applied to brittle materials. In ductile materials, fracture toughness is evaluated through the crack tip opening displacement (CTOD) parameter, also can be evaluated using

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the J-Integral method pioneered by [7] in which the plane-strain fracture toughness is obtained at relatively low specimen thickness compared to the LEFM approach [6]. In a plastic deformed material prior to failure, the CTOD testing can be accurately applied to characterize fracture toughness.

Recently, the fracture toughness behavior in ductile materials including thermoplastics and polymer matrix composites widely be assessed using the EWF approach that divided the fracture energy in two different parts, the w_e and βw_p [8-10]. The use of this method has evolved to characterize the fracture toughness in ductile materials. The EWF test is performed using a double edge-notched tension (DENT) subjected to tensile load in quasi-static conditions as well as single-edge notched bend in impact load (dynamic conditions) [8, 11, 12]. In quasi static state, the test is performed in accordance with the standards set forth in the ESIS protocol which will be explained later in this paper. In the case of fracture due to impact load causing failure, the test is performed according to Charpy impact tester.

2. The EWF method

2.1. Theory

The concept developed in the EWF method is an alternative solution to respond the weaknesses in the previous method in term of the assessment of the fracture parameters of the ductile materials. This method is able to provide clarity of energy partition during the fracture process of materials. Many researchers [13, 14] have developed the EWF method as a testing standard for evaluating fracture behavior in ductile materials including polymers and composites. In the EWF testing, the DENT specimens as shown in figure 1(a) are used as a standard specimen shape. The EWF concept was first introduced by [15] and is based on a study conducted by [16], i.e. the stability of crack growth occurs as a result of autonomous input energy during the fracture process. Consequently, when a DENT specimen is subjected to a tensile load up to total fracture, the total fracture energy (W_f) is consumed by material in two distinct zones (see figure 1(a)). Firstly, the fracture process zone where the fracture takes place and energy is used to create a new crack surface during crack propagation occurs. Second, the plastic deformation zone that is around the ligament length. The energy consumed in both first and second zones is the essential (W_e) and non-essential (W_p) work of fracture, respectively. Consequently, the W_f can be divided into two distinct parts namely W_e and W_p. In mathematical form, the W_f is the sum of both energy and can be written as equation (1) [17, 18].

$$W_\mathrm{f} = W_\mathrm{e} + W_\mathrm{p} \tag{1}$$

According to the EWF method, the crack resistance parameter of the material represents the fracture energy required to form a new cracked surface. Therefore, W_e value are strongly associated with the ligaments length (ℓ) for fixed material thickness, so essential energy also called the surface energy. The plastic work W_f is corresponding to volume of outer zone in which proportional to the quadratic of the ligament length, therefore the non-essential work is the volume energy.

From figure 1, (a) is the schematic illustration diagram for DENT shape showing the location of fracture process zone (FPZ) and outer process zone (OPZ), (b) typical of load-displacement curve and (c) data reduction of EWF. Based on the fracture zone separation as explained, the two zones are assumed to be inside the ligament of the specimen as illustrated in figure 1(a), in specific term, equation (1) can be written into equation (2).

$$W_\mathrm{f} = w_\mathrm{e}.t.\,\ell + \beta.w_{\mathrm{p}.}.t.\ell^2 \tag{2}$$

By dividing the parameters in equation (2) by $\ell.t$, the following specific fracture parameters are obtained as shown in equation (3).

$$w_f = w_\mathrm{e} + \beta.w_\mathrm{p}.\ell \tag{3}$$

The shape factor denoted by β is a factor that characterizes the dimension of the plastic zone and depends on the OPDZ shape on the length of ligaments on the DENT specimen with a thickness t. By using figure 1b, the total work of fracture is equal to the area under load-displacement curve obtained by experimentally from the DENT shape under tensile loading in quasi static condition. In according to the equation (3), the w_f is a linear function of ligament length in plane stress state. By plotting the w_f value against the ligament length (see figure 1(c)), the specific essential work of fracture (w_e) value is the intercept at zero ligament length ($\ell = 0$) and the specific non-essential work of fracture (βw_p) is the slope of the line formed by the linear equation of w_f (see figure 1(c)). From figure 1(c), it can be explained that when the ℓ value is lower than (3-5)t, the materials undergoes a plane strain fracture or in a mixed-mode fracture state. The same thing will also be occurred when the ℓ value is less than or equal to (W/3 or $2r_p$).

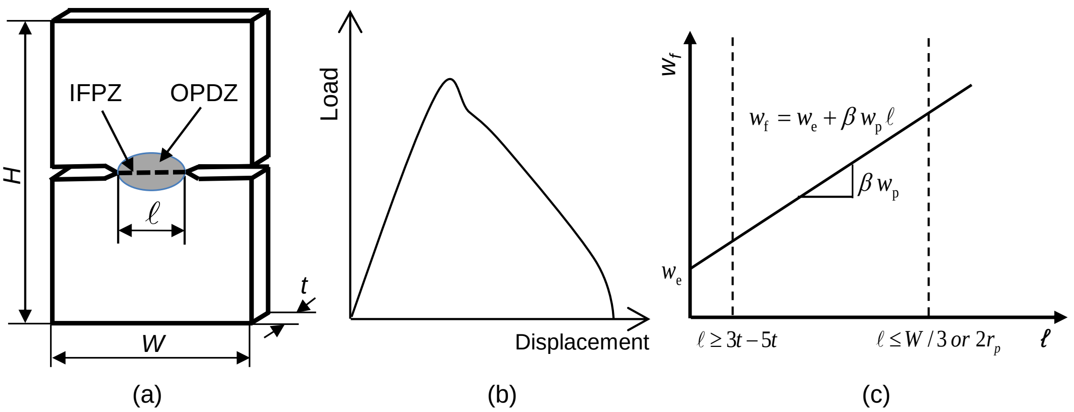

Figure 1. Schematic illustration diagram for (a) DENT shape showing the location of fracture process zone (FPZ) and outer process zone (OPZ), (b) typical of load-displacement curve and (c) data reduction of EWF.

2.2. Experimental Consideration

The requirements that must be met prior to applying the EWF approach to evaluate the plane stress fracture toughness as recommended by European Structural Integrity Society (ESIS) – TC 4 protocol [18] are as follows:

a. Under tensile load, the fully ligament yielded should be reached before the crack is initiated
b. Equation (3) can be applied if the notched specimen (DENT) is in a plane stress fracture condition. Furthermore, the fracture condition be verified according to the Hill's criterion [19].
c. The load-displacement of all specimens tested having different ligament length should clearly exhibit a self-similarity for each ligament length. In this term, the data is obtained from experimental series in DENT shape.

2.2.1. Specimen geometry and testing condition. In materials with ductile fracture, the fracture process zone undergoes a necking process which then breaks into a fracture surface. According to ESIS – TC 4 protocol and many researchers [16, 20], it has suggested that the specimen geometry must meet the specific conditions required so that the fracture occurs in plane stress manner. The required conditions involve the specimen thickness (t), the width of DENT specimen (W), and the plastic zone size (r_p). The relationship between parameters of those requirements can be expressed in equation (4).

$$(3-5)\,t \leq \ell \leq \min\left(\frac{W}{3} \text{ or } 2r_p\right) \tag{4}$$

The parameter r_p (see equation (4)) is related to the essential work of fracture (w_e) as well as the tensile properties of the materials test including the Young's modulus (E), and the tensile yield stress (σ_y). The r_p can be estimated using equation (5).

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$$2r_p = \frac{1}{\pi}\frac{E w_e}{\sigma_y^2} \tag{5}$$

Note that if the left side of equation (5), i.e. $2r_p$ is equal to the ligament length means the ligament of DENT specimen tested is completely full-yielding before the fracture is initiated and subsequently undergoes propagation. To ensure the plane stress fracture was occurred in the test, the ligament length should be met to the value for left hand-side of equation (4). If ligament length is smaller than the lower bound, the material will fall in plane-stress to plane-strain fracture transition. Schematic illustration of the requirement is presented in figure 1(c). Nevertheless, the threshold value is only discussed in a little literature so that the boundary value is not supported by strong theoretical studies. The ESIS protocol was revised [20, 21] with emphasis that Hill's criterion could be improve by the similar stress condition, verified by the highest tensile stresses of all specimens tested. According to this revised protocol, the validity of ℓ under plane stress fracture conditions are checked using formula $0.9 < \sigma_{max}/\sigma_m < 1.1$, in which the σ_{max} is the net section stress while σ_m is the mean value of σ_{max}. This means that if $\sigma_{max} < 0.9\ \sigma_m$ or $\sigma_{max} > 1.1\ \sigma_m$ then the data is declined because it does not match from the terms required in the EWF.

2.2.2. Energy partitioning. Total energy consumed throughout the fracture occurs has been studied and formulated in various expression by many researchers. An approach proposed Mai and co-workers [13] partitioned the total work (W_f) into two distinct parts: (i) work or energy for initiate fracture (W_i), and (ii) the fracture work for crack growth including crack propagation and necking (W_g), as schematically depicted in figure 2(a). The w_e parameter is independent to ℓ while the βw_p one is corresponding to ℓ. A similar approach was also introduced by [12, 22] that divided the W_f into the energy dissipated for yielding (W_y) and the energy for necking and tearing (W_n), as schematically depicted in figure 2(b). Consequently, the energy for yielding is also divided into two parts, the essential and the non-essential energy. This logic applies also to the energy used for the necking and tearing process. The load-displacement curve is partitioned only to explain how stored elastic work is considered. The elastic work is estimated based on the concept of energy initiation that the energy released in the subsequent fracture process as a result of elastic work contributed significantly to the overall energy consumed. Based on energy-partitioned work of fracture methods, it can be written as equation (6) and (7).

$$W_f = W_y + W_n \tag{6}$$

$$w_f = (w_{e,y} + \beta_y . w_{p.y} .\ell) + (w_{e.n} + \beta_n w_{p,n} . \ell) \tag{7}$$

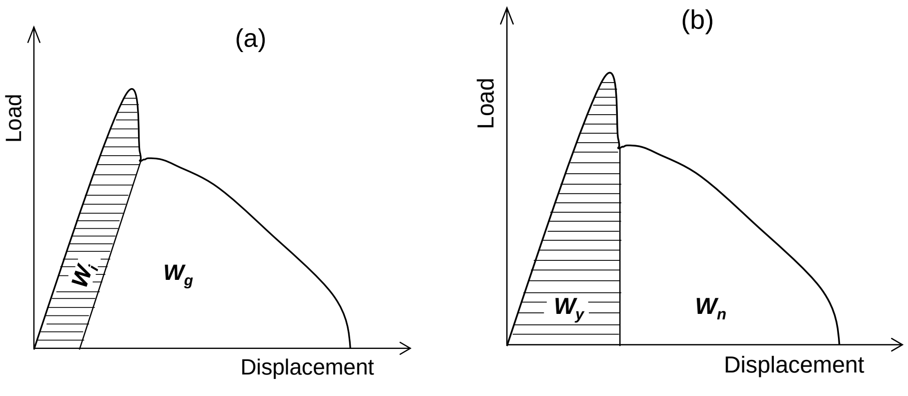

Figure 2. Schematic diagram showing the energy partitioning for initiate fracture (W_i) and growth (W_g) (a), and energy for yielding (W_y) and necking subsequent tearing (W_n) (b).

From equation (6), the specific essential is sum of the essential energy of the composites at the initiation/yielding stage and the necking one. While the non-essential energy is also the sum of both energy components at the yielding stage and necking as in the essential energy. So, it can be expressed in equation (8) and (9).

$$w_e = w_{e,y} + w_{e.n} \tag{8}$$

$$\beta w_p. = \beta_y w_{p,y} + \beta_n w_{p,n} \tag{9}$$

in which the $w_{e,y}$ is the specific essential work for yielding, and the $w_{e,n}$ is the specific essential fracture work for necking and tearing. The parameter $w_{p,y}$ and $w_{p,n}$ are specific work for plastic deformation during yielding and necking subsequent tearing, respectively. Many ductile materials exhibit delayed yielding conditions, therefore the yielding part can be divided into two distinct parameters, i.e., crack tip blunting and ligament yielding [23].

2.2.3. EWF Under Impact Loading. The behavior of deformation and impact fracture toughness are very important to understand in order to gain a deep knowledge on fracture mechanics of ductile materials, especially polymer-based composites. Deformation and composites fracture behavior in this condition can behave somewhat brittle at high strain rates. It should be considered that the experimental fracture toughness in ductile material is not suitable as a basis for the assessment of fracture strength parameters because the specimens tested are often not fully fractured. The use of EWF method has been developed by [24]. They have been developed the application of EWF concept for characterized the fracture of ductile polymer under impact loading by using single edge notched bend (SENB) specimen. Furthermore, Martinatti and Ricco [25] confirmed the validity of the use of this method to evaluate the fracture toughness of polypropylene-based materials. The development for impact loading application, equation (3) is then modified with another terminology [26] into equation (10) as follows:

$$\frac{U}{A} = \mathrm{u}_0 + \mathrm{u}_{\mathrm{d}}.\ell \tag{10}$$

in which U/A is total impact fracture energy per unit area where the fracture occurred, u_o is the limiting specific fracture work, and u_d is the dissipative energy density. In relation to equation (10), Kudva [27] considers that equation (10) is precisely inappropriate, that equation (3) should be more appropriate for dynamic condition (impact loading) or high speed rate. For the validity of the used the EWF method, Fasce *et al.* [28] clarified its use for impact load or other load type mentioned. Finally, they concluded that this method is well suited to characterize the fracture toughness and behavior in polymeric composites and other ductile materials.

2.2.4. EWF Application. At present, the fracture mechanics of various thermoplastic matrix composites and other ductile materials have been effectively assessed using the EWF concept rather than the J-Integral and CTOD. It can be understandable because it provides many advantages over the others. The selected references exploring the application of EWF method for both static and dynamic loading in different polymer matrix composites can be elucidate below. The EWF method has been widely applied to characterize the fracture toughness of various polymer-based materials including polyethylene, polypropylene and polyamide based materials. Among of them, the fracture toughness of polyethylene-based materials most widely investigated using that method. Costa *et al*. [29] have successfully evaluated the fracture behavior of nanocomposites composed of polyethylene incorporated with Mg/Al LDH. In a quasi-static state, the micro composite of HDPE combined with natural zeolite has been effectively assessed by [30, 31] with using the partitioning energy based on the EWF concept. Similar to that done by them, many other researchers [32-35] also conduct the assessment of both the HDPE and MDPE. For the materials in high impact rate test, the EWF concept has been extensively used for assessing the performance of mechanical fractures of the ductile materials, especially polymer-based materials. The researchers [36-39] used a single edge notched bend (SENB) shape to evaluate the impact fracture toughness and behavior of ductile materials. In the case of impact fracture, they have been reported that the EWF method is suitable and should be further developed in assessing the robustness and mechanics of materials fracture widely.

3. Conclusion

The EWF method has grown and is well suited for evaluating the polymer-based composites fracture toughness behavior. The EWF testing parameters can be used as standard testing for fracture toughness of the polymers matrix composites. In fact, EWF techniques show a deeper interpretation of the fracture behavior. The superiority of the EWF method compared with the others, especially the J-Integral and CTOD, is that the fracture energy can clearly be separated into the essential and non-essential parts of the energy during the fracture process. The EWF method has been shown to be effective for use primarily in thermoplastic polymer, allowing the study of the effect of various variables on fracture mechanics that are not available in the other methods. In the last decade, this method continuous to be developed by many researchers and they strongly recommend for the EWF method for assessing the fracture mechanics especially the fracture toughness behavior of the ductile materials widely. This recommendation is reasonable because there are so many advantages offered by that method in solving various problem in mechanical analysis and fracture of ductile materials.

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