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Determining the fracture resistance of thin sheet fiber composites – Paper as a model material

J. Zechner [a,b,*], M. Janko [b,c], O. Kolednik [a]

[a] Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Jahnstrasse 12, A-8700 Leoben, Austria
[b] Materials Center Leoben Forschung GmbH, Roseggerstrasse 12, A-8700 Leoben, Austria
[c] Polymer Processing, Montanuniversität Leoben, Otto Glöckel-Str. 2, 8700 Leoben, Austria

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ABSTRACT

In nonlinear fracture mechanics testing of thin-sheet short-fiber composites, special problems occur that do not appear in other engineering materials, such as steels. The most important problem is the formation of a long process zone, where fiber pull-out, realignment and breakage occur, making an optical crack length measurement impossible. This impedes the determination of a reproducible value of the fracture toughness and the construction of a crack growth resistance curve. Two new approaches are presented to overcome this problem. In the first one, a procedure is presented to determine experimentally the cohesive zone relation on deeply-notched double-edge notch tension specimens. The cohesive zone relation enables us, together with the mechanical properties, to simulate numerically a fracture mechanics test on an arbitrary geometry and to determine a crack growth resistance curve. In the second approach, the displacements and strains around the process zone are measured during in situ experiments under an optical microscope using digital image analysis. With this local deformation analysis, a critical local strain is determined where the load bearing capacity of the material decreases to zero. The knowledge of this critical strain is used to find the location of the crack tip and to determine a crack growth resistance curve. The application of the two approaches is demonstrated on commercial printing paper as model material. It is shown that reproducible fracture toughness parameters can be determined with both procedures.

1. Introduction

Standardized fracture mechanics experiments are available in order to determine the fracture toughness for various classes of materials and composites. Such experiments are conducted by loading a pre-cracked specimen while observing the extension of the crack. The fracture initiation toughness is determined at the onset of crack growth; in cases where the fracture toughness varies during crack growth, it is useful to determine the crack growth resistance as a function of the crack extension.

For some materials the measurement of the fracture toughness properties is still difficult, especially for thin sheet fiber composites that exhibit a nonlinear stress–strain behavior. The main problem in these materials is the measurement of the crack extension. A nonlinear region appears around the crack tip (plastic zone, see Fig. 1a) so that the onset of crack extension cannot be deduced from the nonlinearity of the load–displacement record. Inside the plastic zone, a process zone of length l_{pz} appears close to the crack tip where the micromechanical processes of crack growth occur, such as the fracture of the matrix material, fiber pull-out and -fracture (Fig. 1b). The behavior of the material within the process zone can be described by the cohesive zone model, i.e. a characteristic curve where the local stress perpendicular to the crack plane is plotted against the local separation δ of the crack flanks, Fig. 1c. Different proposals exist in literature how to define the current position of the crack tip in the process zone (which determines the current crack length) [1]. Let us assume, we define the crack tip at the position just behind the last unbroken fiber, where $\delta = \delta^*$ in Fig. 1c. This seems physically appropriate, since no force is transmitted between the upper and lower crack flank behind this position.

A problem now appears, if the process zone becomes very long during the fracture mechanics experiment. Depending on the specimen geometry, the process zone might even extend through the whole unbroken ligament. Paper is an example of a fiber composite where this problem appears. Fig. 2a shows a pre-cracked tensile specimen made of blackened paper where the process zone has extended over three quarters of the initial ligament and the load has dropped to 50% of the maximum load. Nevertheless, even at the

* Corresponding author at: Materials Center Leoben Forschung GmbH, Roseggerstrasse 12, A-8700 Leoben, Austria. Tel.: +43 3842 804 315; fax: +43 3842 804 116.
E-mail address: johannes.zechner@mcl.at (J. Zechner).

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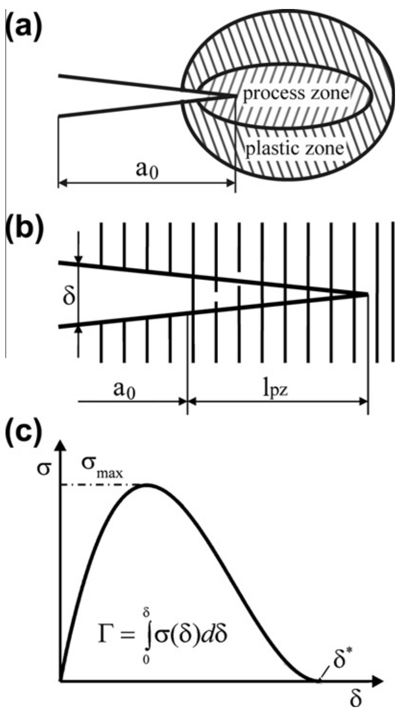

Fig. 1. Schematics of the location of the process and plastic zone around the crack tip (a), of the process zone in a fiber composite (b), and of a cohesive zone relation (c).

initial crack tip region, the fibers have not yet fractured (or are not pulled out completely from the matrix), see Fig. 2b. This means that, according to our definition of the crack tip, the current crack length still equals the initial crack length a_0 and crack growth has not yet been initiated.

This suggests that the position of the crack tip in the process zone should be defined in a different way, but all other definitions are somewhat arbitrary. It is clear that a correct measurement of the fracture initiation toughness or the crack growth resistance is only possible if the current crack length is determined correctly.

In the current paper, two different procedures are proposed to overcome this problem and to get reproducible fracture toughness properties of such materials. The first approach is based on the cohesive zone model and, especially, a procedure to experimentally determine the shape of the traction–separation-relation depicted in Fig. 1c. In the second approach, local deformation analysis is used to directly determine the position of the crack tip from the displacement- and strain fields around the crack. The functioning of the two procedures is demonstrated on commercial printing paper. The two approaches are compared and possibilities and limitations are discussed.

The following section presents a short review about fracture mechanics testing of paper.

2. Fracture mechanics testing of paper

The strength of paper is important in many technical applications, especially for the paper industry. As paper fracture is often initiated at pre-existing flaws, e.g. edge cracks introduced by handling, a fracture mechanical characterization is required to predict the behavior [2].

First works on the subject used linear elastic fracture mechanics to determine a critical energy release rate [2]. This is problematic as most types of paper show pronounced nonlinear behavior in tensile tests [2–4]. More recent works on the topic applied the essential work of fracture (EWF) method [5] and the *J*-integral criterion [4,6,7] to the analysis of paper fracture.

Aim of the EWF concept [5,8] is to determine the essential work of fracture, i.e. the energy needed to create a unit area of fracture surface, using double edge notch tension (DENT) specimens. The key assumption of the concept is that a circular plastic zone forms between the crack tips of a DENT specimen in plane stress conditions, on the contrary to the process zone that extends linearly from crack tip to crack tip [8]. As the plastic work and the EWF scale differently with the ligament lengths, the testing of specimens with similar dimensions but different ligament length, allows the determination of the EWF.

The *J*-integral is a loading parameter of a crack that can be applied in the regimes of nonlinear and linear elastic fracture mechanics [9]. The values of *J* are calculated from the area below the load–displacement record. The *J*-values are plotted versus the crack extension Δa and at a precisely defined point the fracture initiation toughness is determined, denoted as the critical *J*-integral J_c or J_i [10–12]. The slope of the J–Δa-curve is a measure of the crack growth resistance [13]. As discussed above, the problem is the measurement of crack extension in paper. In metallic alloys, indirect methods are often applied to measure crack extension, especially the potential drop technique [14], but this method is not applicable to paper or other insulating materials, e.g. most polymers. Also the unloading compliance technique [14] does not work well in thin fiber composites.

In [7] double edge notch tension (DENT) specimens are tested and a critical *J*-integral J_c is calculated using the single [15] and multiple [16] specimen methods. In the test method proposed in [6], middle cracked tension specimens are used to determine J_c. In both methods J_c is taken as the *J*-value at the maximum load, although it is unclear if crack growth really initiates at this point or not. The disadvantage of this procedure is that the maximum load depends on specimen type (SENT, DENT, etc.), geometry (a_0/

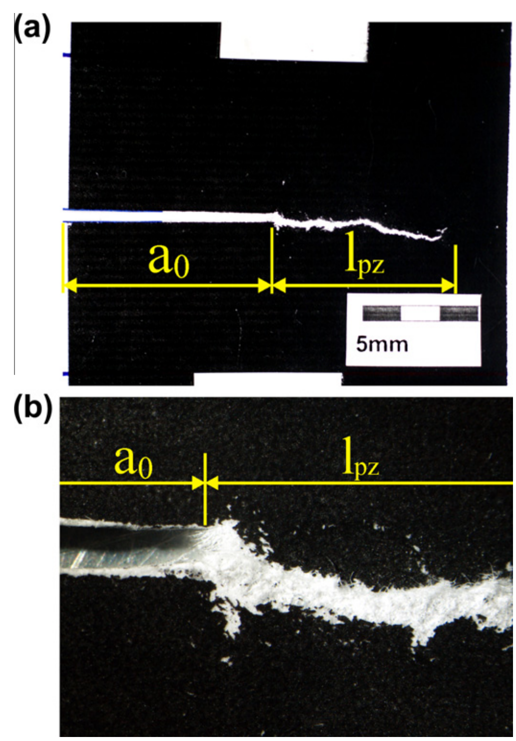

Fig. 2. (a) Specimen surface of the blackened paper specimen showing the initial crack of length a_0 and the process zone of length l_{pz} and (b) detailed view of the process zone near the initial crack tip.