EVIDENCE FOR THE RELATIVE IMPORTANCE OF DYNAMIC FRACTURE TOUGHNESS

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Abstract

Dynamic fracture toughness values may be the same as that of crack arrest fracture toughness. It has been postulated that although a fracture may be initiated by static loading, the material some small microscopic distance ahead of the initiation site will be effectively loaded under dynamic conditions and therefore, dynamic fracture toughness is a better indication of a materials resistance to crack propagation than is that from static loading. Undetected small embrittled areas could exist in a nuclear pressure vessel as a result of welding and/or the service exposure to neutrons. The surrounding material must have adequate resistance to dynamic fracture initiation for prevention of catastrophic structural failure.

This paper presents the results of a study to demonstrate that when a localized embrittled area fractures, the surrounding material exhibits characteristics like that for dynamic loading. The material employed in this investigation was ASTM A533 Grade B Class 1 steel. Specimens were prepared from material at the 1/4 thickness area of plates ranging in thickness from 180 to 250 mm. Fracture toughness tests employed three point bend specimens of 20 and 50 mm thickness. Dynamic fracture toughness (K_{Id}) was determined by the computational methods of ASTM Method E399 and the specimens were loaded by impacting with a drop weight system. The dynamic tests were performed over the temperature range of -50 to +30°C. Machined notch specimens (0.1 mm radius) with and without a small embrittled zone (0.3 to 0.5 mm thick) at the notch tip were also evaluated. The embrittled zone was produced by soaking the specimens in NH_3 gas at 550°C for 40 hours and then quenched.

Static tests of the machined notch specimens with the local embrittled zone produced linear elastic fracture K_Q values of the same magnitude as for the dynamic K_{Id} values from fatigue precracked specimens. The equivalent energy method for estimating lower bound values of toughness for elastic-plastic fractures produced the same results for both 20 mm and 50 mm thick specimens.

The results of this study indicate that the role of dynamic fracture toughness characteristics in a nuclear pressure vessel safety analysis may be larger than that of an over conservative approach to a low probability incident.

1. Introduction

The fracture toughness of ferritic nuclear pressure vessel steels decreases as the rate of loading increases. There are low probability of occurrence conditions which could result in the pressure vessel material being dynamically loaded. Existing requirements for fracture safe design include considerations of the dynamic fracture toughness characteristics of these materials. Although the nuclear pressure vessel is primarily loaded statically and the probability of dynamic loading is quite low, the importance of dynamic fracture toughness may not have been over emphasized; Kraft and Irwin [1], ASME [2], WRC [3].

Dynamic fracture toughness values may be the same as that of crack arrest fracture toughness. It has been postulated that although a fracture may be initiated by static loading, the material some small microscopic distance ahead of the initiation site will be effectively loaded under dynamic conditions and therefore, dynamic fracture toughness is a better indication of a materials resistance to crack propagation than is that from static loading, Pellini [4]. Undetected small embrittled areas could exist in a nuclear pressure vessel as a result of welding and/or the service exposure to neutrons.

This paper presents the results of a study to demonstrate that when a localized embrittled area fractures, the surrounding material exhibits characteristics like that for dynamic loading. The material employed in this investigation was ASTM A533-B steel. Bend specimens ranging in thickness from 20 to 50 mm were tested statically and dynamically. The static loading of specimens having an embrittled layer of 0.3 to 0.5 mm at the machined notch tip, produced fracture toughness values comparable to that found by dynamic loading of a fatigue precracked specimen.

2. Material and Specimen Preparation

The material used in this investigation was ASTM A533-B steel. Three-point bend specimens were prepared from the 1/4 thickness position of plates which ranged in thickness from 180 mm to 250 mm. The dimensions of the three different specimen types (I, II and III) employed are shown in Figure 1.

Three different specimen notch conditions were used in this investigation, see Figure 2. The fatigue precracking was in accordance with the recommendations of ASTM Method E399. The cracks were extended by fatigue to a depth which provided specimen a/W ratios of .45 to .55. The machine notches (Figures 2b and c) were cut to a depth which provided an a/W ratio of 0.5 and a notch tip radius of 0.1 mm. Selected Type III specimens with machined notches were soaked in nitrogen gas (NH_3) at a temperature of 550° C for forty hours and then quenched to ambient temperature. This treatment produced an embrittled area at the notch tip which varied in depth between 0.3 and 0.5 mm, see Figure 2c.

3. Experimental Procedures

Static fracture toughness tests were performed in accordance with the recommendations of ASTM Method E399 for three-point bending. These tests employed a universal testing machine equipped with an XY plotter for monitoring the applied load versus specimen clip gauge displacement.

The dynamic fracture toughness tests were performed in impact through use of a Dynatup instrumented drop weight system. The drop weight system had a variable 2000 kg crosshead which could be dropped from heights varying up to 1.5 meters. The load data was obtained from an instrumented tup (striker) attached to the crosshead. The dynamic fracture toughness test and analysis procedures were consistent with those suggested by EPRI and currently under consideration by ASTM for instrumented impact testing; Ireland et. al. [5], ASTM E636 [6].

4. Fracture Toughness Computation

In this investigation, fracture was assumed to be initiated at maximum load. For fractures before general yield, (see Figure 3a) linear elastic fracture mechanics (LEFM) was used to compute plane strain fracture toughness (K_{Ic}) from the following:

$$K_{Ic} = P_m SY/BW^{3/2} , \tag{1}$$

where P_m is the maximum load, S is the specimen support span, Y is a function of a/W, and B, a, and W are specimen dimensions as defined in Figure 1.

In this study, K_{Id} was defined as the dynamic plane strain fracture toughness as evaluated in impact, where the stress intensity rates are from 5×10^5 to 5×10^6 $kg/mm^{3/2}/S$. Dynamic plane strain fracture toughness was computed from the same relationship shown above for K_{Ic}. Although impact conditions do not necessarily warrant utilization of static mechanics relationships, the requirement of the EPRI test procedures [4] for time to fracture to be equal to or greater than three times the inertial period of vibration of the specimen provides conditions for which eq. (1) is appropriate for the K_{Id} computation.

When fracture occurred after general yield, ($P_m > P_{GY}$) an elastic-plastic estimate of lower bound elastic fracture toughness (K_{Ic}, K_{Id}) was made through use of the equivalent energy method. In this method, the fracture initiation energy (E_I) for the elastic-plastic case is assumed to be the same as that which would have been required if the specimen had remained elastic up to fracture, see Figure 3b. This hypothetical fracture load (P_m^*) is calculated from the following relationship:

$$P_m^* = \left(2E_I / C_s \right)^{1/2} , \tag{2}$$

where C_s is the elastic compliance of the specimen. A lower bound estimate of plane strain fracture toughness is then made by substituting the hypothetical P_m^* for P_m in eq. (1) above.

For each test in this study, the P_m value was used to calculate a provisional value of K_{Ic} or K_{Id} (depending on the particular rate of loading) from eq. (1) and the E_I value was used to compute an equivalent energy value of fracture toughness. General yielding was clearly indicated when the later value of toughness exceeded that determined from P_m.

5. Results and Discussion

The variability of dynamic plane strain fracture toughness (K_{Id}) with test temperature for ASTM A533-B steel, was determined through use of specimen Types I, II and III. The results of these tests are shown in Figure 4 as the solid line curve. Also shown in this figure, is a comparison of the relative fracture toughness measurement capacities for the smaller Type I specimen and the larger Type III specimen.

At temperatures below 0° C, there is excellent agreement between the toughness values determined by Type I and Type III specimens. At approximately 0° C, the toughness value determined by the 50 mm thick Type III specimen, satisfies the requirement of ASTM Method E399. The toughness value of the 20 mm thick Type I specimen at approximately 0° C exceeds the ASTM requirement for validity, but is consistent with the "valid" results of the 50 mm thick Type III specimen. This suggests that the ASTM criteria for validity may be overly conservative for bend-tests of ASTM A533-B steel.

At approximately 15° C, the Type I specimen fractured after general yielding. The K_Q value calculated from the maximum load is indicated by the open square in Figure 4. Equivalent energy analysis of this test record yielded the half-closed square value which falls on the curve and is consistent with the LEFM value for the Type III specimen, at approximately the same temperature. The results shown in Figure 4 indicate the equivalent energy lower-bound estimate for fracture toughness, produces good agreement between tests of specimens of various thicknesses and geometry. This is further illustrated by the results at approximately 30° C where the equivalent energy calculations produce essentially the same results for the tests of Type I and Type III specimens.

Dynamic fracture toughness results for ASTM A533-B are substantially less than those for static loading. A fracture safe design based on dynamic fracture toughness results, would be conservative. It is unlikely that a nuclear reactor pressure vessel will see a dynamic loading comparable to that for the data shown in Figure 4. Therefore, a more realistic safety design might be one based on the static fracture initiation toughness (K_{Ic}). However, it is suggested that a localized embrittled area (e.g., in a weld) in the reactor pressure vessel, could fracture under static loading and still result in catastrophic failure of the reactor vessel. Although the fracture is initiated in the localized embrittled area under static loading conditions, the surrounding material can respond as though it had been dynamically loaded. To explore this hypothesis further, specimens were prepared of a Type III geometry with a machine notch and also with a small embrittled area at the tip of the machine notch, as indicated in Figure 2b and c.

A comparison of the static and dynamic fracture initiation toughness of the machined notch, embrittled notch, and fatigue precracked notch are shown in Figure 5. The solid curve in this figure represents the results of the impact tests of fatigue precracked specimen Types I, II and III, shown in Figure 4. Dynamic initiation toughness values determined from the machined notch (radius 0.1 mm) are indicated by the open circles and as would be expected the results are considerably higher than that for the fatigue precracked specimens. Dynamic initiation of the specimens with the embrittled area at the notch tip indicate toughness results (closed triangles in Figure 5) comparable to that obtained with the fatigue precracked samples. This result is consistent with the fracture of the embrittled area producing notch conditions similar to those for a fatigue crack.

Specimens with the embrittled area at the tip of the machine notch were tested in accordance with the static test requirements of ASTM Method E399. These results are indicated by the open triangles in Figure 5. Although the fracture was initiated in the local embrittled area under static conditions, the resulting toughness value is comparable to that for dynamic loading of fatigue precracked samples. These results strongly suggest that fracture eminating from a localized embrittled area, will result in effective dynamic loading of the surrounding material and catastrophic failure may occur in a manner indicative of the dynamic fracture toughness response of the material.

In a nuclear reactor pressure vessel, local embrittled areas may develop with the inservice exposure to neutrons. A relatively high copper concentration may occur locally in a weld area and the fracture toughness properties of this area will be severly degraded by the exposure to neutrons. A low probability service condition may cause the locally embrittled area to be fractured. It is then imperative that the surrounding material have sufficiently high resistance to dynamic fracture loading, as to resist catastrophic failure of the reactor vessel. Therefore, it is suggested that reactor pressure vessel safety analyses give strong consideration to utilization of the dynamic fracture initiation properties of reactor pressure vessel steels, including the welds and heat affected zones.

6. Conclusions

6.1 The equivalent energy method for fracture toughness calculations yields comparable results for 20 mm thick and 50 mm thick specimens of ASTM A533-B steel.

6.2 The results of this study suggest the ASTM size requirement for the validity of plane strain fracture toughness results, is overly restrictive. The results indicate that valid dynamic plane strain fracture toughness results can be obtained up to the point of general yielding of the specimen. After general yielding the equivalent energy method produces lower bound estimates of plane strain fracture toughness which are consistent with that derived from thicker specimens.

6.3 Static initiation of fracture from a locally embrittled area at a machine notch, will cause the surrounding material to behave as though it had been dynamic loaded at a rate comparable to that produced by impact loading. Nuclear reactor pressure vessel design should include consideration for the effective dynamic loading of the material as a result of static fracture initiation from locally embrittled areas.

References

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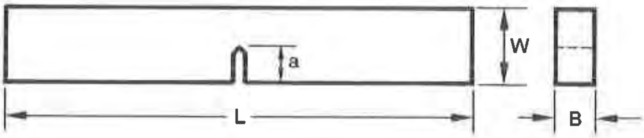
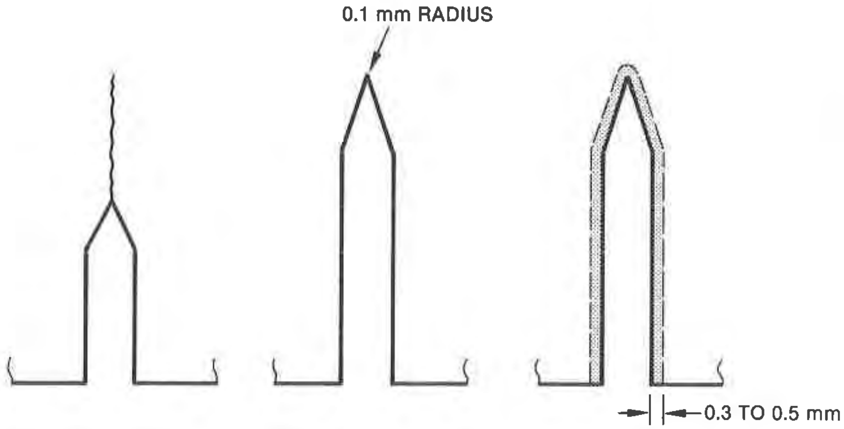


TYPE	B (mm)	W (mm)	L (mm)	a (mm)
I	20	20	100	10
II	20	40	200	20
III	50	100	500	50

Figure 1. Specimen Dimensions



A. FATIGUE CRACKED B. MACHINED NOTCH C. EMBRITTLED SURFACE LAYER

Figure 2. Notch Conditions

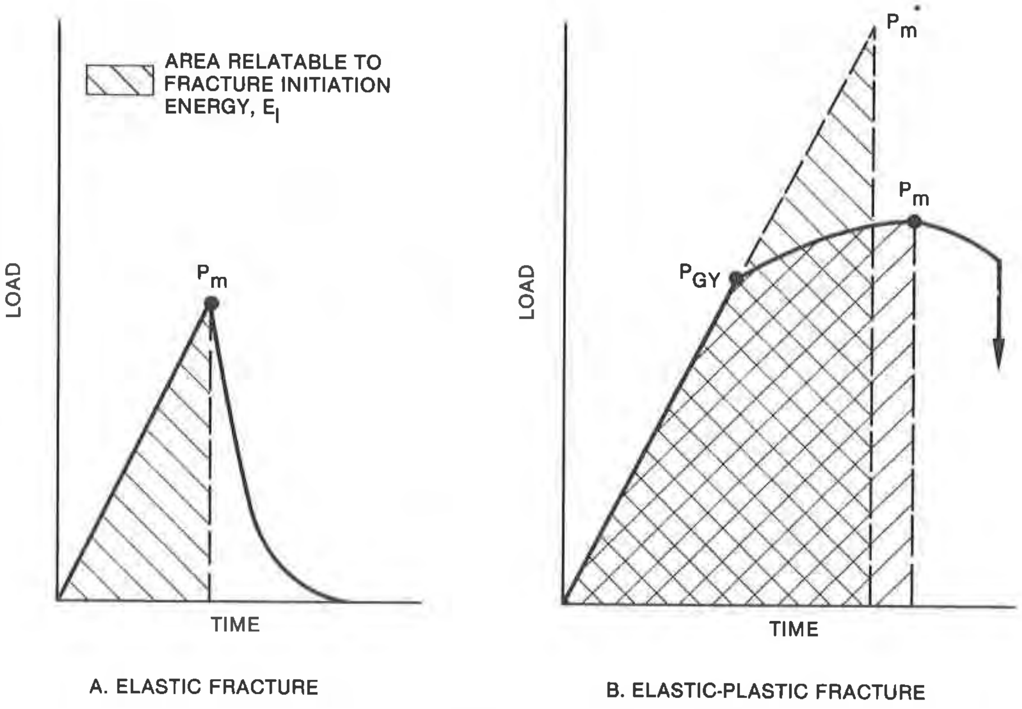


Figure 3. Data Records for LEFM and Equivalent Energy Analyses

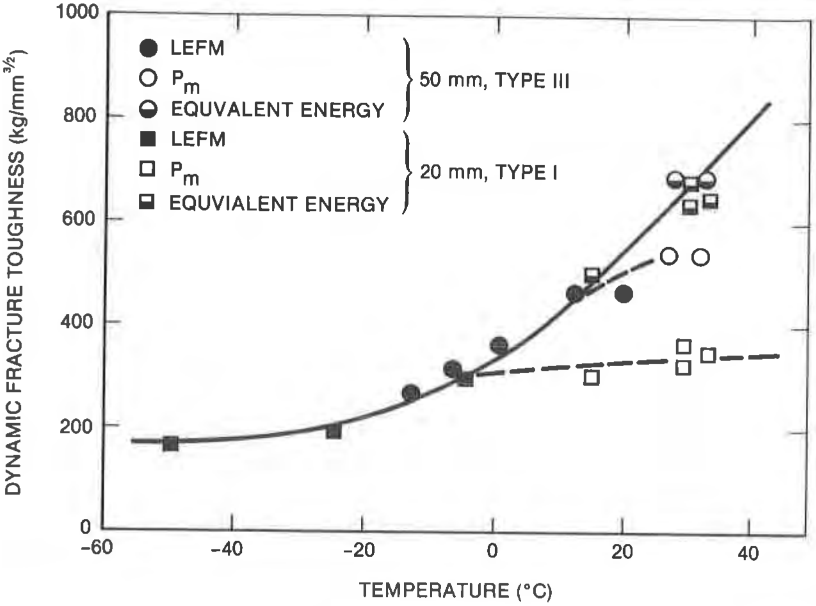


Figure 4. Dynamic Fracture Toughness Results for ASTM A533-B Steel

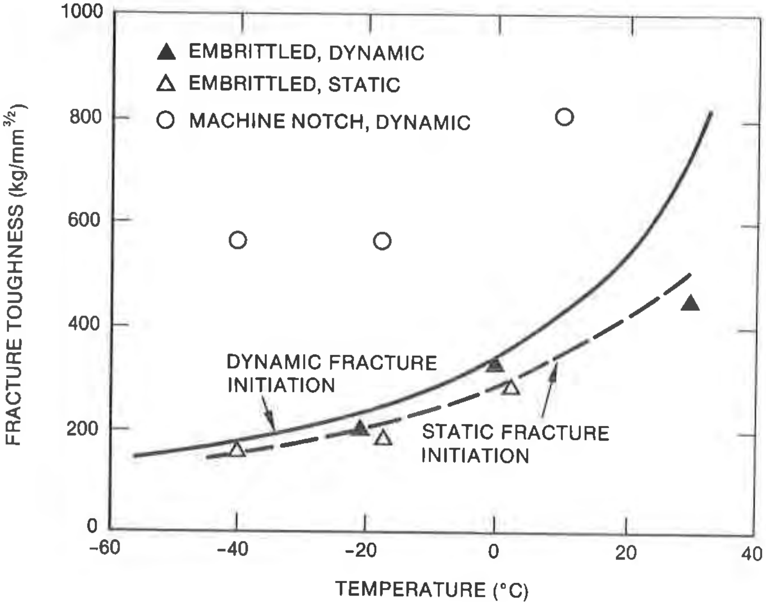


Figure 5. Static and Dynamic Initiation Toughness for Embrittled Notches in ASTM A533-B