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On the influence of moisture content on the fracture behaviour of notched short glass fibre reinforced polyamide 6

F.T. Ibáñez-Gutiérrez, S. Cicero*, I.A. Carrascal

LADICIM (Laboratory of Materials Science and Engineering), University of Cantabria, E.T.S. de Ingenieros de Caminos, Canales y Puertos, Av/ Los Castros 44, 39005, Santander, Cantabria, Spain

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ABSTRACT

The aim of this work is to analyse the influence of moisture content on the fracture behaviour of notched short glass fibre reinforced polyamide 6 (SGFR-PA6). For this purpose, the study combines two fibre contents (10 wt% and 50 wt%) with three different moisture contents (dry, 2% and 4–5%). Fracture tests were conducted on Single Edge Notched Bending (SENB) specimens, considering five notch radii (from 0 to 2 mm) for each combination of fibre and moisture content. Although notch effect is clearly observed in dry conditions, when the moisture content increases this effect tends to decrease for the notch radii considered here. The Line Method of the Theory of Critical Distances has been calibrated and validated for the conditions studied, providing a reasonable prediction of the apparent fracture toughness of the material in notched conditions. Concerning the fractographic observations, a Scanning Electron Microscopy analysis was performed, revealing the evolution of fracture micromechanisms when the moisture content increases.

1. Introduction

Since the mid-20th century, fibre-reinforced composite materials have become an important type of technical plastics which are replacing other materials in engineering, industrial and construction components due to their easy fabrication and good mechanical properties [1–3]. Among the different commercial grades of aliphatic polyamide, Polyamide 6 (PA6) is one of the most widely used thanks to its combination of good processability, high mechanical properties, and chemical resistance [4]. The main advantage of reinforcing PA6 with short glass fibres is the increase in stiffness, strength, abrasion resistance and heat distortion temperature, without any loss of impact strength [5]. Nevertheless, these materials are sensitive to environmental conditions such as temperature and moisture. A common property of all polyamides (PAs) is their high moisture absorption capacity [4], which can be a major disadvantage in applications where, during their service life, water is expected. Absorbed water in PAs leads to a significant variation in many properties: a decrease in elastic modulus, yield stress and glass transition temperature (T_g), while both strain under maximum load and toughness may increase [6].

Regarding the aforementioned increasing number of components fabricated with SGFR-PA6, this may imply the presence of stress risers in the material (i.e, notches), not necessarily crack-like defects, that could lead to failure. In such cases, it may be over-conservative to consider that notches behave as cracks, given that notched components develop an apparent fracture toughness (i.e, the fracture resistance in notched conditions) which is greater than the fracture toughness observed in cracked components. Consequently, specific approaches for the fracture analysis of this type of defects have been performed using different failure criteria: the Strain Energy Density (SED) criterion (e.g. [7–11]), the Global Criterion (e.g, [12,13]), different methodologies included within the Theory of Critical Distances (TCD) (e.g. [14–19]), stress based criteria (e.g. [20–22]), Cohesive Zone models (e.g, [23–25]), andmechanistic models [26], among others. The application of the TCD methodologies (see below) has been validated in different failure mechanisms and materials, and has also been used together with Failure Assessment Diagrams (FAD) in structural integrity assessments of notched components [27–29].

Previously, the present authors have validated the use of the TCD in notched SGFR-PA6 in dry conditions (and at room temperature) with five different amounts of fibre content [18], as well as providing structural integrity assessments in these materials combining the FAD methodology with the TCD [29]. These works have provided a better understanding of the fracture behaviour of SGFR-PA6 material without the influence of any other environmental variable, but the fact is that components made of SGFR-PA6 may operate under significantly different working conditions and, particularly, with substantial amounts of moisture. Thus, the aim of this paper is to analyse the influence of

* Corresponding author.
E-mail address: ciceros@unican.es (S. Cicero).

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moisture on the notch effect in SGFR-PA6 with medium and high fibre contents, and to validate the use of the TCD for the mentioned conditions. This would provide a wider more practical scope about the fracture behaviour of structural components made of SGFR-PA6. To the knowledge of the authors, this is the first work analysing simultaneously the effects of notch radii and moisture content on the fracture behaviour of a composite material, opening a line of research that will lead to a greater knowledge of the fracture behaviour of composite materials in real conditions.

With all this, Section 2 gathers a brief theoretical overview of the TCD, Section 3 presents the materials and methods, Section 4 describes the analysis of the notch effect for the different conditions of moisture content, including the observation of fracture micromechanisms and, finally, Section 5 provides the conclusions.

2. The theory of critical distances

The Theory of Critical Distances (TCD) is actually a set of methodologies, all of which have two principal features in common: the use of linear-elastic analysis and a characteristic material length parameter (the critical distance, L) when performing fracture or fatigue assessments [14,30]. The origins of the this theory are related to the work of Neuber [31] and Peterson [32] developed in the middle of the twentieth century, but it has been in the last decades that the TCD has been widely studied for the analysis of different type of materials (e.g., metals, polymers, composites or ceramics), failure processes (e.g., fracture and fatigue) and conditions (e.g., brittle fracture vs. ductile fracture, etc) [17–19,33–35].

In fracture analysis, the expression of the critical distance L is as follows:

$$L = \frac{1}{\pi}\left(\frac{K_{mat}}{\sigma_0}\right)^2 \tag{1}$$

K_{mat} being the material fracture toughness and σ_O is the inherent strength, a material strength parameter. In those situations where there is a linear-elastic behaviour, σ_O coincides with the ultimate tensile strength, σ_u. However, when the material behaviour is not fully linear-elastic, σ_O is generally larger than σ_u and the application of the TCD requires the fracture testing of notched specimens, finite elements modelling, or both, in order to calibrate the material parameters involved. This constitutes one of the main practical issues for the engineering application of the TCD. However, it should be noted that, although the TCD has in principle a linear-elastic nature, the results obtained under elastic-plastic conditions have also been accurate once the corresponding calibration has been adequately performed [14,33].

From a theoretical point of view, the physical meaning of L is not yet completely clear and is still the major concern, although there have recently been some significant insights into this topic (e.g. [14,36]).

Among the different methodologies included within the TCD, the Point Method (PM) is the simplest version (Fig. 1) and it states that fracture takes place when the stress (σ) at a distance of $L/2$ from the defect tip reaches the inherent strength (σ_O):

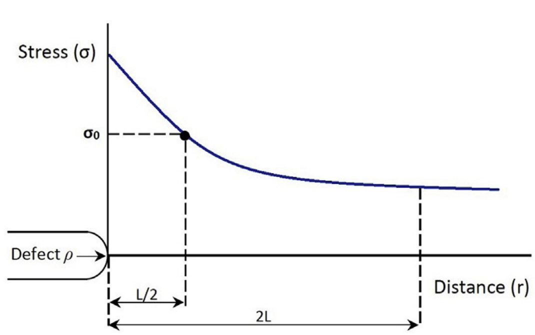

Fig. 1. Definition of the point method (PM) and The lined method (LM).

$$\sigma\left(\frac{L}{2}\right) = \sigma_0 \tag{2}$$

As an alternative to the PM, three other methods within the TCD also use the elastic stress field in the vicinity of the notch: the Line Method (LM), the Area Method (AM) and the Volume Method (VM). In these methods, the stress conditions are defined as the average value over some domain of the stress field, rather than that at a particular point [14]. The LM (Fig. 1) provides similar predictions to the PM, and it proposes that fracture will occur when the mean stress over a distance of 2L from the defect tip is equal to the inherent strength (σ_O):

$$\frac{1}{2L}\int_0^{2L} \sigma(r)dr = \sigma_0 \tag{3}$$

Whilst both the AM and the VM also provide accurate predictions, these methods are more difficult to apply than the PM and the LM.

Both the PM and the LM are capable of providing expressions for the apparent fracture toughness (K_{mat}^N), which is here understood as the fracture resistance developed by a material in notched conditions. Once K_{mat}^N is known, the fracture analysis in a notched component is reduced to an equivalent situation in a cracked component, with the only particularity of considering K_{mat}^N instead of K_{mat}. Thus, fracture will occur when:

$$K_I = K_{mat}^N \tag{4}$$

K_I is the stress intensity factor for a crack with the same dimensions of the notch being analysed. This parameter defines the stress field ahead of the crack tip under linear-elastic conditions.

Creager-Paris [37] derived a stress distribution for U-shaped notches from the mode I stress intensity factor (K_I), the notch radius (ρ) and the distance existing from the notch tip to the point being assessed (r), giving:

$$\sigma(r) = \frac{K_I}{\sqrt{\pi}}\frac{2(r+\rho)}{(2r+\rho)^{3/2}} \tag{5}$$

Equation (5), together with the fracture conditions established by the PM and the LM (equation (2) and (3), respectively) provide the above referred expressions of K_{mat}^N [14] for both the PM and the LM (equation (6) and (7), respectively):

$$K_{mat}^N = K_{mat}\frac{\left(1+\frac{\rho}{L}\right)^{3/2}}{\left(1+\frac{2\rho}{L}\right)} \tag{6}$$

$$K_{mat}^N = K_{mat}\sqrt{1+\frac{\rho}{4L}} \tag{7}$$

As mentioned above, and as shown in the literature (e.g. [14,17,18]), the PM and the LM provide similar results, although the LM tends to generate slightly more accurate predictions when compared to experimental results. This, together with the more simple expression of K_{mat}^N derived from the LM makes that, for the sake of simplicity, the analysis in this paper will be focused on the LM estimations.

With all this, it may be concluded that the main advantages of the TCD are its simplicity, its versatility to be applied to different types of materials, processes and defect types, and its extensive validation performed in the last few decades. Among the main disadvantages are both the lack of a clear understanding about the physical meaning of L, and the need for the calibration of this parameter in many practical situations.