Predicting the Crack Growth Behavior in a Filled Elastomer

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Abstract

In this study, single-edge cracked uniaxial specimens with an initial crack length of 0.1 in or 0.3 in and wedge-shaped sheet specimens with an initial crack length of 0.3 in were tested at a constant displacement rate of 50 in/min under 1000 psi confining pressure. The specimens were made of a highly filled polymeric material, containing 86% by weight of hard particles embedded in a rubbery matrix. The uniaxial crack growth data were used to develop a crack growth model, relating crack growth rate da/dt and Mode I stress intensity factor K_I. The developed crack growth model was used to predict the crack growth behavior in the wedge-shaped specimen. The results of the analysis indicated that the predicted crack growth rate compared well with the experiment.

Introduction

In designing a structural component, a thorough knowledge of the material properties of the material and the pertinent failure criterion for a specific failure mode is required. During past years, the fracture mechanics approach has been used frequently as a failure criterion for high strength materials. According to the fracture mechanics approach, fracture occurs when the stress intensity factor attains the critical value, which is a material property to define the onset of brittle, or unstable, fracture of the material. This fracture initiation criterion implies that a structure will fail as soon as a crack is initiated. It is based on the assumption that a crack, once it is initiated, will propagate at a very high speed and the structure will fail immediately. However, under certain conditions, subcritical cracks in a structure can slowly extend and result in a time-dependent fracture process as well as fracture stress. Therefore, under this condition, a structure's useful life will be governed by the subcritical crack growth in the material. Thus, in an attempt to predict the ultimate service life of a structure, the failure criterion should include the crack growth aspect of the subcritical crack growth, and a detailed knowledge of the characteristics of the crack growth behavior in the material is required.

During the past years, the fracture behavior of particulate composites has been investigated experimentally (1-4).The basic approach is to determine the kinetics of the crack growth in terms of the relationship between the crack growth rate da/dt and the Mode I stress intensity factor $K_{I.}$ Experimental data indicate that power law relationships exist between da/dt and $K_{I.}$ This experimental finding supports the theories developed by Knauss (5) and Schapery (6) in their studies of crack growth behavior in linear viscoelastic materials. It is known that classic fracture mechanics principles, especially linear elastic fracture mechanics including small scale yielding, are well established for single phase materials. However, experimental data indicate that linear fracture mechanics theories are applied to particulate composites with varying degrees of success.

Keywords: Fracture Mechanics, Crack Growth Behavior, Particulate Composites

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14. ABSTRACT
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In this study, single-edge cracked uniaxial specimens with an initial crack length of 0.1 in or 0.3 in and wedge-shaped sheet specimens with an initial crack length of 0.3 in were tested at a constant displacement rate of 50 in/min under 1000 psi confining pressure. The specimens were made of a highly filled polymeric material, containing 86% by weight of hard particles embedded in a rubbery matrix. The crack growth data obtained from the single-edge cracked specimens were used to develop a crack growth model, which was used to predict the crack growth behavior in the wedge-shaped specimen. The results of the analysis indicated that the predicted crack growth rate compared well with the experiment.

The Experiments

In this study, two series tests were conducted on pre-cracked uniaxial and wedge-shaped specimens at a constant displacement rate of 50 in/min under a confining pressure of 1000psi. The specimens were made of a highly filled polymeric material, containing 86% by weight of hard particles embedded in a rubbery matrix. For the pre-cracked uniaxial specimens, an initial crack was cut at the edge of the specimen with a razor blade and the initial crack length was either 0.1 in. or 0.3 in. For the wedge shaped specimen, a 0.3 in. initial crack was cut at the tip of the notch with a razor blade. The geometries of the two specimens are shown in Fig.1. Prior to conducting the tests, the specimen was loaded in the testing machine inside a pressure chamber. When the pressure inside the pressure chamber reaches 1000 psi the specimen was deformed at the constant displacement rate until the specimen fractured. During the test, a high-speed camera was used to monitor the test. In addition, the load and time were also recorded. The raw data was used to determine the stress, strain, Mode I stress intensity factor, and crack growth rate.

To determine the stress intensity factor at the crack tip, it is necessary to relate the load on the specimen to crack and specimen dimension. In this study, a finite element computer code, ABAQUS, was used to determine the stress intensity as a function of the crack lengths for a given load P applied at the boundary of the specimen. The calculated Mode I stress intensity factor K_I was normalized with respect to the applied load P. A liner regression analysis was conducted to determine the relationship between the normalized Mode I stress intensity factor K_I/P to the crack length a. The developed equation was employed in the reduction of experimental data to calculate K_I in term of actual instantaneous load and crack length. Since there were two different specimen geometries, we derived two regression equations for the two specimens. A typical plot of the finite dimension correction factor for the wedge-shaped specimen is shown in Fig. 2. It is important to note that the regression equation, relating K_I/P to a, can be used to calculate K_I for both elastic and viscoelastic materials and it is insensitive to Poisson's ratio ν and is virtually unchanged when ν is changed from 0.45 to 0.4999.

To determine the crack growth rate da/dt, a polynomial method was used. This method involved fitting an n^{th} order polynomial to a set of crack length and time data. The coefficients of the polynomial function were estimated by the method of least squares. The crack growth rate was calculated by taking derivative of the polynomial function at a give time.

Results and Discussion

It is well known that, on the microscopic scale, a highly filled polymeric material can be considered an inhomogeneous material. When these materials are stretched, the different sizes and distribution of filled particles, the different crosslinking density of polymeric chains, and the variation in bond strength between the particles and the binder can produce highly inhomogeneous local stress and strength fields. Also, this material may contain randomly distributed microvoids, incipient damage sites, and microcracks with statistically distributed sizes and directions. Therefore, the local strength in the material varies in a random fashion, so the failure sites in the material do not necessarily coincide with the maximum stress location. Hence, the failure location as well as the degree of damage induced in the material will also vary in a random fashion. Depending on the magnitude of the local stress and the local strength, damage can be developed in the material, especially near the crack tip region. The damage developed in the material may be in the form of microvoids or microcracks in the binder or dewetting between the binder and the filler particles. When the particle is dewetted, the local stress will be redistributed. With time, additional binder/particle separation and vacuole formation take place. The damage growth in the material may take place as material tearing or as successive nucleation and coalescence of the microcracks. These damage initiation and evolution processes are time-dependent, and are the main factor responsible for the time-dependent constitutive and fracture behavior of the material. It should be pointed that the aforementioned damage initiation and evolution processes are commonly observed in the particulate composite material when the material is subjected to a monotonically increasing load under low confining pressure. However, when the confining pressure is very high, the damage mechanisms may changed, which is a subject of an ongoing study.

Experimental results indicate that crack tip blunting takes place both before and after crack growth. The material at the tip of the crack suffers very large elongation and is nearly straight. The highly strained or damage zones extends ahead of the crack tip, appearing as an equilateral triangle with the crack tip as its base. This damage zone is known as the failure process zone, which is a key parameter in viscoelastic fracture mechanics. When the local strain reaches a critical value, small voids are generated in the failure process zone. Due to the random nature of the microstructure, the first void is not restricted to the surface where the maximum normal strain occurs. Since the tendency of the filler particle to separate from the binder under a triaxial loading condition is high, it is expected that voids, or a damage zone, will also be generated in the specimen’s interior. Consequently, there are a large number of strands, essentially made of binder material, which separate the voids that form inside the failure process zone. Under this condition, the transverse constant is minimized. As the applied strain increases with time, material fracture occurs at the blunted end of the crack tip. This will always be the location of the maximum local strain. The failure of the material between the void and the crack tip causes the crack to grow into the failure process zone. This kind of crack growth mechanism continues until the main crack tip reaches the front of the failure process zone. When this occurs, the crack tip reshapes temporarily.

The damage and crack growth mechanisms discussed in the above paragraphs are the basic mechanisms observed in this material under both ambient and 1000 psi confining pressures. The effect of pressure is to suppress the damage and evolution processes and delay the onset of crack growth.

Figure 3 shows the uniaxial crack growth data, plotted Log da/dt versus Log K_I, for different initial crack length of 0.1 in and 0.3 in. It is noted that the crack growth curve of the short crack is above the long crack. In other words, for a give K_I the short crack grows faster than the long crack. However, the scatter of the crack growth rate is probably within the scatter of experimental data. Therefore, on the first approximation, we assume that the crack growth behavior is independent of the initial crack length. Under this condition, the short and the long crack growth data were combined and regression analysis was conducted to determine the regression equation relating crack growth rate da/dt and Mode I stress intensity factor K_I. The regression equation, or the crack growth model, is shown below.

$$\text{Log } da/dt = -6.0246 + 2.4375 \text{ Log } K_I; \quad R = 0.893 \qquad (1)$$

or

$$da/dt = 9.45 \times 10^{-7} \ (K_I^{\ 2.4375})$$

where R is the correlation coefficient.

Similar, the crack growth data obtained from the wedge-shaped specimen are shown in Fig.4, and the regression equation, relating Log da/dt and Log K_I, is shown below.

$$\text{Log } da/dt = -5.400 + 2.1900 \text{ Log } K_I \text{;} \quad R = 0.985 \qquad (2)$$

or

$$da/dt = 39.8 \times 10^{-7} (K_I^{2.1900})$$

In addition, for a given K_I, Equation 1 was used to predict the crack growth rate in the wedge-shaped specimen. For K_I equal to 223.87 psi $in^{1/2}$, the predicted and the measured crack growth rates are 0.5053 in/sec and 0.5578 in/sec, respectively. And, for K_I equal to 426.58 psi $in^{1/2}$, the predicted and the measured crack growth rates are 2.4322 in/sec and 2.2909 in/sec, respectively. The predicted crack growth rates are also shown in Fig.4. The good correlation between the predicted and the measured crack growth rates implies that the crack growth behavior is controlled by the local stress at the crack tip.

Conclusions

In this study, the crack growth behavior in uniaxial specimens and wedge-shaped specimens subjected to a constant displacement rate of 50 in./min under 1000 psi confining pressure were investigated. Experimental findings reveal that, on the first approximation, the crack growth behavior in the uniaxial specimen is independent of the initial crack length. It also reveals that a good correlation exists between the predicted crack growth rate, based on the crack growth model obtained from the uniaxial crack growth data, and the measured crack growth rate for the wedge-shaped specimen. This important experimental finding indicates that the crack growth behavior is controlled by the local stress, and for the same material and loading condition, the crack growth model can be used to predict the crack growth behavior in a large structure.

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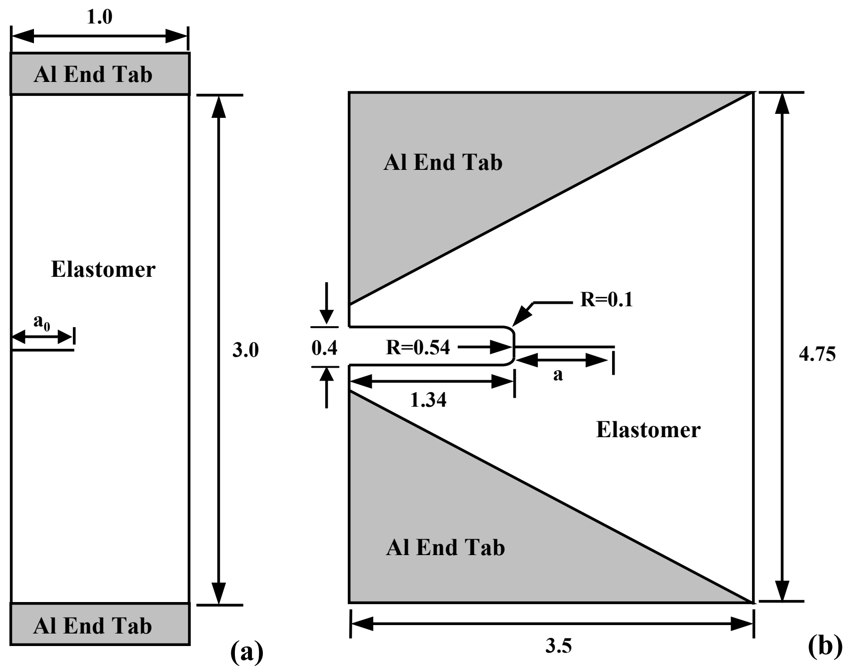

Fig. 1 Specimens geometry; (a) Uniaxial specimen (b) Wedge specimen; all of the dimensions are in the unit of inch

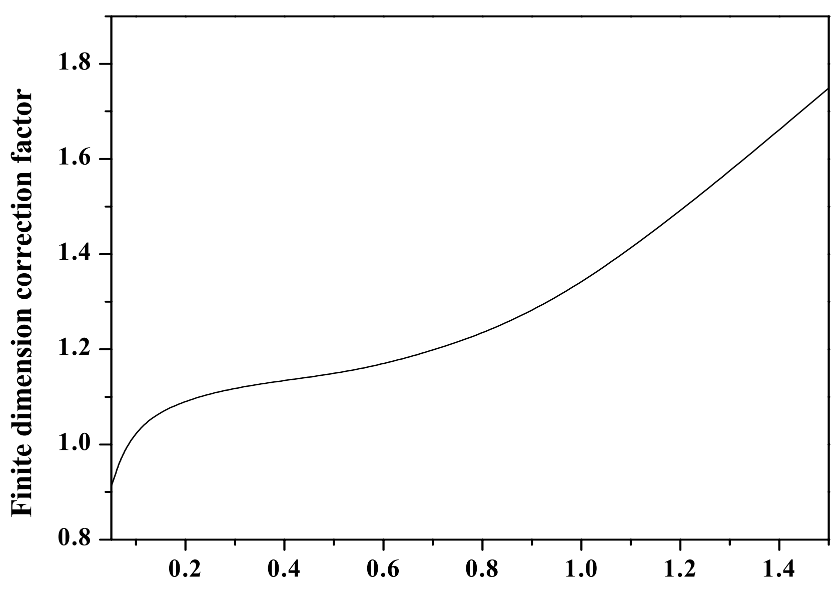

Fig. 2 Variation of the finite dimension correction factor of the wedge specimen with crack length when Poisson's ratio ν = 0.49

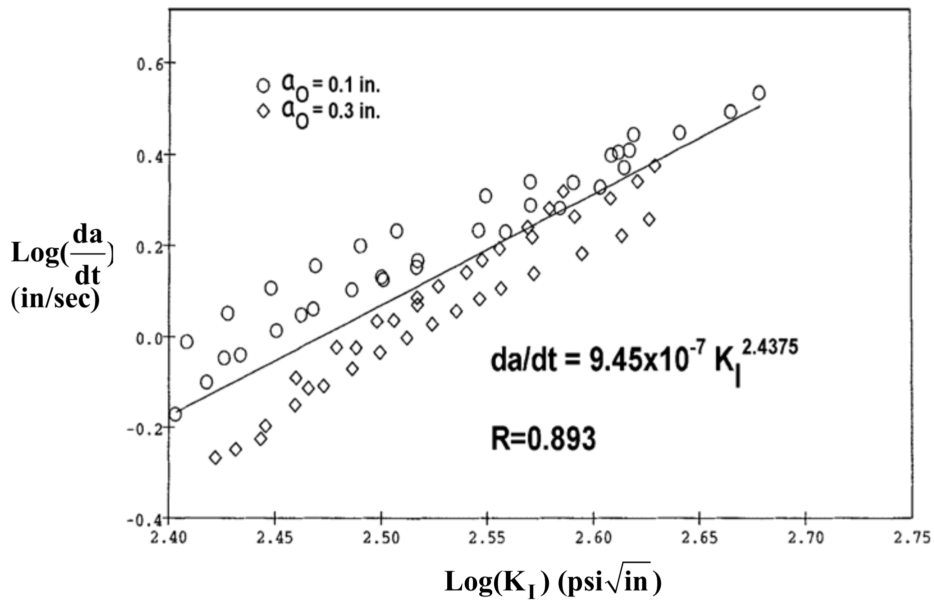

Fig. 3 Crack growth rate versus mode I stress intensity factor (uniaxial specimen)

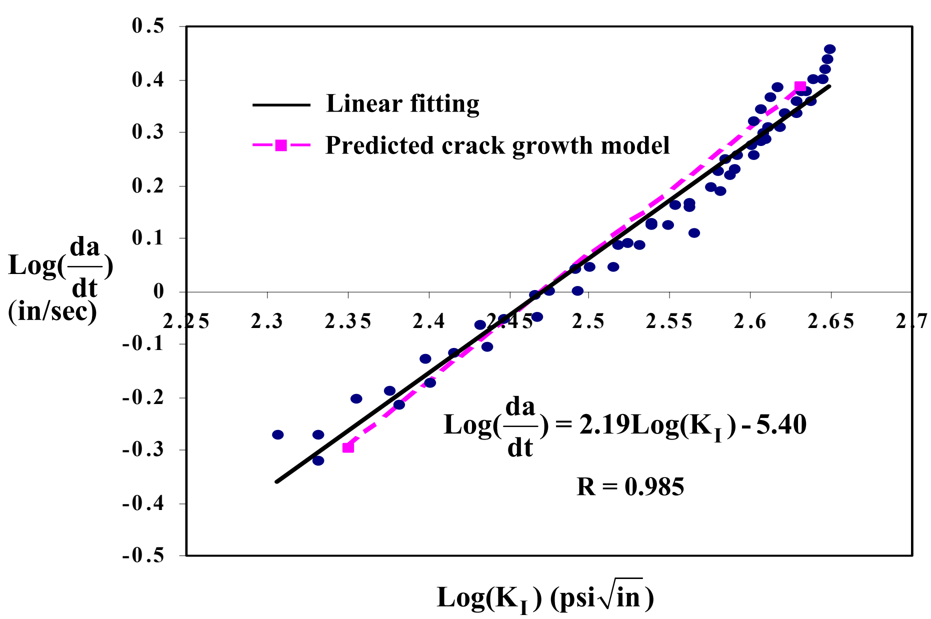

Fig. 4 Crack growth rate vs. mode I stress intensity factor (wedge-shaped specimen)