DETERMINATION OF DYNAMIC FRACTURE TOUGHNESS FOR BRITTLE MATERIALS WITH A MODIFIED SHPB

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ABSTRACT

The experimental procedure for determining the fracture toughness for advanced ceramic materials under quasi-static loading conditions has been well established by an ASTM standard (C 1421-99). The development of experimental methods for determining the dynamic fracture toughness for such materials faces two main challenges in experiment design that must be overcome before valid results can be obtained. Dynamic equilibrium over the entire specimen needs to be approximately achieved. This is necessary to interpret the crack tip loading state with the far-field loading conditions using relations derived under quasi-static conditions. Furthermore, the loading rate at the crack tip should be nearly constant during an experiment. This is a required condition in order to determine the loading-rate effects on the dynamic fracture toughness. A new experimental technique, based on a split Hopkinson pressure bar (SHPB), has been developed to determine the valid dynamic fracture toughness for brittle materials. A precise control of the loading pulse profile facilitates the dynamic equilibrium in the specimen and a nearly constant loading rate at the crack tip. Sensitive piezoelectric force transducers are used to monitor the dynamic equilibrium and constant loading rate on the precracked specimen. The feasibility of the new technique is demonstrated through the determination of the dynamic fracture toughness as a function of loading rate for a model brittle material.

INTRODUCTION

When the stress intensity factor at a crack tip in a brittle material reaches a critical value, i.e., the fracture toughness of the material, under either quasi-static or dynamic loading conditions, the crack will start to propagate through the material. The fracture toughness, which represents the material's resistance to cracking, must be accurately determined before the structural integrity can be ensured for the structures or components involving the material. ASTM Standard C 1421-99 in USA specifies the standardized procedure to determine the fracture toughness of advanced ceramic materials. In this procedure, precracked beam specimens are loaded in three- or four-point bending configurations. The precrack can be a straight-through crack, a semi-elliptical crack, or a Chevron notch. The measured toughness values correspond to the specific types of precracks. The loading rates during these quasi-static tests are controlled through the actuator displacement rates, which are between 0.0005 to 0.005 mm/s on the testing machine. The employment of such slow rates is necessary to ensure that the peak load measured at the load cell corresponds to the fracture toughness value locally at the crack tip.

As brittle materials are increasingly used in impact related applications, accurate determination of dynamic fracture toughness remains a challenge to the experimental mechanics community. Many dynamic techniques have been proposed over the past two decades, which can be approximately categorized into three groups: high rate bending, high rate tension, and dynamic wedging. Most investigations attempted to extend the quasi-static ASTM standard into dynamic loading range through various approaches, resulting in a series of high rate bending techniques (e.g., Böhme and Kalthoff, 1982; Rittel et al., 1992; Yokoyama, 1993; Bacon et al. 1994; Sharpe and Böhme, 1994; Anderson et al. 2000; Weisbrod and Rittel, 2000; Martins and Prakash, 2002). Among this group of experimental techniques, Böhme and Kalthoff (1982) employed a three-point bending configuration with a drop weight impacting at the loading point. Their experiments were among the most extensively instrumented. They measured the load histories at the loading point and the two supporting points, the displacement histories between the supports and the specimen, and the crack tip stress-intensity factor history. The results showed that the load history recorded from the loading point did not synchronize with the load histories at the supports, nor with the crack tip stress-intensity factor history. Furthermore, when the loading point was impacted, the specimen jumped off the supports at the supporting points before regaining contact ~400 μs later. Their results also showed that the loading rate at the crack tip was far from constant during the entire loading process. The detailed information revealed by Böhme and Kalthoff's experiments indicates that the crack tip stress intensity factor does not synchronize with far-field load measurements for these dynamic bending experiments. There is evidence that significant vibration/resonance is coupled with the bending deformation of the specimen, as indicated by the out-of-phase displacements measured at the supporting points. Quasi-static equations relating the far-field peak loading to fracture toughness are therefore no longer valid. Local direct CTOD measurements do correspond to the dynamic fracture toughness (e.g., Sharpe and Böhme, 1994). However, under an impact loading, the loading rate at the crack tip is far from constant due to large-amplitude stress waves sweeping back and forth through the crack tip. Constant loading rate is a necessary condition to determine the fracture toughness, which may be a function of loading rate. Essential remedies are therefore necessary to obtain valid dynamic fracture toughness with loading rate as a parameter from dynamic bending experiments.

The second type of dynamic fracture toughness measurement methods involves the application of direct dynamic tensile loads on notched rods, compact tension (CT) specimens, or precracked beams (e.g., Suresh et al., 1990; Deobald and Kobayashi, 1992; Owen et al., 1998). The third type, dynamic wedging experiments, were proposed by Klepaczko (1982) and employed by other researchers (e.g., Maekawa and Shibata, 1995). Both of these types of experiments have similar non-equilibrium issues that affect the accurate measurement of dynamic fracture toughness.

DYNAMIC EQUILIBRIUM AND CONSTANT LOADING RATES

It is critically important to achieve a nearly constant loading rate during an experiment designed to determine the toughness as a function of loading rate. If the loading rate varies drastically over the duration of one experiment, as a result of the stress waves propagating and being reflected back and forth between the boundaries of the precracked specimen, resulting in significantly fluctuating stress and strain fields near the crack tip, the resultant dynamic fracture toughness value will be ambiguous when interpreted in terms of loading rate. These loading fluctuations at the crack tip bring significant uncertainties to the measured fracture toughness in terms of (1) unevenly distributed loading in the specimen, (2) rapidly varying loading rate (stress intensification rate) at the crack tip, and (3) unrealistic interpretation of fracture toughness from far-field loading history. Under such conditions, it is very difficult to accurately determine the loading rate sensitivity of the fracture toughness of the material.

The methods that facilitate the achievement of constant loading rates at the crack tip in an experiment for dynamic fracture toughness will certainly depend on the loading configuration and the specimen material. Split Hopkinson bars modified with pulse shaping are ideal tools to apply dynamic loading at controlled loading rates (e.g., Chen et al., 2002). When the dynamic fracture toughness of a brittle material is to be measured on a four-point bending specimen with a split Hopkinson pressure bar, the incident pulse profile should be controlled such that the specimen is near dynamic equilibrium except during the early moments of the loading process. Under a carefully controlled valid loading condition, the specimen will be near the state of dynamic equilibrium, the amplitudes of the stress intensity factor fluctuations near the crack tip will be minimal since the loading is ramped up by small increments, and a nearly constant loading rate (stress intensification rate) will be achieved. The loading rate can also be controlled precisely by systematically varying the slope of the linear ramp of incident pulse in a split Hopkinson bar by pulse shaping.

EXPERIMENTAL SETUP

In the dynamic experiments reported in this paper, a split Hopkinson pressure bar (SHPB) at the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD was employed. This SHPB facility was modified with a specially designed gage section for dynamic fracture experiments and a pulse shaping technique for dynamic equilibrium and constant loading rate. The specimen configuration was selected to be ASTM standard Chevron notched beams for more consistent manufacturing quality of brittle specimens. A schematic of the experimental setup is shown in Fig. 1.

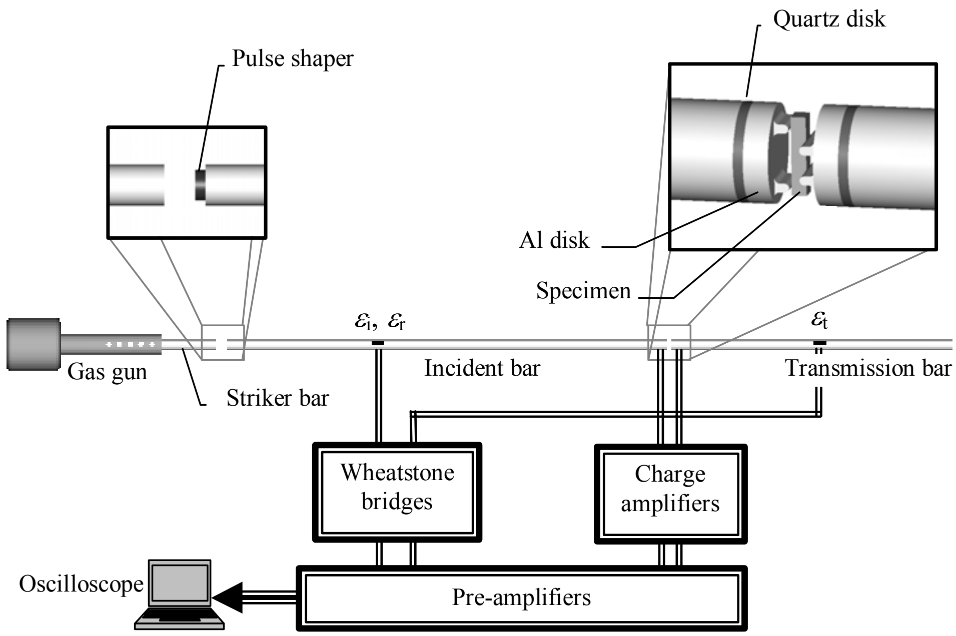

Fig. 1. A schematic of the experimental setup.

Since the specimen is under dynamic equilibrium, a quasi-static equation can be employed to relate the peak far-field load to the dynamic fracture toughness (ASTM Standard C 1421-99).

$$K_{Ivb} = Y^*_{\min}\left[\frac{P_{\max}\left(S_0 - S_i\right)\times 10^{-6}}{BW^{3/2}}\right] \tag{1}$$

$$Y^*_{\min}\left(\frac{a_0}{W},\frac{a_1}{W}\right)=\frac{0.3874-3.0919\left(\frac{a_0}{W}\right)+4.2017\left(\frac{a_1}{W}\right)-2.3127\left(\frac{a_1}{W}\right)^2+0.6379\left(\frac{a_1}{W}\right)^3}{1.000-2.9686\left(\frac{a_0}{W}\right)+3.5056\left(\frac{a_0}{W}\right)^2-2.1374\left(\frac{a_0}{W}\right)^3+0.0130\left(\frac{a_1}{W}\right)}$$

where K_{Ivb} is the fracture toughness of a brittle four-point bending beam specimen with a Chevron notch, P_{max} is the measured peak axial force by the quartz crystals, B is the width of the specimen with a height W, dimensions a_0, and a_1, are associated with the Chevron notch, S_0 is the distance between the two supporting points on the notch side of the specimen, and S_i is the distance between the two loading points on the other side of the specimen. An examination of this equation also shows the importance of achieving dynamic equilibrium in the specimen. If P_{max} is not in phase with the maximum stress intensity factor near the crack tip, the dynamic initiation fracture toughness determined from the experiment cannot be valid.

SUMMARY

Based on a split Hopkinson pressure bar and a quasi-static fracture toughness ASTM standard for advanced ceramic materials (C 1421-99), a new experimental technique has been developed to determine the dynamic fracture toughness of brittle materials as a function of loading rate. A precise control of the loading pulse profile facilitates the dynamic equilibrium in the specimen and a nearly constant loading rate at the crack tip, thus relating the fracture toughness at the crack tip to the far-field peak loading through quasi-static relations.

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