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Side-groove influenced parameters for determining fracture toughness of self-healing composites using a tapered double cantilever beam specimen

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ABSTRACT

The influence of side grooving on the parameters, m and β, in the calculation of fracture toughness for self-healing composites is investigated with 3D tapered double cantilever beam models. The impact of side grooving is elucidated through investigation of both specimen compliance and stress intensity factors along the crack front for models differing in crack length and groove ratio, the ratio of specimen thickness to crack width. The models exhibit a linear change in compliance (C) with crack length (a), allowing for a crack-length-independent determination of fracture toughness owing to a constant m value. However, dC/da increases by ~20% as the groove ratio changes from 1 to 6 showing that the parameter m is groove ratio dependent. This influence on m has not been accounted for in previous studies on self-healing composite fracture toughness. Stress intensity factors were also found to depend on groove ratio. Those at the specimen mid-plane were exponentially fitted as a function of groove ratio and the determined exponent agrees with the analytical form of β that is suggested by ASTM. Stress intensity factors at the intersection of the crack front with the side groove give a higher exponent due to the local stress concentration. Exponents from both simulation and experimentation fall within the theoretical bounds set forth by Freed and Krafft while the value currently used in self-healing literature falls outside these bounds. In the light of these findings, an alteration to the current method of calculating fracture toughness for self-healing material is suggested.

1. Introduction

For a little more than a decade interest in a new class of composites, known as self-healing material, has brought about the development of a broad range of material systems capable of autonomous damage repair. The pioneering work of White et al. [1], who first utilized microencapsulated healing agent to enable an epoxy composite to recover fracture toughness after an initial fracture event, has inspired demonstrations of self-healing composites composed of materials ranging from polydimethylsiloxane [2] to concrete and asphalt materials [3]. The microstructure of these composites has grown in complexity from microcapsule and particulate inclusions [4,5] to fiber reinforcement [6] and even microvascular networks enabling repeated fracture-heal-fracture-heal cycles [7]. The ability of these composites to mend themselves after damage has occurred is impressive. However, this does not alleviate the necessity to design composites which resist the onset of damage. As this technology continues to mature and a push toward commercialization is sought, an accurate determination of material properties such as fracture toughness is a necessary component of the characterization of self-healing composites.

Fracture testing of self-healing composites has relied heavily on the use of the tapered double cantilever beam (TDCB) specimen because this specimen geometry greatly simplifies the calculation of healing efficiency [8]. As certain self-healing composites are able to autonomously recover mechanical properties after damage, the healing efficiency has aptly been defined as the ratio of the healed fracture toughness to the virgin fracture toughness [9]. It is often difficult, however, to determine the crack length of a specimen after healing has occurred by direct inspection within the damage zone. The TDCB specimen has a significant advantage over other fracture specimens, such as the popular compact tension and

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notched beam specimens, because the calculation of fracture toughness can be performed independent of the crack length. This allows for calculation of both virgin and healed fracture toughnesses without knowledge of crack length. The definition of healing efficiency is thus reduced to the ratio of the critical loads at failure for the healed and virgin fracture tests [8,9].

The simplicity of the healing efficiency characterization based on the critical failure load precludes the need for the actual calculation of fracture toughness. Nevertheless, the fracture toughness of self-healing composites is a critical property and composite toughening may be an advantageous result of modifying materials for the healing functionality. In fact, the incorporation of microcapsules had been reported to impart significant fracture toughening to an epoxy composite when utilizing poly(urea formaldehyde) microcapsules containing dicyclopentadiene [10], a well-established material system for self-healing composites. The toughening mechanisms were found to be similar to those observed in other modified epoxies utilizing inclusions such as hollow latex spheres and other rubbery particles [11,12]. Further toughening of self-healing composites was shown to result from controlling the overall size distribution of microcapsules [13]. However, while fracture toughness can be determined directly from the critical load, P_c, that causes failure of the TDCB specimen, it requires knowledge of two parameters, m and β, as seen in Eq. (1).

$$K_{Ic} = \frac{2P_c\sqrt{m}}{\beta} \tag{1}$$

The first parameter, m, relies on the assumption that the specimen compliance changes linearly with crack length. Both fracture testing [8] and finite element calculations [14] have confirmed that these specimens indeed possess a linear relationship between specimen compliance and crack length for a given range of crack lengths. The second parameter, β, accounts for the impact of the side grooves, weighing the influences of specimen thickness and crack width. Finite element analysis of compact tension and arc-shaped specimens confirm a marked change in the distribution of crack front stress intensity factors (SIFs) induced by side grooving [15,16]. These studies conclude that the value of β suggested by ASTM E1820 reasonably predicts the magnitude of the SIF at the specimen mid-plane. On the other hand, the interpretation of β as an effective thickness in a previous numerical study of a TDCB specimen [14] resulted in β values similar to those currently used in self-healing material literature [8–10]. These values are larger than that suggested by ASTM E1820 and fall outside the bounds for β suggested by Freed and Krafft [17].

Although side grooves were introduced to these specimens to ensure stable crack propagation and for prevention of loading arm breakoff, their influence on parameters m and β is not fully understood. These parameters were originally derived from combined strain energy and beam theory analyses of a double cantilever beam (DCB) specimen without side grooves [18]. Additionally, TDCB specimens composed of self-healing composites are typically cast in silicone rubber molds as opposed to being machined to specifications [9]. These compliant molds and specimen shrinkage during the curing process can often result in small variations in specimen thickness and significantly influence groove ratio, the ratio of specimen thickness to crack width. However, neither a comprehensive experimental determination nor a numerical investigation of the parameters m and β over a range of groove ratios has been found in literature.

In this work, we employ a finite element model of a TDCB specimen, similar to that used previously in literature [14], to elucidate the impact of side grooves on the determination of the two geometry parameters, m and β. Both specimen compliance and the distribution of SIFs at the crack front are determined using this model for a wide range of crack lengths and groove ratios. FEA results are compared to experimental fracture data to more accurately calibrate parameters used in fracture toughness calculations with a TDCB specimen.

2. Calculation of fracture toughness

Both parameters m and β are analytically dependent on the geometry of the specimen with m having been derived from the specimen compliance changing with crack length and β accounting for the specimen thickness and crack width. The analytical forms of these parameters stem from the relationship between fracture toughness and the critical energy release rate, G_{Ic}. As determined through the strain energy analysis of Irwin and Kies [19], the energy released over the width of the propagating crack, B_n, is proportional to the change in compliance, C, with crack length, a, as seen in Eq. (2).

$$\frac{K_{Ic}^2}{E} = G_{Ic} = \frac{P_c^2}{2B_n}\frac{dC}{da} \tag{2}$$

The derivative of specimen compliance with respect to crack length can be determined directly from beam theory. Mostovoy et al. [18] used this type of analysis to derive this compliance change, as seen in Eq. (3), for a DCB specimen with uniform thickness (B), uniform height (h), Young's modulus (E) and Poisson's ratio (ν).

$$\frac{dC}{da} = \frac{8}{EB}\left[\frac{3a^2}{h^3} + \frac{3}{4}\left(1+\frac{\nu}{2}\right)\frac{1}{h}\right] \tag{3}$$

For a TDCB specimen however, the height of the tapered profile from the crack plane, h, is a function of crack length, a. Mostovoy et al. then examined Eq. (3) to determine the function $h(a)$ that provides a constant compliance change or rather a constant m value. The analytical form of the parameter m is thus given in Eq. (4).

$$m = \left[\frac{3a^2}{h^3} + \frac{3}{4}\left(1+\frac{\nu}{2}\right)\frac{1}{h}\right] \tag{4}$$

As can be seen, the solutions of $h(a)$ which result in a constant value of m are complex curves. However, these functions can be approximated by a line over the appropriate crack length range to within 1% [8] leading to the linear taper of the TDCB specimens used in common practice [9].

One can then combine the strain energy analysis from Eq. (2) with the beam theory analysis of Eqs. (3) and (4) to arrive at Eq. (1). It is from this simple treatment where the analytical form of the parameter β stems as seen in Eq. (5).

$$\beta = \sqrt{BB_n} \tag{5}$$

Here, B and B_n represent the specimen thickness and crack width respectively with the difference arising from the presence of side grooves in the TDCB specimen. However, this analysis does not take into account the increased stress concentration due to the intersection of the crack front with the bottom of the side grooves.

Freed and Krafft [17] subsequently suggested an alternative form of the parameter β, as seen in Eq. (6), that can be used to put Eq. (1) in the form of a nominal fracture toughness, K_{nom}, as seen in Eq. (7).

$$\beta = B^{1-\alpha}B_n^{\alpha} \tag{6}$$

$$K_{Ic} = \frac{2P_c\sqrt{m}}{B}\left(\frac{B}{B_n}\right)^{\alpha} = K_{nom}\left(\frac{B}{B_n}\right)^{\alpha} \tag{7}$$

They suggested bounds for α in order to account for the stress concentration introduced by the side grooves. The lower limit is specified by the combined beam theory and strain energy analyses