Recent Developments in Drop Tower J Integral Testing of Elastic Plastic Structural Steels

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ABSTRACT

During the past six years a test method has been developed for dynamic testing of fracture mechanics specimens which is specifically designed for application to the upper transition temperature range. The method uses drop tower loading rates of 2.5 m/sec and obtains a J_{IC} or a J–R curve using an analytical key curve approach verified by initial and final crack length measurements obtained from the fracture surface. A J–R curve is obtained from each specimen and contains crack growth corrections so that it is directly comparable with static results obtained in accordance with the ASTM E1152 J–R curve test method.

Static test results have shown that the J at cleavage initiation (which is presently an unstandardized quantity) is specimen a/W independent throughout the ductile to brittle transition but of course demonstrates considerable statistical scatter in the vicinity of the ductile upper shelf.

Dynamic J–R tests have shown an increase in J_{IC} with test rate for most, but not for all, materials. Separation of J into elastic and plastic components shows that the elastic J component increases with loading rate in a fashion consistent with the materials tensile sensitivity to loading rate but the plastic J component decreases with loading rate – an apparent visco–plastic phenomena. For A106 steel the plastic J decrease exceeds the elastic J increase and the upper shelf toughness falls – while the other materials have demonstrated a relatively larger increase in the elastic J component and a smaller decrease in the plastic J component giving an overall increase in upper shelf toughness.

KEYWORDS

Dynamic fracture, dynamic J_{IC}, dynamic J–R, ductile–brittle transition, key curve method.

INTRODUCTION

Many important structural applications involve loading application times on the order of one to five milliseconds. Laboratory material testing, including both standard tensile mechanical tests and fracture mechanics tests, are generally done at quasi static loading rates and occur over time periods of minutes rather than milliseconds. When tensile tests are done at elevated rates the yield and ultimate stresses are generally elevated, (with the yield stress elevation generally larger than the ultimate stress elevation) and the laboratory test rate is taken to be conservative. Some alloys demonstrate lower elongations and reductions in area when tested rapidly – but this is generally ignored.

High rate fracture mechanics tests have only recently been developed(1),(2),(3) and the test results that are being obtained from these tests are showing rather conclusively that structural materials which are to be used for dynamic loading applications should be characterized by laboratory tests conducted at similar loading rates. The following sections look at a new method used for high rate fracture testing and at the important observations that have come to light which support the above statement that dynamic fracture initiation work should be required when choosing structural materials for dynamically loaded applications.

The test procedure has been applied to A106 steel, A533B steel and US Navy HY80 and HY100 steels at temperatures from –200F to 150F. Standard 1T three point bend specimens have been used for all materials and additional 2T three point bend specimens were used for the A533B and the HY100 steel.

EXPERIMENTAL PROCEDURE

An experimental procedure to allow J_{IC} and J–R curve evaluation for drop tower tests on ductile structural materials has been developed under U.S. NRC and U.S. Navy co–sponsorship over the past six years. The basic test apparatus (except for the drop tower) is shown schematically in Fig. 1. Major features of the test procedure are the following. Direct measurements are made of load, using a full strain gage bridge on the specimen, load line displacement, and two crack opening displacements along the notch surface as shown in Fig. 1. Soft aluminum absorbers are used to reduce the initial oscillations normally produced by the tup impact. A key curve method(1)(2)(3) is used to obtain crack growth beyond crack initiation. The key curve method also allows separation of J into elastic and plastic components for detail analysis. Finally, a chamber is used to control subambient temperatures to give a more accurate and uniform temperature value.

ANALYSIS AND JUSTIFICATION

The deeply cracked three point bend bar used for these drop tower tests has the simple J integral formulation(5)

$$J = \frac{2\ A}{B_N b} \qquad (1)$$

where: b = uncracked ligament
B_N = specimen net thickness
A = area under the specimen load versus load point displacement record.

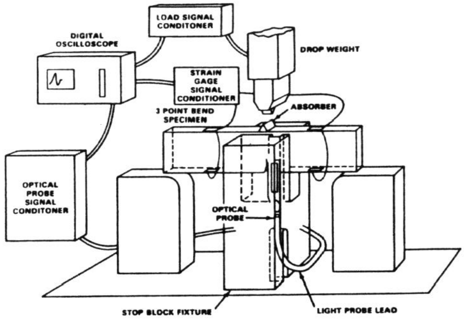

Fig. 1 Schematic of Drop Tower Test Apparatus

Equation 1 is of course a static equation which is not corrected for crack growth. The crack growth correction could easily be added and is automatically obtained by a key curve analysis. If a dynamic calculation is needed, a much more advanced analysis is necessary. For the test geometry used here an analysis using a three dimensional finite element model of a dynamically loaded three–point bend bar has been done by Nakamura, Shih and Freund.(6)(7) They used a full field analysis of the specimen, and based on this analysis, introduced a concept called a transition time to provide a practical lower bound for the time range over which conditions of J dominance prevailed near the crack tip and for which the deep crack J formulation of Equation 1 was applicable. Verification experiments were conducted by Hackett, Joyce, and Shih(8) which showed that drop tower test specimens loaded at 2.5 m/s were in substantial agreement with the finite element results and that the J_{IC}, J_{clv} and J–R curves normally obtained for such specimens were accurate because they were measured over times much greater than the 300 microsecond transition times characteristic of these specimens.

J–R CURVE EFFECTS

The observation that tensile and yield strengths are elevated by test rate, and the text book(9) presentation of the elevated toughness of most Charpy data tested dynamically, has led to the general conclusion that dynamic elastic plastic toughness always exceeds static elastic plastic toughness.

This conclusion has in general been observed in drop tower J integral fracture toughness results, specifically for HY130(10), HY80(2), and A533B(11). A typical J–R curve result for HY80 steel is shown in Fig. 2. Recent work has, however, shown that this effect is not always observed. For A106 steel, as reported in reference(3), the load displacement record can be greatly elevated by drop tower loading, as shown in Fig. 3. Analysis of the data using the key curve method to give J–R curves gave the rather surprising results shown in Fig. 4. Some further thought showed that the J–R curves are consistent with the observed changes in shape present in the load displacement records of Fig. 3. The principal observation here is that the maximum load point of the rapidly loaded specimen has shifted to a much smaller displacement value than was the case with the static test. Separation of the J–R curves into elastic and plastic components, see

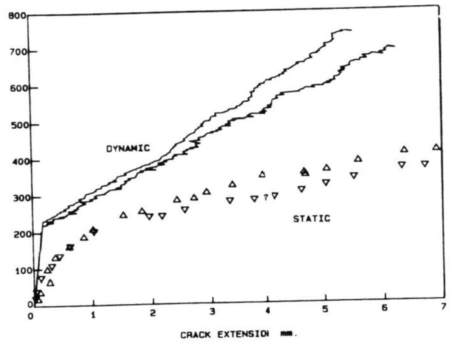

Fig. 2 Comparison of Static and Dynamic J–R Curves for a Rate Sensitive 3% Nickel Structural Steel

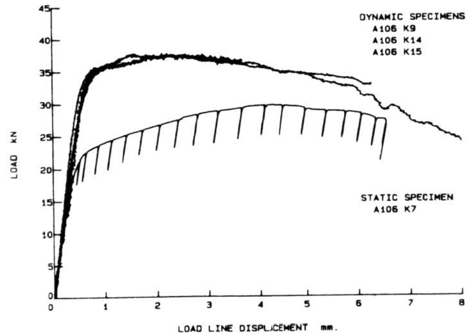

Fig. 3 A106 Steel Static and Dynamic Load Displacement Curves

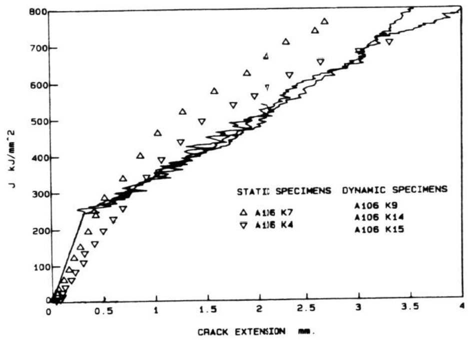

Fig. 4 Comparison of Static and Dynamic J–R Curves for the A106 Steel

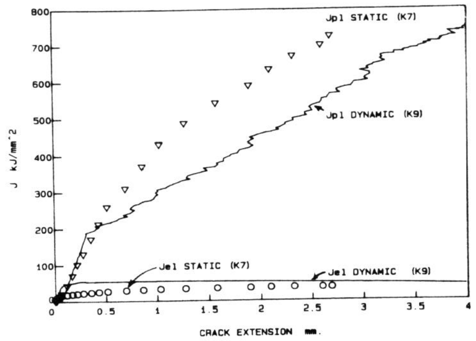

Fig. 5 Separation of J Into Elastic and Plastic Components

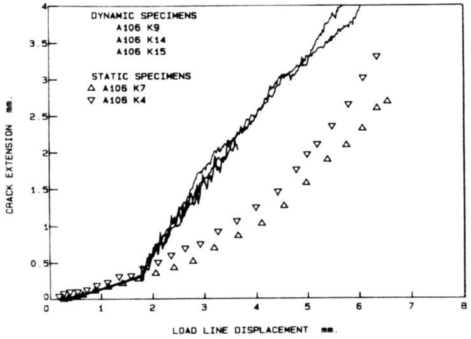

Fig. 6 Crack Extension Versus Load Line Displacement for A106 Steel

Fig. 5, shows that while the rapid loading has elevated the elastic component of the J–R curve it has dramatically reduced the plastic component of the J–R curve. The total J–R curve for the dynamic loading case is reduced in this case, not elevated, as would generally be expected.

Fig. 6 shows, further, that more crack extension is present at a given specimen bend angle for the dynamic loading than for the nearly identical static specimen. This relates directly to the reduced elongation at fracture demonstrated by rapidly loaded tensile specimens of this alloy in comparison with identical round tensile bars loaded statically(3).

TRANSITION TEMPERATURE SHIFTS

One of the major features of the drop test system described above is that it can be used over a range of temperatures and the analytic key curve method generates a J–R curve for each specimen. This makes J–R, J_{IC}, and J at

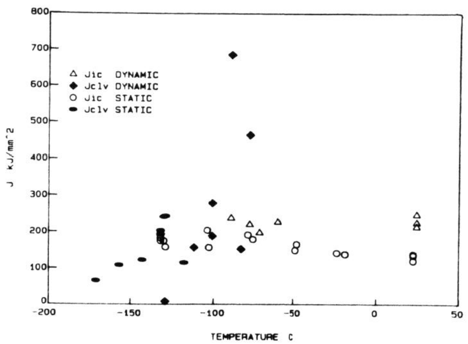

Fig. 7 Static and Dynamic J_{IC} and J_{clv} Results for the 3% Nickel Steel

cleavage (J_{clv}) testing practical even in, or near to, the ductile to brittle transition region of ferritic steels. In this region multiple tests are necessary because of the variability of the measured results, and test methods requiring more than one specimen to define a toughness value are impractical.

Figs. 7 and 8 show static and dynamic toughness transition results for two structural steels, the first a 3% Nickel quench and temper alloy steel with 550 MPa yield and the second an A533B nuclear containment vessel steel. In both cases the test rate greatly affects the temperature at which the ductile to brittle transition occurs with a shift of 50°C and 40°C occurring for the two alloys respectively. Fig. 8 also shows that specimen size appears to have a much smaller effect on the transition temperature than test rate, at least for the A533B alloy, with 2T specimens plotting in the data band of 1T specimens – though at present only a small number of 2T specimen results are available.

CRACK ARREST/INITIATION COMPARISON

In many structural applications crack initiation and growth can be expected during overload or accident conditions and the crack arrest properties of the material are sought in an attempt to assure that such a crack will stop before a catastrophic failure occurs. Crack arrestors are welded into ship hulls and other structures, but the true value of such expensive additions can only be determined from experimental tests or from experience with the structures. Recent work at the National Bureau of Standards(12) using wide plates of A533B steel have attempted to measure the crack arrest toughness of the steel as a dynamic elastic crack runs into an increasingly tough material. The material used to develop the toughness transition curve of Fig. 8 was obtained from one of these wide plates and a direct comparison can be made between the ductile initiation results and the elastic dynamic crack arrest results obtained by NBS. The comparison is made in Fig. 9 using the elastic stress intensity factor obtained from the J integral at cleavage (or ductile initiation as the case may be) using

$$K = \sqrt{JE/(1-\nu^2)} \tag{2}$$

The NBS tests were conducted on four inch thick plates with a rapid crack velocity while the J integral crack initiation tests were conducted on much smaller standard 1T and 2T three point bend bars. Nonetheless the comparison of Fig. 9 shows that the toughness values at arrest and initiation for this alloy are very similar. The crack arrest toughness should be a lower bound toughness at each temperature in comparison with the crack initiation toughness. The close agreement between the two results shown here seems to verify that the dynamic ductile initiation toughness test, using the J integral, gives a reasonable lower bound toughness – at a fraction of the cost of the crack arrest tests.

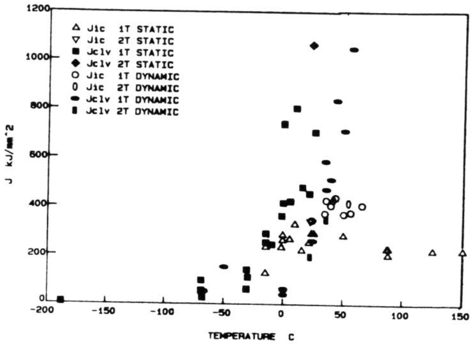

Fig. 8 Static and Dynamic J_{IC} and J_{clv} Results for an A533B Steel

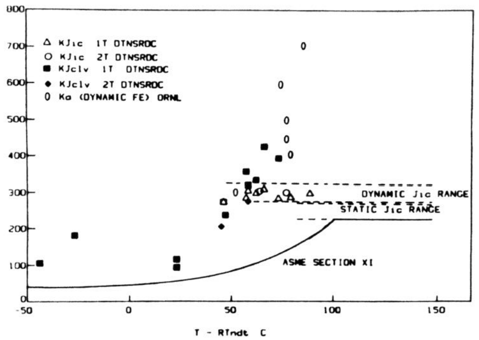

Fig. 9 A533B Steel Initiation Toughness and Crack Arrest Toughness

CONCLUSIONS

This work has demonstrated that drop tower rate J_{IC} and J–R curves can be evaluated from single specimen tests conducted over a wide range of temperatures. This experimental technique should allow developing the fracture mechanics data that is needed to understand and characterize the ductile to brittle toughness transition of ferritic steels. Results to date show that the upper shelf toughness generally is elevated by rate.

Separation of J into elastic and plastic components shows, however, that while the elastic component is elevated by rate the plastic component is reduced, sometimes dramatically. Test rate does produce a large shift of the transition temperature (as observed for years with Charpy type tests) with A533B demonstrating a shift of about 40°C while HY80 shows an even larger shift on the order of 50°C.

Comparison of dynamic crack initiation toughness and crack arrest toughness of the A533B alloy shows an unexpectedly good correspondence between these rather dissimilar toughness measures. For these tests the geometries are different, the crack velocities are dissimilar, and the specimens vary from 25 mm to 100 mm thick and yet the toughness at initiation for the drop tower bend specimens overlay the calculated toughness at arrest obtained for the edge cracked tensile mode crack arrest tests.

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