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Dynamic Fracture Characteristics of Highly Brittle Materials by Using Instrumented Charpy Impact Test

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In This study we investigate the dynamic fracture characteristics of a tungsten carbide cobalt (WC-6wt%Co) composite material. The dynamic fracture initiation toughness and some of the dynamic fracturing characteristics are evaluated by using the Instrumented Charpy Impact Testing (ICIT) procedure. The dependence of measured time-to-fracture on the tup impact velocity and the dynamic fracture toughness for the WC-6wt%Co composite material are obtained by using ICIT. The effect of the loading rate on fracture initiation toughness is found to be negligible when the time- to-fracture is on the order of 50μsec. At significantly higher rates of loading it is impossible to determine the apparent dynamic fracture initiation toughness because of the influence of the inertia force on fracture loading. It is found that the impact velocities affect the time-to-fracture significantly at lower impact velocities for various engineering materials. It is shown that with the decrease of tup impact velocities the time-to-fracture is increased and the dynamic fracture initiation toughness converges to static fracture toughness.

Key Words: Dynamic Fracture Initiation Toughness, Inertia Force, ICIT (Instrumented Charpy Impact Test), Stress Intensity Factor, Strain, Tungsten Carbide Cobalt Composites, Time-to-Fracture, Tup Impact Velocity

1. Introduction

The Instrumented Charpy Impact Test (ICIT) has been widely used as method for evaluating fundamental dynamic fracture characteristics of compoite materials because of its experimental simplicity. Furthermore, the dynamic fracture initiation toughness, K_{Id}, of some semi-ductile materials has been determined easily using ICIT (Ewing, 1974 : Im, 1996 : Kobayashi, 1984 : Lueth, 1974). However, the applications of ICIT to measure K_{Id} of very brittle materials are rare since it is relatively difficult to determine the precise fracture initiation load because of the pronounced inertial effects on the total load. In this study, we attemp to investigate dynamic fracturing behavior of a hard material, WC-6wt%Co composite, by using ICIT technique for the purpose of extending its usability into very brittle materials.

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Wheatstone bridge circuits are positioned on both the impact tup and the specimen to simultaneously measure dynamic tup loads and dynamic bending displacements of the Charpy impact specimens. The Charpy impact tup signal is converted to impact load by calibration procedures. In evaluation of the dynamic fracture initiation toughness, the relationship between the dynamic tup load and the dynamic bending displacements of the specimen is used to determine the dynamic fracture initiation loading point (i.e., where dynamic compliance changes rapidly).

2. Dynamic Fracture Initiation Toughness

The typical impact tup load-time traces obtained by ICIT method are shown in Fig. 1. In Fig. 1(a), the load increases linearly until maximum load is reached where fracture seems to be initiated. When fracture is believed to be initiated before general yielding occurs, the dynamic fracture initiation toughness may be estimated by using linear elastic fracture mechanics (LEFM) theory (Koppenaal, 1974 : Lawn, 1975):

$$K_{Id}=\frac{6YP_mL}{4tW^2}\sqrt{a} \tag{1}$$

where

$$Y=1.93-3.07\left(\frac{a}{W}\right)+14.53\left(\frac{a}{W}\right)^2 -25.11\left(\frac{a}{W}\right)^3+25.8\left(\frac{a}{W}\right)^4$$

W : specimen width,

t : specimen thickness,

a : crack length,

P_m : maximum load (considered as fracture initiation load),

L : span between loading points.

The other type of load-time traces is observed as shown in Fig. 1(b). In this case, the general yielding occurs prior to the maximum load. Therefore LEFM theory cannot be applied to evaluate dynamic fracture initiation toughness. For this case, dynamic fracture initiation toughness is evaluated using the equivalent energy method developed by Witt (Koppenaal, 1974). In this theory an equivalent amount of energy is assumed necessary to reach maximum load if the specimen is thick enough to avoid general yielding prior to fracture.

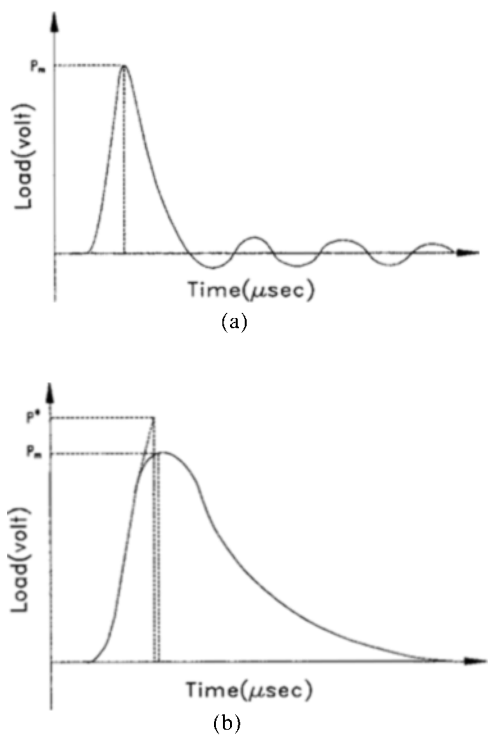

Fig. 1 Typical impact tup load time traces obtained by ICIT.

3. Experimental Procedures

A tungsten carbide cobalt (WC-6wt% Co) composite is used as the specimen material. The specimen is tested using 300 Joule-capacity Charpy impact testing machine, and rapidly changing histories of dynamic loads on impact tup are recorded. The Wheatstone bridge circuits are located on both the impact tup and the specimen as shown in Fig. 2 to measure dynamic tup loads and dynamic bending displacements of the Charpy impact specimens. As shown in Fig. 2, the two active gages are mounted on the impact tup in the loading direction. To ensure linear output characteristics, attention is paid to make sure that the gages are symmetrically located (Broek, 1989). The signals of the Wheatstone bridge amplified by dynamic strain conditioning amplifier are displayed and stored on a digital storage oscilloscope. The configuration of the Charpy impact specimen is shown in Fig. 3. The radius of the machined V-notch is 0.085 mm for the WC-6 wt% Co specimen.

Linear load output characteristics are ensured by a static load calibration procedure with the application of compressive load at low speed using a universal testing machine as shown in Fig. 4.

To find the precise fracture initiation instant, the recorded trace of the dynamic load-bending displacement is utilized. The fracture initiation load is determined corresponding to a point where the rapid change of compliance is observed on the dynamic load bending displacement curves. The rapidly changing dynamic load bending displacement trace is obtained by using an experimental procedure as shown in Fig. 5. This was designed and fabricated as follows: ①

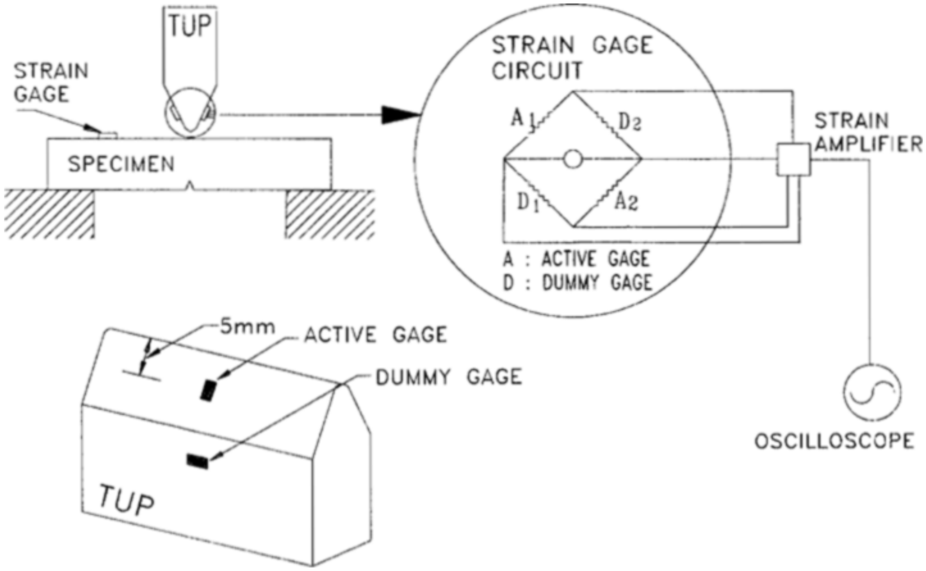

Fig. 2 Layout of ICIT system including full bridge circuit.

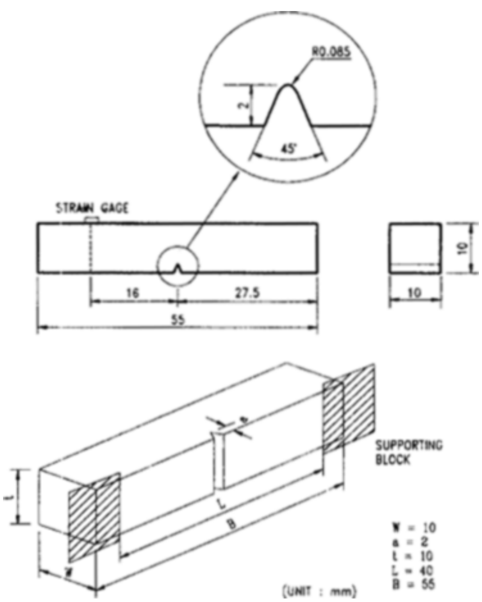

Fig. 3 Charpy impact specimen and strain gage location for obtaining dynamic load displacement curve.

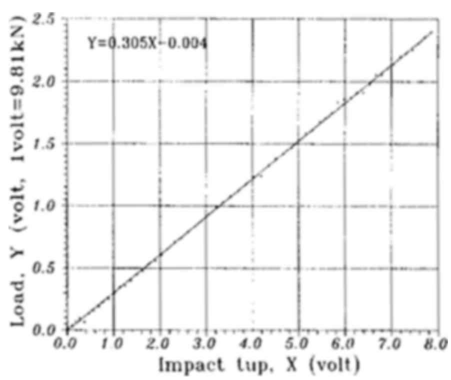

Fig. 4 Output characteristics of static load calibration.

locate strain gages on Charpy impact specimen as shown in Fig. 3; ② apply a restraint condition equivalent to Charpy impact testing using compressive procedure in the universal testing machine; ③ attach displacement gage on the Charpy impact specimen; ④ find the relation between strain gage and bending displacement gage signals with the application of gradually increasing compressive load; ⑤ apply impact load and record the impact tup load and strain gage signals in ICIT; ⑥ find the dynamic load-bending displacement trace.

4. Results and Discussions

Results obtained by ICIT with two kinds of strain amplifiers having different output charac-

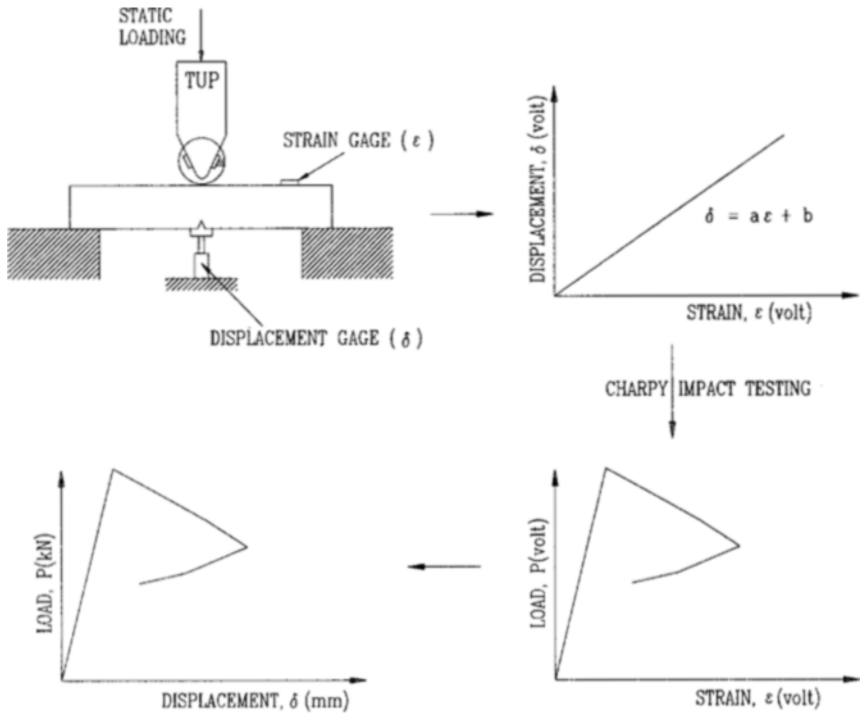

Fig. 5 A new experimental procedure to obtain dynamic load bending displacement curve.

teristics are shown in Figs. 6(a) and 6(b) for alloy tool steel (STD-11) specimens. Changes of impact tup load signal corresponding to two output bandwidth valves of the strain amplifier (2.5 kHz, 125 kHz) for alloy tool steel (STD-11) are shown in Figs. 6(a) and 6(b). From these two figures we find that the proper dynamic conditioning amplifier should be chosen to obtain valid experimental data (load in this paper).

Changes of impact tup load (volt, kN) with varying time in the full capacity of ICIT for WC-6 wt%Co specimen are shown in Fig. 7. It is impossible to distinguish the fracture initiation load because of the dominant inertial effect which overshadows the real fracture initiation load (Liu, 1991, 1993). The impact velocity of the tup is 5.46 m/sec. The dominant inertial effect in the impact test appearing in Fig. 7 is reduced by changing the tup impact velocity for WC-6 wt% Co specimens as shown in Figs. 8 and 9.

The time variation of the impact tup load (volt, kN) and dynamic strain output are shown in Fig. 8(a) for a WC-6 wt%Co specimen. The dynamic load bending displacement diagram obtained by using the method discussed earlier is also shown in Fig. 8(b) when the tup impact velocity is 3.23 m/sec. With an impact velocity of 3.23 m/sec, it is still very hard to draw a clear line between inertia force and fracture initiation loads even when the inertia load is decreased from 21 kN with the full capacity of ICIT to 11 kN as shown in Fig. 8(a).

With further reduction of the impact tup velocity to 1.69 m/sec, we can separate the dynamic fracture initiation load as pointed out in Fig. 9(a), which is in good agreement with that selected from the dynamic load bending displacement curve shown in Fig. 9(b). Dynamic fracture initiation toughness was evaluated by substituting the fracture initiation load into Eq. (1), which is applicable to very brittle materials. In Fig. 9(a), the second peak load is used as the dynamic fracture initiation load (1.55 volt=4.58 kN), since it is postulated that the first peak load is the inertia force (Ireland, 1974). The point in the dynamic load bending displacement diagram (where the slope (compliance) changes abrupt-

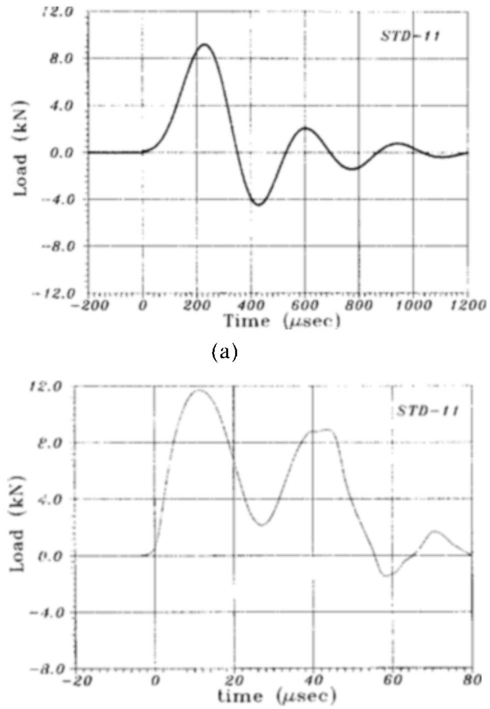

Fig. 6 Dynamic load time curve for STD-11 specimen (output bandwidth: 2.5 kHz(a), 125 kHz (b), impact velocity : 5.46 m/sec).

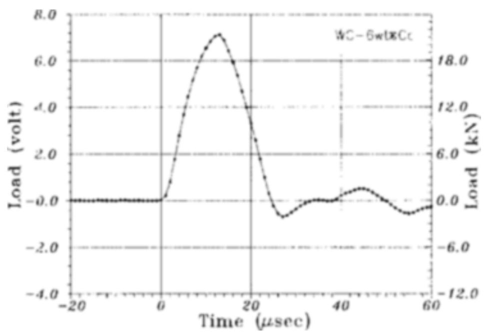

Fig. 7 Dynamic load time curve for WC-6 wt%Co specimen (impact velocity : 5.46 m/sec).

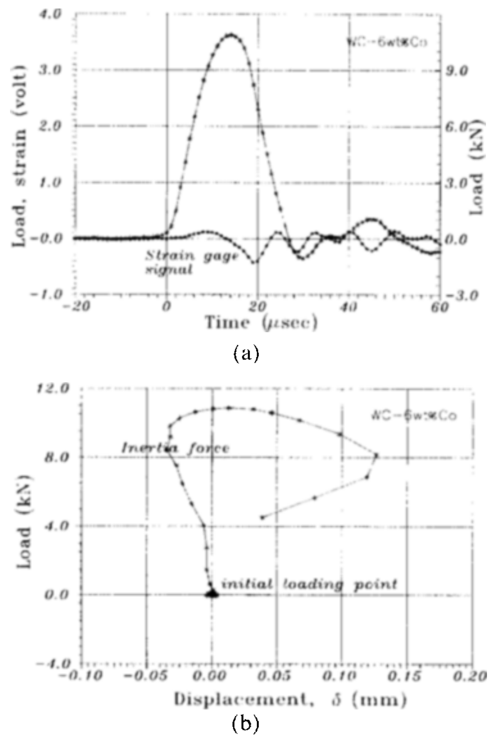

Fig. 8 Dynamic load time and strain time traces (a), dynamic load displacement trace (b), for WC-6 wt%Co specimen (impact velocity : 3.23 m/sec).

ly), which we regard as the fracture initiation point, agrees with the second peak loading point.

The inertial effect of the full capacity of the Charpy impact testing machine (300 Joule) for WC-6 wt%Co composite specimens is believed to be so strong that the fracture initiation load may not be distinguished (separated). When inertia force and fracture initiation load are separated distinctly as shown in Fig. 9(a), it is easy to determine fracture initiation load as is the case for semi-ductile material specimens. The fracture initiation load for the WC-6 wt%Co composite specimen is verified from the dynamic load bending displacement curve as shown in Fig. 9(b). We can locate the exact dynamic fracture initiation time accurately by identifying the loading point where the compliance of the specimen changes rapidly. The dynamic fracture initiation toughness and static fracture toughness obtained by using micro-Vickers indentation method of the WC-6 wt%Co specimen is estimated to be 21.35 $MPa\sqrt{m}$ and 12.00 $MPa\sqrt{m}$, respectively.

The impact tup load variations for three WC-6 wt%Co specimens with different impact velocities of 5.46, 3.23 and 1.69 m/sec are shown together in Fig. 10. The impact velocities are found to affect the tup signal significantly. It is clearly shown that the inertia forces decrease with the decrease

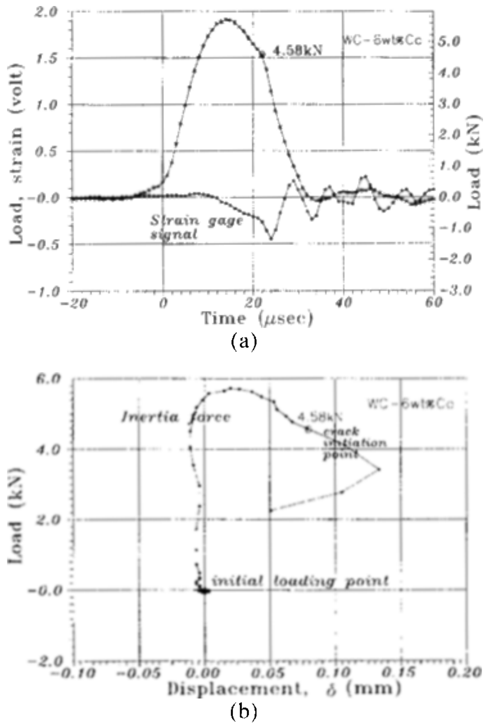

Fig. 9 Dynamic load time and strain time traces (a), dynamic load displacement traces (b), for WC-6 wt%Co specimen (impact velocity : 1.69 m/sec).

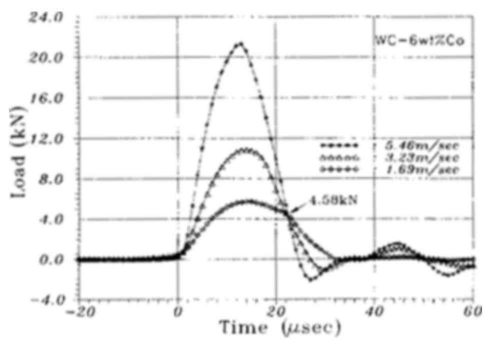

Fig. 10 Three dynamic load time traces for WC-6 wt%Co specimen with different impact velocities of 5.46 m/sec, 3.23 m/sec and 1.69 m/sec.

of impact velocities. Therefore it is relatively easy to distinguish between the fracture initiation load and the inertia force. Figure 10 shows that two signals are divided at the impact velocity of 1.69 m/sec, indicating a fracture initiation load, of 4.

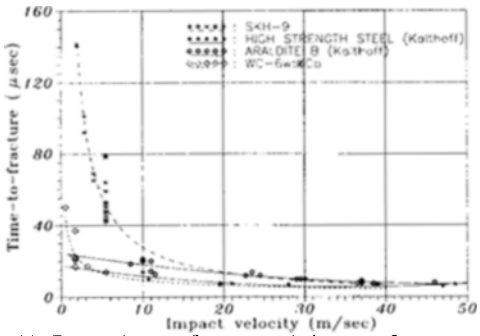

Fig. 11 Dependence of measured time-to-fracture on impact velocity for various specimen materials.

58 kN.

The dependence of time-to-fracture on the tup impact velocity for WC-6 wt%Co composite material is measured and shown in Fig. 11. Some published experimental data (Kalthoff, 1986 : Lee, 1995) for various engineering materials are also included in this Figure. It is found that the impact velocities affect the time-to-fracture significantly at the lower impact velocity range for varying engineering materials. As shown in Fig. 11, when tup impact velocity is greater than 20 m/sec, time-to-fracture becomes less than 10 μsec. It also seems to difficult to separate inertia force and fracture initiation load distinctly.

The variation of dynamic fracture toughness with respect to the time-to-fracture for WC-6 wt%Co composite material is shown in Fig. 12. It is shown that with the decrease of tup impact velocities, the time-to-fracture is increased and the dynamic fracture initiation toughness converges to static fracture toughness. Some published experimental data (Kalthoff, 1986 : Lee, 1995) for various engineering materials are also included for comparison.

From the limited experimental data shown in Fig. 12 for the WC-6 wt%Co composite material, it is postulated that the effect of the rate of loading on the dynamic fracture initiation toughness is negligible when the time-to-fracture is on the order of 50 μsec. At moderately higher rates of loading, the dynamic fracture initiation toughness increases with an increasing rate of loading. At a much higher rate of loading we can not determine

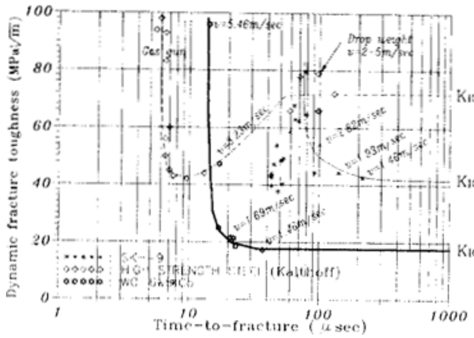

Fig. 12 Dependence of dynamic fracture toughness on time-to-fracture for various specimen materials.

the apparent dynamic fracture initiation toughness because of the high influence of the inertial effect on the fracture loading.

5. Conclusion

In this experimental investigation, dynamic fracture characteristics of the tungsten carbide cobalt composite material (WC-6 wt%Co) were evaluated. The dynamic fracture initiation toughness and some of the dynamic fracturing characteristics were evaluated by using ICIT procedures. For the WC-6 wt%Co composite material, since inertia force and fracture initiation load can not be separated in full capacity of ICIT, the fracture initiation load can not be easily distinguished. Under various experimental conditions the inertia force and fracture initiation load can be separated distinctly with a tup impact velocity of 1.69 m/sec. An experimental procedure in which rapidly changing dynamic load displacement traces can be obtained was used. The fracture initiation loads were verified by observing the dynamic load displacement curve. We were able to locate the dynamic fracture initiation time accurately at a moderate higher rate of loading by locating the loading point where the compliance of the specimen changed rapidly. At a much higher rate of loading, we could not determine the apparent fracture initiation toughness because of high influence of the inertial effect on the fracture loading. It is found that the impact velocities affect the time-to-fracture significantly at the lower impact velocity range for various engineering materials. It is shown that with the decrease of the tup impact velocities the time-to-fracture is increased and dynamic fracture initiation toughnesses converge to the static fracture toughness.

Acknowledgment

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