Engineering Fracture Mechanics 78 (2011) 2042–2051

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Significance of K-dominance zone size and nonsingular stress field in brittle fracture

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ARTICLE INFO

Article history:
Received 8 September 2010
Received in revised form 15 March 2011
Accepted 23 March 2011
Available online 30 March 2011

Keywords:
Brittle fracture
Fracture toughness
K-dominance zone
Nonsingular stress field
Two-parameter model

ABSTRACT

Stress intensity factor has been used to characterize the fracture toughness of a brittle material. This practice is apparently based on the assumption that the singular stress alone at the crack tip is responsible for fracture and that the nonsingular part of the near tip stress has no effect on fracture. In this study, mode I fracture experiments were conducted on a brittle material (PMMA) with four different specimen configurations. The result indicated that fracture toughness cannot be described by stress intensity alone and that a second parameter representing the influence of the nonsingular stress is needed. A two-parameter fracture model was proposed and validated with the experimental result. This two-parameter model was shown to be able to account for various effects created by specimen configurations, crack sizes, and loading conditions, on the fracture behavior of brittle materials.

1. Introduction

Within the framework of linear elastic fracture mechanics (LEFM), it is known that stress intensity factor can characterize the fracture behavior of brittle materials and, thus, can be regarded as a material constant. This characterization is based on the assumption that the singular stress field is dominant near the crack tip. However, several researchers [1–4] have found that critical stress intensity factor or plane strain fracture toughness, K_{IC}, can be dependent on specimen geometries. For example, Larsson and Carlsson [1] and Rice [2] analyzed different specimen geometries and found that there was a crack tip boundary layer effect on the fracture behavior of elastic–plastic materials. The boundary layer stress around the crack tip, which varies with specimen configurations, has been shown to play an important role in determining the size and shape of a crack tip plastic zone. Larsson and Carlsson [1] explained this effect based on the nonsingular constant stress term in William's asymptotic crack tip solution [5]. Rice [2] considered the similar problem as Larsson and Carlsson [1] and used the constant nonsingular stress term (the T-stress) to explain the limitation in using stress intensity factor for plastic zone size calculation. Based on a similar concept, Leevers and Radon [3] showed the effect of specimen dimensions on stress biaxiality ratio which is a function of the near tip constant stress terms. Similar to Leevers and Radon [3], Kardomateas et al. [4] showed the effect of crack length on stress biaxiality ratio.

Recently, some authors [6–9] have conducted fracture experiments using polymethylmethacrylate (PMMA) specimens and showed significant variations in fracture toughness resulting from specimen geometry and loading condition. To explain this behavior which contradicts the generally accepted notion of brittle fracture, a number of authors have attempted to retain nonsingular stress terms such as the T-stress in addition to the singular term in the William's crack tip solutions. The effect of T-stress on fracture toughness is through its influence on the crack tip plasticity. Smith et al. [10] used PMMA

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0013-7944/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engfracmech.2011.03.015

specimens to study the effect of T-stress on mode I and mode II fracture toughnesses and found that the T-stress has a significant effect on mode II toughness and its effect on mode I toughness is slight unless the level of T-stress is very high. It is possible that the effect on mode I observed by Smith et al. [10] could be attributed to the nonsingular term in the opening stress as discussed in the present work. Chao et al. [7] explained the dependency of fracture toughness on the specimen geometry based on the assumption that the fracture event is controlled by either a critical opening stress or a critical opening strain. Chao et al. [7] and Chao and Zhang [8] considered various specimen configurations and proposed a critical stress (σ_c) and critical distance (r_c) parameters for stress based fracture and critical strain (ε_c) and critical distance (r_c) parameters for strain based fracture. For the same set of experiments, it was found that r_c varies depending on the type of fracture considered. For example, r_c for stress based fracture was found to be 2.32 mm, while it was 0.86 mm for strain based fracture. It means that critical stress location is not the same as the critical strain location. Moreover, σ_c and r_c seem to be sensitive to the specimen and loading configurations and cannot be regarded as material constants.

The present study follows the work by Sun and Qian [9] who took consideration of the nonsingular stress ahead of the crack tip in characterizing the fracture toughness of PMMA. The effect of K-dominance zone size is used to explain why apparent fracture toughness depends on specimen configuration and loading condition. Fracture experiments are conducted on four different specimen configurations each with varying crack length. The test results cover a wide range of K-dominance zone size. These data validate the capability of a two-parameter fracture model in characterizing the fracture toughness of brittle materials including the effect of specimen geometry, crack size, and loading condition.

2. Experimental details

PMMA sheets were used for conducting the fracture tests. PMMA was used because it is brittle and its fracture toughness is insensitive to specimen thickness as shown in Fig. 1 [11]. Note that, in Fig. 1, the thickness of specimen covered a range of 1.59 mm to 17 mm.

In this study, four different specimen configurations were adopted to determine the fracture toughness of PMMA. These configurations were

- Double cantilever beam (DCB) specimen with metal and PMMA layers.
- Single edge notched tension (SENT) specimen.
- Four point bend (FPB) specimen.
- Center-cracked tension (CCT) specimen.

Various dimensions were used in all four types of specimen geometries in order to vary the K-dominance size near the crack tip. For example, crack length (a) was varied in the FPB specimen; thickness ($2h$) of the PMMA layer in the DCB specimen was varied; and the gage length ($2h$) in the SENT and CCT specimens were varied.

2.1. Double cantilever beam (DCB) specimen

For the DCB specimens, two Al-7075 alloy strips were used as loading arms and a PMMA sheet was sandwiched between the two aluminum strips for fracture test. It should be noted that this DCB configuration is different from that used by Chao et al. [7] who used only PMMA as the two arms of the DCB with different crack lengths. The present DCB geometry is similar to the conventional DCB specimen [12,13] which is often used to test the bond strength of adhesives in bonded joints. In the present work, the DCB specimen resembles that for bond strength test with the structural paste adhesive replaced by a PMMA layer/sheet.

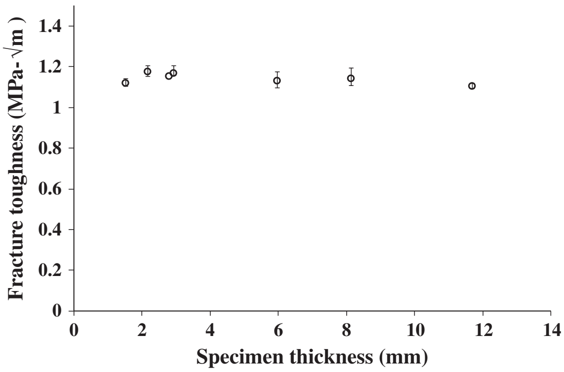

Fig. 1. Fracture toughness of PMMA as a function of specimen thickness.