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Dynamic Initiation Fracture Toughness of High Strength Steel Alloys

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ABSTACT

Determination of fracture toughness for metals under quasi-static loading conditions can follow well-established procedures and ASTM standards. The use of metallic materials in impact-related applications requires the determination of dynamic fracture toughness for these materials. There are two main challenges in experiment design that must be overcome before valid dynamic data can be obtained. Dynamic equilibrium over the entire specimen needs to be approximately achieved to relate the crack tip loading state to the far-field loading conditions. The loading rate at the crack tip should be maintained nearly constant during an experiment to delineate rate effects on the values of dynamic fracture toughness. A recently developed experimental technique for determining dynamic fracture toughness of brittle materials has been adapted to measure the dynamic initiation fracture toughness of high strength steel alloys. A split-Hopkinson pressure bar is used to apply the dynamic loading. A pulse shaper is used to achieve constant loading rate at the crack tip and dynamic equilibrium across the specimen. A four-point bending configuration is used at the impact section of the setup.

INTRODUCTION

Failure of engineering materials has been at the forefront of research for scientists and engineers for centuries. The pioneering work of Griffith [1] during the first part of the 20th century steered material failure research towards a crack-dominated analysis and the field of fracture mechanics was founded. Irwin's [2, 3] work introduced us to the idea that the stress field near a crack could be modeled in a linear elastic fashion with only a small plastic zone near the crack tip. This idea of small scale yielding led to a parameter that could be used to describe the state of stress near the crack tip, called the stress intensity factor, K. The stress intensity factor is essentially a measure of the driving force at the crack tip, , and it's critical value, K_C, is a crack's resistance to propagate and is referred to as the fracture toughness, which is a material property. ASTM standard E399 [4] defines a procedure for finding the quasi-static plain strain fracture toughness of metallic materials. The quasi-static loading configurations are precracked compact tension specimens, three-point bending beams, or notched tensile rods.

At high loading rates, the critical value of stress intensity factor is postulated as three independent material properties: initiation fracture toughness, propagation fracture toughness, and crack arrest toughness. The dynamic parameter similar to the quasi-static fracture toughness is the initiation fracture toughness, that is, the critical value of stress intensity factor under dynamic loading at which an existing crack will propagate. Many experimental techniques have been proposed to characterize a material's dynamic fracture initiation toughness, but no standard has been adopted. The techniques generally attempt to extend the quasi-static ASTM standards into the dynamic loading range. They included high-rate bending, high-rate tension, and dynamic wedging experiments. The dynamic loads have been applied with a modified split-Hopkinson bar (pressure and tension), drop weight towers, modified Charpy testers, and electromagnetic loading schemes. Some researchers attempted to use far field boundary measurements and quasi-static relationships to reduce the local crack tip stress intensity factor. Among the early investigators, Böhme and Kalthoff [5], used a three-point bend configuration with a drop weight tower to apply the dynamic load. Measurements of the load histories at the loading point and the two supports as well as a local crack tip opening displacement (CTOD) history were compared and it was discovered that the loading history at the loading point did not correspond with the load history at the supports. When calculating the stress intensity factor for the boundary loads and comparing with the local CTOD derived stress intensity factor, these measurements did not synchronize either. It was shown that under these loading conditions, the loading rate was neither constant, nor was the sample in dynamic equilibrium, therefore the quasi-static equations are not valid. Other investigators have used combined experimental/numerical techniques to evaluate the dynamic fracture initiation toughness. Recognizing that most experimental techniques in the high-rate loading regime do not yield a situation where the quasi-static analysis is valid, they simply use the far field loading history and time-to-fracture from the experiment, combined with either an analytical or numerical model to process the dynamic initiation fracture toughness. One such model, given by Rittel [6], proposes that the loading time history can be decoupled from the dynamic sample response through the use of a convolution integral. The dynamic sample response is then calculated once with a finite element model (FEM), then used with an algorithm to solve the convolution integral utilizing the measured loads from each experiment to find the dynamic fracture initiation toughness. One serious drawback to this methodology is the need to use FEM to derive a material property. The fracture initiation toughness is only as accurate as the FEM. While FEM techniques have been extensively validated for many applications, their accuracy in high rate loading regimes is still developing. A truly accurate result would require independent material property tests at each loading rate to accurately characterize the parameters needed in the assumed constitutive model.

An ideal experimental technique for the measurement of dynamic fracture initiation toughness would be one that could ensure dynamic stress equilibrium in the sample so that quasi-static equations could be utilized in the data reduction, as well as provide a constant loading rate. Constant loading rate is important because dynamic fracture initiation toughness may be a function of loading rate and therefore must be single valued to be reported as such. In addition, for any experimental technique to become standardized it is advantageous for the technique to be conducted as simply as possible and without the need for extremely elaborate measurement equipment.

Weerasooriya et al. [7] created a four-point bend apparatus that could be used in conjunction with a standard split-Hopkinson pressure bar (SHPB) in dynamic fracture testing of ceramics. Controlled loading pulses where created through the use of copper pulse shapers on the incident bar. This created a linear rise incident pulse to ensure a constant loading rate. They used quartz force transducers imbedded in the incident and transmission bars to verify stress equilibrium in the sample. The results showed repeatable results at constant loading rates of 10^{-1}, 10, and 10^{5} MPa-$m^{1/2}$-s^{-1}. A dynamic analysis of the system resonant frequency is also included to show there is a limiting value of loading rate in which the quasi-static analysis is valid. In other words, the inverse of the incident pulse rise time must be below the fundamental frequency of the system for dynamic equilibrium to be achieved. Most recently, Fengchun and Vecchio [8] have evaluated this four-point bend SHPB technique to investigate the dynamic fracture of steel. They used the technique on unnotched, notched, precracked beam specimens made from Fe-10Cr steel in three different heat treatments. While they do not publish any actual dynamic fracture initiation toughness data, they do show through pulse shaping that near constant loading rates and dynamic equilibrium can be achieved in steel samples, therefore quasi-static data reduction is valid.

In this paper, the four-point bend SHPB technique is used to evaluate the dynamic fracture initiation toughness of 4340 steel with a heat-treatment that produces a hardness of approximately Rc 45. Three different loading rates where utilized between 2.5 x 10^{6} MPa-$m^{1/2}$-s^{-1} and 5.5 x 10^{6} MPa-$m^{1/2}$-s^{-1}. Utilizing annealed copper pulse shapers of varying diameter and thickness, near constant loading rates and dynamic stress equilibrium were achieved.

EXPERIMENTAL PROCEDURE

To apply the dynamic loading for these experiments a modified SHPB at Purdue University was used. A standard SHPB with incident bar length of 416 cm and transmission bar length 137 cm was modified to accept impact wedges to facilitate the four-point bending in the sample region. Both bars are nominally 19 mm in diameter and manufactured from maraging steel. Strain gauges where placed at 187 cm and 33 cm from the sample ends of the incident and transmission bars, respectively. The strain signals were used to determine the loading time history on the sample and to verify dynamic equilibrium during the experiment. A schematic of the setup is shown in Figure 1. Annealed copper pulse shapers were used to generate ramp incident pulses. When impacted by the striker, the copper disk flows plastically, which increases the diameter and allows the striker momentum to transfer through the disk into the incident bar creating a stress pulse with increasing amplitude. With proper selection of thickness and diameter of the pulse shaper and the striker velocity magnitude, the shape of the increasing ramp stress pulse can be controlled. In this set of experiments the stress pulse was near linear.

The sample region, or gage section, for this setup was too small to use any standard ASTM sample sizes, but guidelines described in ASTM E399 were followed in the design of the samples. The samples were nominally 63.5 mm long by 15 mm wide by 7.5 mm thick made from 4340 steel hardened to nominally Rc 45. The crack length was nominally 1/2 the width of the sample. A wire EDM starter notch was utilized to reduce the time it takes to generate the precrack. Fatigue cracks where propagated by cycling a load using an MTS 810 load frame following the K calibration guidelines of ASTM E399.

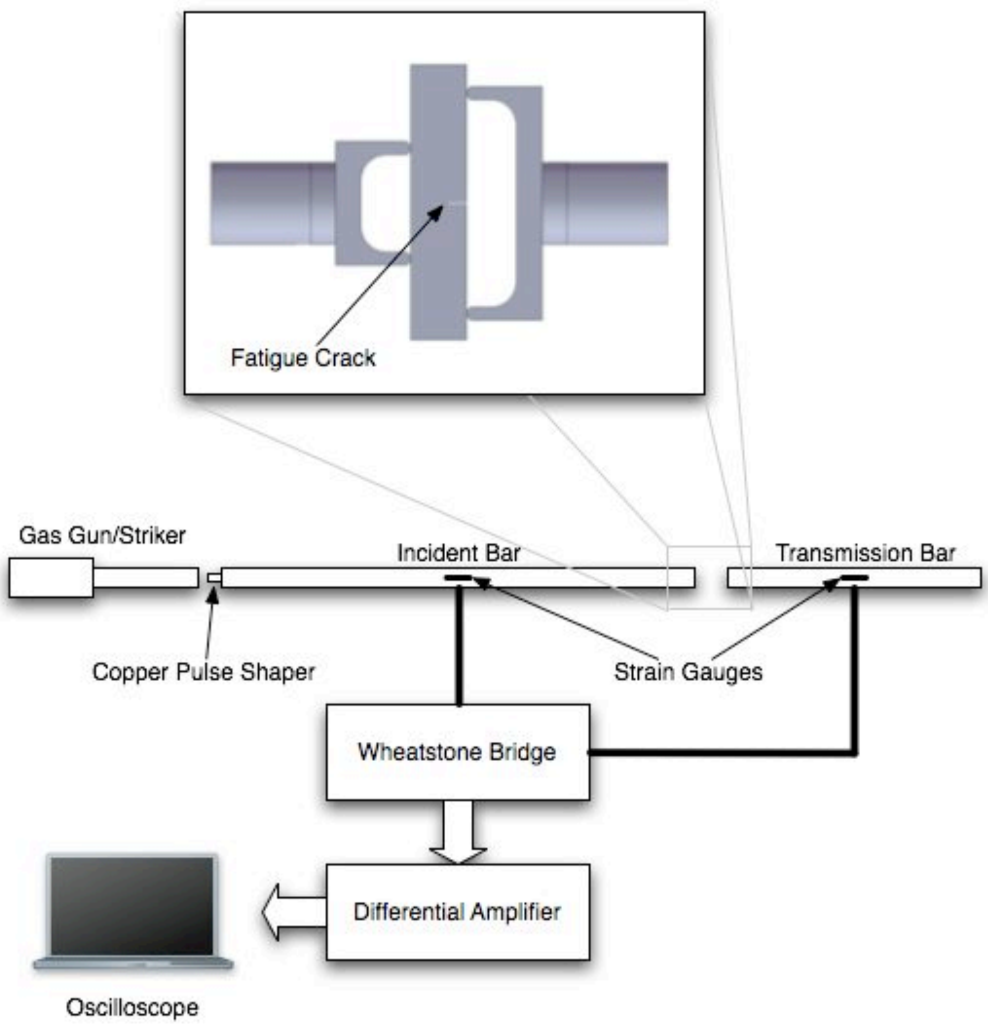

Figure 1. Schematic of the modified SHPB

A Vishay Micromeasurements single wire crack detection gauge, CD-02-10, was adhered to the surface of the sample at the root of the fatigue precrack. These gauges where installed under an optical microscope to ensure that the wire was precisely at the crack tip (within ~0.1 mm). These gauges where intended to provide a time-of-fracture to determine the value of fracture initiation toughness. In addition to the crack gauges, a Cordin high speed digital rotating mirror camera was used to verify the time-of-fracture. Because the time-to-fracture is defined as the time between the onset of loading to the sample and the time the crack propagation initiates, and the fact that the Cordin camera at Purdue only has 32 frames to sample, a frame rate of nominally 250,000 frames per second was used. This allowed the capture of both the onset of loading and the crack initiation during approximately 128 μs of total framing time. This means that the time between frames in around 4 μs, which means that the accuracy of the time-to-fracture measurement from the camera is ± 4 μs. This is important because the total time-to-fracture on many of these experiments is approximately 40 μs, therefore the uncertainty in the time-to-fracture using the camera can be as much as 10%. Unfortunately, the crack detection gauges did not perform adequately on every test, the wire would deform elastically somewhat before breaking after the crack had already began to propagate, therefore the camera data had to be utilized to get time-to-fracture data for some tests.

A one-wave, two-wave technique was used to solve for the stress at the incident end, σ_1, and the transmission end, σ_2, of the bars. Figure 2 shows that the sample is in dynamic stress equilibrium through the time-to-fracture, t_f. These results are representative of a typical test.

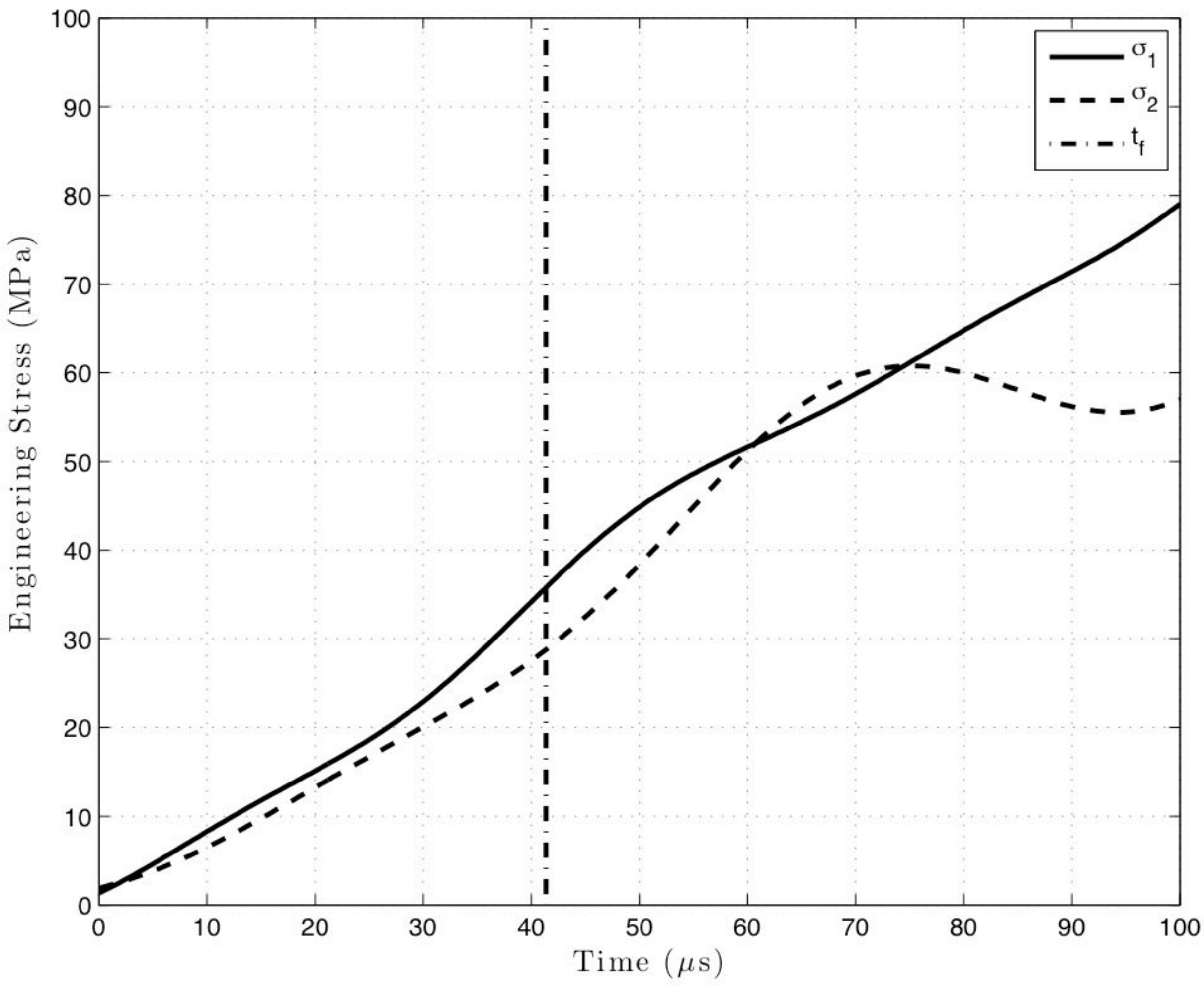

Figure 2. Stress Equilibrium Plot from a Typical Test

Since it is verified that the sample is under stress equilibrium up to the time of fracture, a quasi-static equation can be used to relate the far field load to the plain strain dynamic fracture initiation toughness [9].

$$K_{IC}^{dyn} = \frac{6SP(t_f)}{4BW^2}\sqrt{\pi a}\cdot\beta\left(\frac{a}{W}\right) \quad (1)$$

$$\beta\left(\frac{a}{W}\right) = 1.12 - 1.39\left(\frac{a}{W}\right) + 7.32\left(\frac{a}{W}\right)^2 - 13.1\left(\frac{a}{W}\right)^3 + 14\left(\frac{a}{W}\right)^4$$

where, K_{IC}^{dyn} is the dynamic plain strain fracture initiation toughness. *S* is the difference between the span on the supports, $P(t_f)$ is the time varying load evaluated at the time-to-fracture, *W* is the width of the specimen, *B* is the thickness of the specimen, and *a* is the crack length. Figure 3 shows the results of the stress intensity factor as a function of time for a typical test. The dashed line represents the time-to-fracture and the intersection of the two lines the fracture initiation toughness. It should be noted that the dynamic stress intensity factor rate is near constant up to the time-of-fracture. This allows the dynamic fracture initiation toughness to be reported as a single valued loading rate.

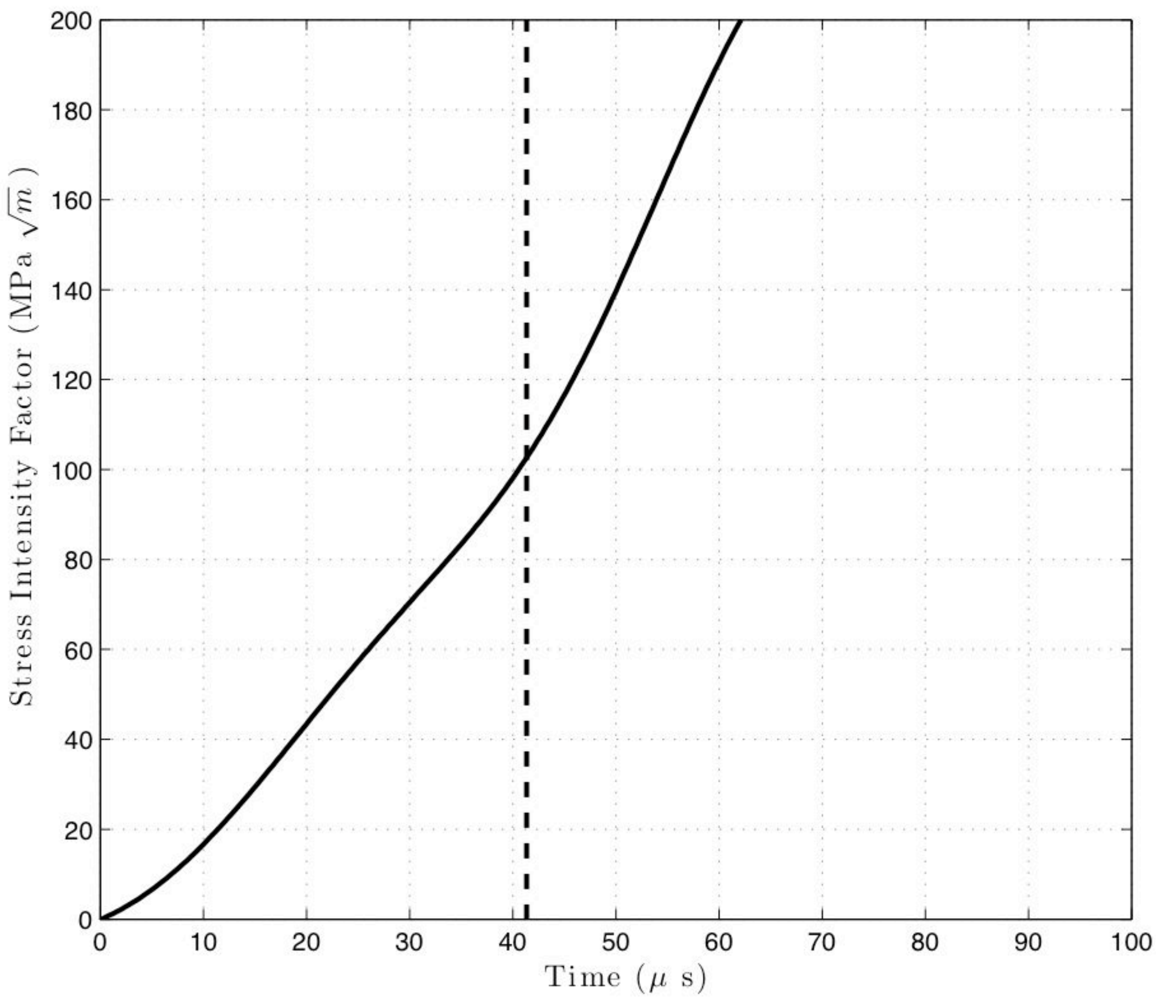

Figure 3. Stress Intensity Factor as a Function of Time

Experiments where conducted at three loading rates ranging between 2.5 x 10^6 and 5.5 x 10^6 MPa-$m^{1/2}$-s^{-1}. It is shown in Figure 4 that as loading rate increases the dynamic initiation fracture toughness increases over this range of loading rates. The spread in the data appears to be about 10% at each respective loading rate. This could be explained by having an approximate 10% uncertainty in the calculation of the time-to-fracture from the camera data. This could possibly be eliminated by using a more robust method of calculating the time-to-fracture.

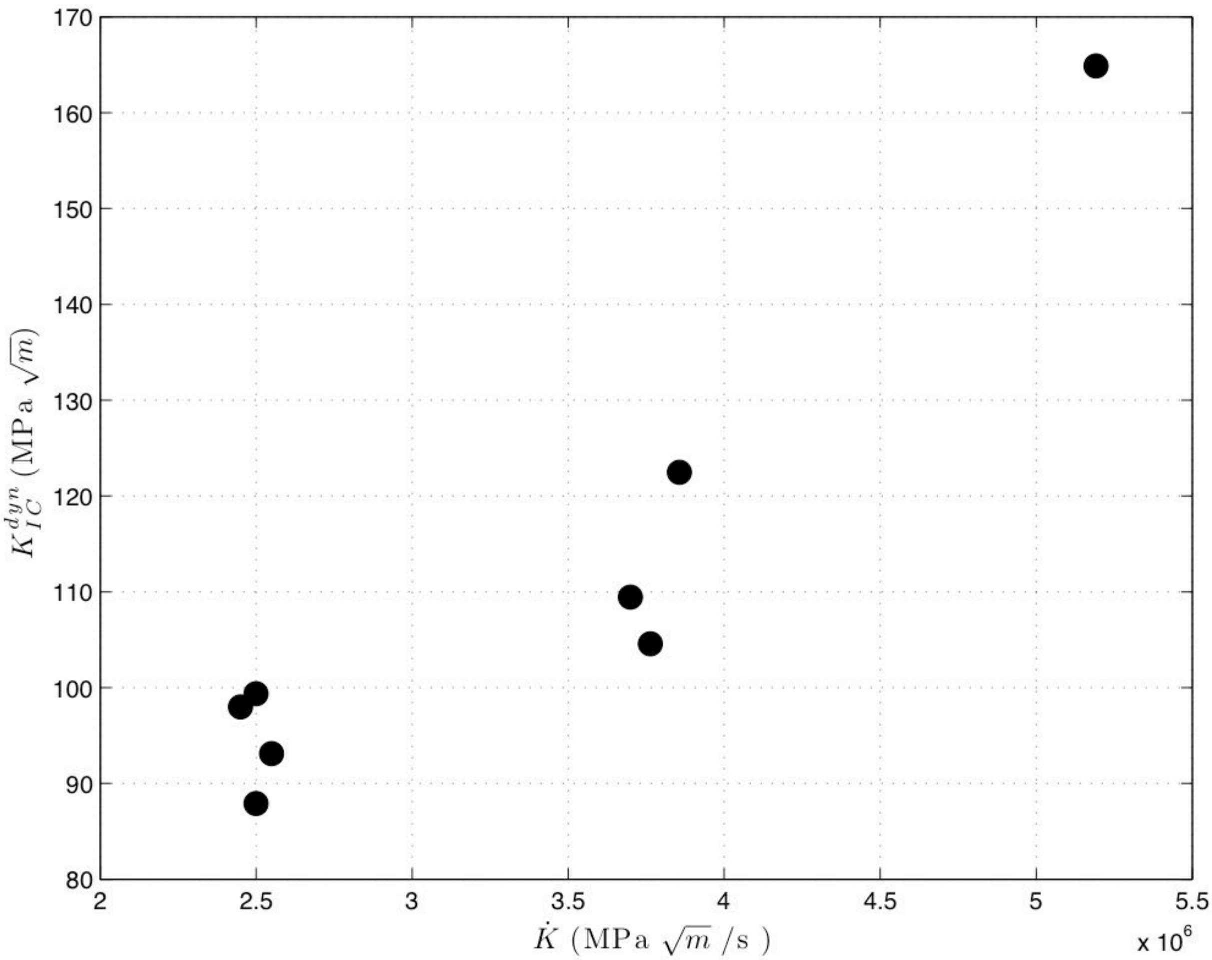

Figure 4. Dynamic Initiation Fracture Toughness as a Function of Loading Rate

CONCLUSION

Using a modified SHPB, four-point bend dynamic initiation fracture toughness experiments where conducted using a pulse shaped incident pulse to ensure a constant loading rate. The loading rate ranged from 2.5 x 10^6 to 5.5 x 10^6 MPa-$m^{1/2}$-s^{-1}. The pulse shaping ensured the sample was in dynamic equilibrium through the fracture time and equilibrium was checked using the one-wave, two wave technique. Since the sample was in dynamic equilibrium, a quasi-static analysis was used to evaluate the initiation fracture toughness based on the far field measurement recording with the SHPB transmission bar. The constant loading rate allowed the reporting of dynamic fracture initiation toughness as a function of loading rate. The results show an increase in initiation fracture toughness with an increase in loading rate.

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