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Dynamic Fracture Toughness Measurements of Ferritic Ductile Cast Iron

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Abstract

Fracture toughness testing of ductile cast iron (DCI) at elevated loading rates has been performed at Sandia. The intent of the test program was to generate rigorously measured dynamic fracture toughness data in order to enhance the DCI material property data base and to evaluate the effect of rate on the upper-shelf fracture toughness. The test requirements outlined in the ASTM Standard Test Method for J_{Ic}, A Measure of Fracture Toughness (E 813-87) were adapted to elevated loading rates in a manner which allowed the inherent rigor of this test method to be maintained. The actual measurements were performed on compact tension specimens using a closed-loop servo-hydraulic test frame with special fixturing to enhance test control. The DCI alloy examined was a high quality casting of the type used in European-produced casks (i.e., it had a fully ferritic matrix, with only Type I and II graphite nodules). The test results show that there is essentially no effect of loading rate on the upper-shelf fracture toughness over the range tested. The current results are in contrast to other reports which suggest that there is a decrease in the upper-shelf toughness as the loading rate is raised above a certain level.

Introduction

Hypothetical accident conditions for testing transport casks require the cask to withstand a 9 meter drop onto an unyielding target at a temperature of -29°C (1). The primary materials issue for ductile cast iron (DCI) under these loading conditions is its potential to fail via low-energy brittle fracture. DCI can in fact, undergo a failure mode transition (with decreasing temperature and/or increasing loading rate) from a high-energy ductile tearing to a low-energy brittle fracture. Therefore to be qualified for use in transport casks, the fracture toughness of candidate alloys should be measured at the elevated rates and low temperatures that match those required for licensing. Under such conditions, it should be demonstrated that the material has sufficient toughness to preclude crack initiation.

The measurement of fracture toughness is covered by two ASTM approved test methods. The ASTM Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials E 399-83 (2) is used for determining the fracture toughness in alloys which fail with at most, only small amounts of plasticity. This produces a characteristic load-displacement test record for a precracked specimen which shows failure occurs in the linear portion (or soon thereafter). The fracture toughness from E 399-83 test methods is labeled K_{Ic} which is the stress intensity (in units of MPa-$m^{1/2}$ or ksi- $in^{1/2}$) at which extension of a preexisting crack begins under loading. The ASTM Standard Test Method for J_{Ic}, A Measure of Fracture Toughness E 813- 87(3), allows the measurement of the fracture toughness in samples which exhibit significant plasticity prior to crack extension (i.e., samples exhibit elastic-plastic behavior). The load-displacement test record for an elastic-plastic test shows considerable non-linearity; when load is increased above a certain value, increased loading increments are accompanied by displacements which are substantially greater than those observed in the "elastic" region. The characteristic test record for elastic-plastic materials is distinctly different from those produced by samples which satisfy the requirements of ASTM E 399-83 testing. J_{Ic} values can be converted to equivalent stress intensity units according to:

$$K_{Ic} = [J_{Ic} \cdot E] \qquad \text{Eqn. 1}$$

where E is Young's modulus. This equation is valid for conditions in which elastic stresses are dominant in the loading of a specific structure.

Elevated loading rate fracture toughness data are sparse, due at least in part, to the lack of an approved test procedure. This is particularly true for alloys, such as ferritic DCI, which behave in a elastic-plastic (as opposed to a linear elastic) manner for standard test specimen sizes. ASTM E 813-87 provides a means of rigorously determining the fracture toughness of elastic-plastic materials, but this test procedure is approved only for static (i.e., very low) rate testing. One reason for the static rate limitation in the results from difficulties involved in precisely applying and measuring the loads displacements that are required for elevated rate testing. It is possible nonetheless, to successfully employ the guidelines embodied in E 813-87 to perform toughness testing up to certain reletively high loading rates. This can be done by employing specially designed fixturing which allows enhanced test control: one method for doing this is described in this paper. At very high loading rates however, E 813-type measurements become (mechanically) increasingly difficult, and in addition, measurement interpretation becomes a problem due to the increased presence of so-called "inertial" effects of the specimen and test apparatus (4). The fracture toughness measurements in this program were performed to meet all the requirements presented in ASTM E 813-87, even though the loading rate was above that allowed by the standard. All of the loading rates used in this work were however, kept low enough so as to ensure that inertial effects would have at most, a negligible effect on the measurements and data analysis (as detailed in E 813-87). Thus in this paper, the inherent rigor of the ASTM E 813-87 Standard Test Method was properly extended to elevated rates, without forcing the method into a region where interpretation of data is obscured by inertial effects.

Due to the lack of an approved dynamic fracture toughness test method, the precracked Charpy (PCVN) test has often been used to provide estimates of J_{Id}, the elastic-plastic fracture toughness property measured in ASTM E 813-87 at dynamic loading rates. The values thus obtained can be considered as being only crude approximations of the actual J_{Id}, since ASTM E 813-87 requirements are not met. Specifically, in the PCVN test, the load line displacement is not measured directly, but is rather inferred from velocity measurements. Further, crack initiation is assumed to occur at the peak load value; an assumption which does not match the definition of crack initiation established by ASTM E 813-87. Figure 1 shows the PCVN fracture toughness values (5) at dynamic rates compared to fracture toughness values measured previously (6) according to ASTM E 813-87. The PCVN generated curve suggests that there is a decrease of approximately 30% in the upper-shelf fracture toughness at dynamic rates. This decrease appears even though there is no apparent change in the failure mode as evidenced by scanning electron microscope (SEM) examinations of the fracture surfaces of both PCVN and E 813-87 specimens.

The test method shortcomings inherent in the PCVN test gave rise to Sandia-sponsored efforts to directly measure the parameters required by E 813-87 directly on three point bend specimens loaded at elevated rates (7). The methods, equipment, and analysis are described in detail in the reference, and will only be outlined here. For these tests, the load was applied by a drop tower with an instrumented tup (or impacting head). Displacement of the tup was limited by a stop block arrangement. Load line displacement (LLD) of the sample was taken to be the same as the displacement of the tup (after contacting the sample) until it impacted the stop blocks. A multiple specimen test was conducted as outlined in E 813-87. The load and tup displacement records were used to generate a load-LLD curve, from which a J value was determined and associated with the crack extension value determined for that specimen. Crack extensions were determined by direct measurement of the fracture surface as recommended in the ASTM standard. Five specimens were used to determine the "R-curve" (which is a plot of J versus crack extension). The extrapolation of this curve back to the effective crack initiation point as defined by E 813-87 provided the value for J_{Id}. This measured value (from the same heat of DCI used in this work) agreed with the estimate from the PCVN tests in which the upper shelf toughness was in the 66 to 72 MPa-$m^{1/2}$ (60 to 65 ksi-$in^{1/2}$) range (in terms of linear elastic stress intensity units). These data are shown in Figure 1 as discrete points since values over the full temperature range were not measured. The three point bend testing also showed that the apparent drop off in upper shelf fracture toughness seemed to occur even though it was still obvious from the test records and the fracture surfaces (i.e., ductile tearing) that this DCI alloy was still behaving as an elastic-plastic material.

Given the apparent discrepancies suggested by the results summarized above, a research program was undertaken at Sandia to determine whether or not the rigorously measured fracture toughness does indeed show any decrease with increased loading rates over a range which is applicable to cask drop events. Fracture toughness of DCI was thus measured at various rates to assess the effect of rate on upper-shelf toughness.

Experimental Procedures

Material

The material tested in this program was mainly ferritic with Types I and II graphite nodules. Previous reports (8,9) have shown that this type of DCI has the highest fracture toughness properties. The composition, microstructure, and mechanical properties for the material used in this study are also available in these previous reports.

Test Method

The test technique uses a standard MTS (MTS Systems, Corp.) closed-loop servo-hydraulic frame and load cell. The load line displacement (LLD) is measured directly on the compact tension specimen using an MTS clip gage extensometer. Precision control of the total LLD is provided by a stop block - shear pin arrangement as shown schematically in Fig. 2. The total applied LLD is predetermined by the stop block arrangement. The load on the shear pin (but not on the specimen) rises rapidly after the stop block is contacted, which causes the pin to fail and which further allows the sample to be immediately unloaded. The experimental set-up provides precise control over total applied LLD, as well as limiting the time duration of the loading event. In addition, the special fixturing allows a constant LLD rate to be maintained during the test. A more detailed description of the apparatus and test technique is provided in Reference 10.

Multiple specimen tests were performed according to E 813-87 in which four to five identically precracked specimens were used to determine the R-curve at each loading rate. Each specimen was pulled at a constant LLD rate to a specific LLD value. For our specimen geometry, total LLD's in the range of 0.6 to 1.5 mm (0.025 to 0.060 in) led to crack extensions in the range of 0.25 to 1.65 mm (0.010 to 0.065 in). The integration of the load-LLD trace for each specimen leads to a "J" energy which correlates to the specific amount of crack growth which took place during the loading event. The crack extension (corresponding to an input energy) was determined by examining the fracture surface post-test and measuring the actual crack growth on a macrophotograph (@ 6.7X magnification). The four/five specimens thus produced the data for a "J" versus crack extension plot (a.k.a. the R-curve). The power law fit of the J-crack extension data was then used to find the extrapolated initiation (or "critical") value for J, called J_{Ic}, as specified in E 813-87.

All tests were conducted at -29°C (-20°F) to meet the licensing requirements for hypothetical accident conditions (1). Loading rates were determined by the stroke speed of the actuator. Three test rates were used: 5, 50, and 250 mm/sec (0.2, 2, and 10 in/sec). The highest rate coincided with the maximum speed available on the test frame. The fracture toughness loading rate was reported as an average stress intensity loading rate, $\dot{K}_{JId}$. The equivalent plane-strain fracture toughness value, K_{JId}, was derived from the measured elastic-plastic J_{Id}. The stress intensity rate is then K at the time of crack initiation divided by the time from start of the test to crack initiation. The $\dot{K}_{JId}$ value was calculated since it is the most commonly reported fracture toughness loading rate parameter, and it is also a value which is of specific interest for actual design analysis.

Experimental Results

Table 1 lists the loading rates used in this work along with the times to initiation and the resultant average stress intensity loading rates. Fig. 3 shows the J - crack extension plots for the three loading rates. All of the specimens behaved in an elastic-plastic fashion for all of the loading rates investigated, and fracture occurred by ductile tearing only. It is clear from the figure that all the J - crack extension data, regardless of loading rate fall on essentially the same power law (E 813-87) curve fit. The power law curve fit parameters are presented in Fig. 3. The E 813-87 determination of J_{Id} from the data in Figure 3 is 64 kJ/m^2 (368 in-psi), which translates (via Eqn. 1) into a K_{JId} of 110 $MPa\text{-}m^{1/2}$ (100 $ksi\text{-}in^{1/2}$). The initiation fracture toughness which was determined in these experiments thus, did not vary with loading rate.

Discussion

The results from the tests on the compact tension specimens show that there is no effect of loading rate on the fracture toughness for $4 \times 10^2 < \dot{K} < 3 \times 10^4$ $MPa\text{-}m^{1/2}/sec$ (the values are approximately the same in $ksi\text{-}in^{1/2}/sec$ units). This result is extremely important with respect to ductile cast irons being used in transportation applications. Recent analytic work at Sandia (11) has shown that a stress-intensity rate for a cask drop test in which there are no energy absorbing impact limiters produce a worse case stress-intensity rate of $\dot{K} = 1 \times 10^4$ $MPa\text{-}m^{1/2}/sec$. This rate corresponds to a time to peak load in the 2 - 3 msec range. A cask equipped with energy absorbing impact limiters normally has a time to peak load in the 20 - 40 msec range; acceleration ("G") values and stress-intensity rates would be commensurately lower. The cask loading rate (under the most severe hypothetical accident conditions) thus falls within the range of loading rates experimentally applied in this fracture toughness testing program. The fracture toughness (rigorously determined) of DCI is essentially a constant over this range, and thus does not present any unusual concerns.

Previously published work (6) has established the static fracture toughness (J_{Ic}) of this alloy as 56 to 61 kJ/m^2 (320 - 350 in-psi). Equivalent stress intensity values are 101 to 106 MPa-m$^{1/2}$ (92 to 96 ksi-in$^{1/2}$). There is a slight increase in the upper shelf level in moving from static loading rate to the loading rates reported in this paper. Such an increase in toughness can be explained by a moderate increase in the flow stress which has been measured as the loading rate is increased (5). However, it is important to underscore that this DCI alloy did not exhibit any changes in fracture behavior for all combinations of temperature and loading rates which are required for licensing. This particular DCI alloy (ferritic with Types I and II graphite nodules) could be used in transport cask applications (in which elevated loadings rates combined with low temperatures must be considered) and still behave as an elastic-plastic material (i.e. brittle fracture will not occur). The fracture toughness determined at a static loading rate (through E 813-87) can be used in calculations for structures in which the actual loading rate is up to 3 x 10^4 MPa-m$^{1/2}$/sec, without compromising the accuracy of the fracture mechanics analysis.

In comparing the current results to the other experimental methods previously mentioned, it should be noted that the loading rates used in this work do not quite reach those applied by the other techniques. Nonetheless the data taken during these experiments provides a strong indication that the major difference between the results presented here and those measured by other methods is due primarily to experimental technique, and not to the small differences in maximum applied loading rate. In the PCVN testing, the LLD is not directly measured, but must be calculated from the measured velocity of the tup (just before the sample is contacted and just after the sample is completely broken). Further, the point of fracture initiation is assumed to be coincident with maximum load. Both of these assumptions can introduce substantial error; certainly enough to cause the upper shelf to apparently decrease from 102 to 71 MPa-m$^{1/2}$ (93 to 65 ksi-in$^{1/2}$). For a measurement to be in compliance with ASTM E 813-87, a direct measurement of displacement must be made. Also, the application of the total displacement which the sample receives must be controlled in order to make an accurate assessment of how much the crack length is changed for a given strain energy input. The (single specimen) PCVN test does not approach the requirements imposed by the ASTM standard test method, and thus, it is not surprising to suggest that the resulting fracture toughness value can be in considerable error.

The method used for the three point bend specimens tested in the drop tower set-up is more controlled, but still falls short of the requirements imposed by E 813-87. The test set-up used in the three point bend experiments measures the displacement of the tup, not the sample. Control of the total displacement (of the tup) is accomplished precisely with the stop blocks. The specimen itself however, (driven by inertial effects) may continue to move (i.e., bend) and cause additional crack growth. The LLD is not measured directly on the three point bend specimen, and the motion of the sample after the tup has contacted the stop blocks cannot be exactly determined. Since the entire load-displacement behavior is not measured, the full value of J for each sample is underestimated. This is an "inertial" effect, which can significantly lower the measured value of initiation toughness compared to the more rigorous values determined through the procedures of E 813-87.

In the experiments conducted in this research (on compact tension specimens) at the highest loading rate (actuator rate = 250 mm/sec (10 in/sec)), the increase in the sample LLD after the stop block was encountered was directly measured. An example of this is shown in Figure 4. The sample motion (after the stop block was contacted) occurred prior to the failure of the shear pin, and the load and LLD on the sample continued to be measured until the failure of the shear pin relieved the load on the sample. This provided a direct measurement of the (strain) energy available to drive the extension of the crack after the stop block was contacted. In some samples, the energy measured after the stop block was contacted was as high as 25-30% of the total measured during the entire test. This energy was not accounted for in the three point bend tests. Thus it appears that differences in experimental procedure can account for the discrepancy in measured values between the methods used in this research and those used previously by others.

Conclusions

1. The fracture toughness of a fully ferritic DCI has been measured rigorously (meeting all aspects of ASTM E 813-87) as a function of loading rate. The alloy behaved as an elastic-plastic material for all conditions tested. The initiation fracture toughness was found to be 110 MPa-m$^{1/2}$ (100 ksi-in$^{1/2}$), and independent of loading rate for $\dot{K}$ from 2 x 10^2 to 3 x 10^4 MPa-m$^{1/2}$/sec, at a temperature of -29°C (-20°F).

2. The highest loading rate used in this research exceeds that which can be imparted to heavy walled transportation casks during hypothetical accident conditions which must be considered for licensing. This DCI alloy thus displays <u>no</u> anomalies in fracture toughness (as a function of loading rate - even at low temperatures) which would keep it from being considered as a viable material for transportation applications.

3. The decrease in the fracture toughness that has been found by other methods, is in all probability due to measurement technique. These other methods do not directly measure all of the data required to rigorously determine initiation fracture toughness.

References

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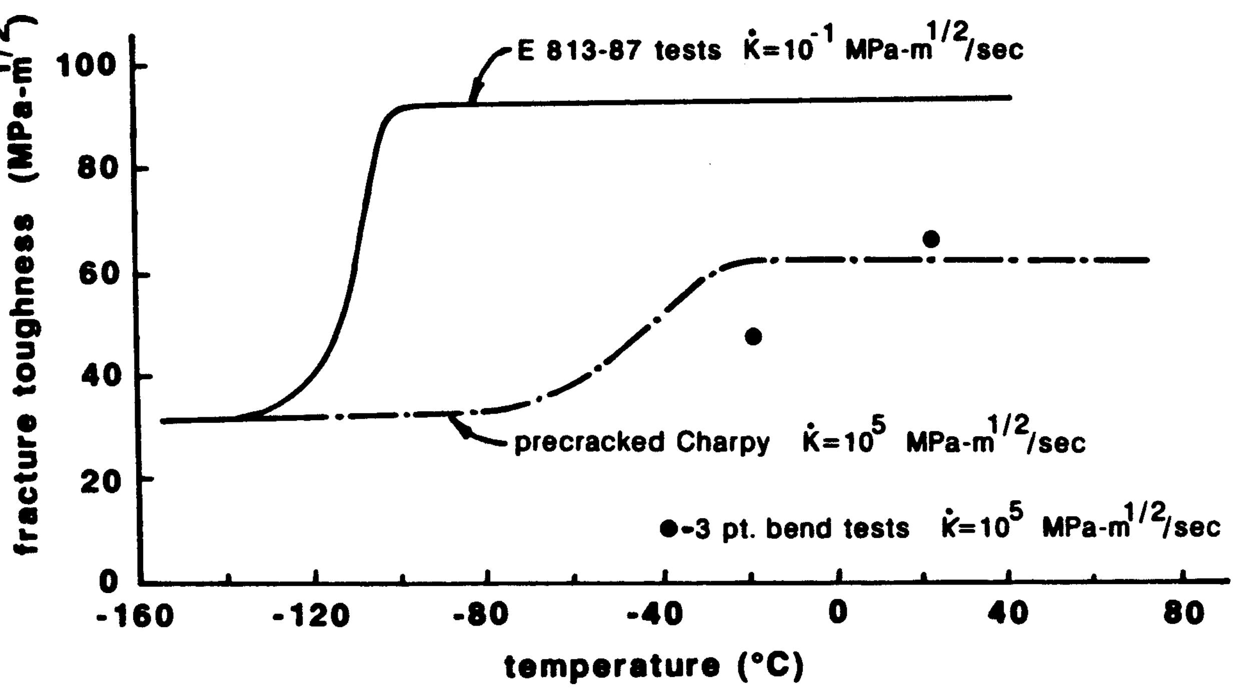
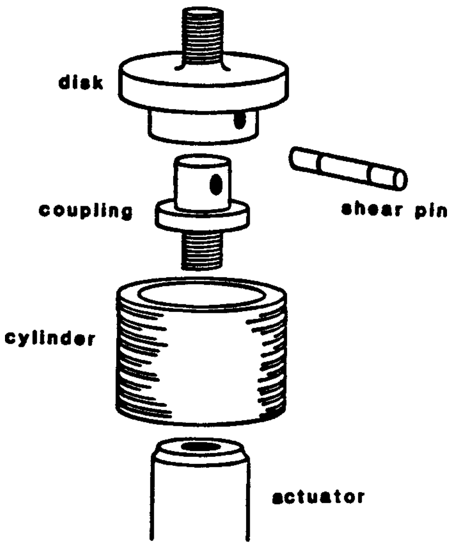
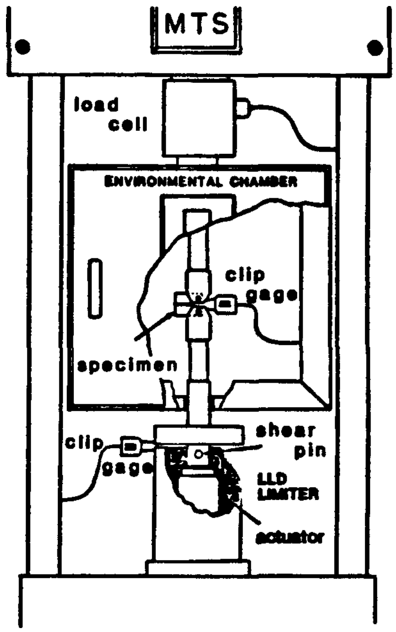


Figure 1. Comparison of static rate fracture toughness (as per ASTM E 813-87) as a function of temperature, with toughness values estimated from precracked Charpy impact and three point bend drop tower tests.



Schematic of the fixture components



Schematic representation of how the fixturing mates to the MTS frame

Figure 2. Schematics of the special fixturing and test set-up used for the elevated loading rate fracture toughness measurements.

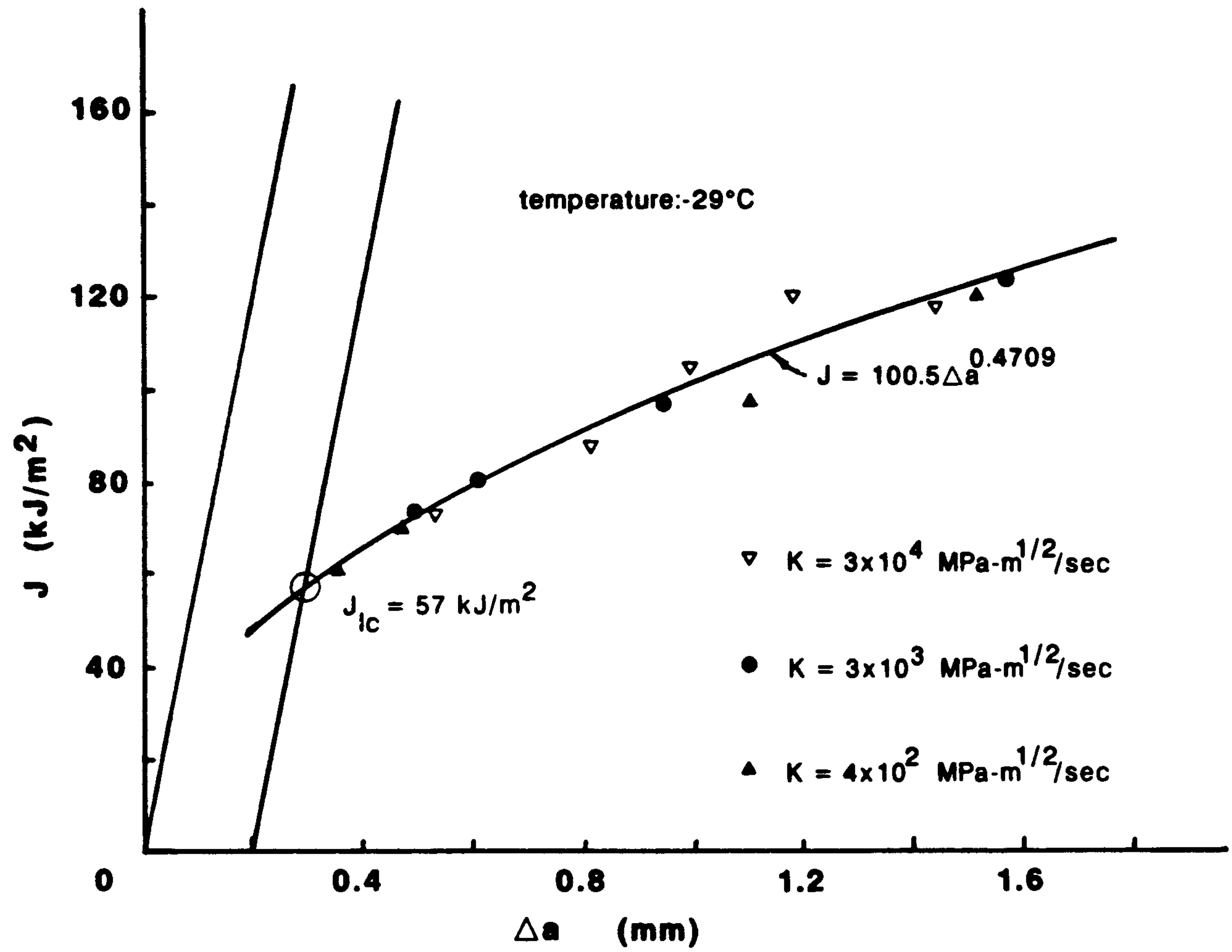


Figure 3. Fracture toughness measurements (as per ASTM E 813-87) for a DCI alloy at three different loading rates.

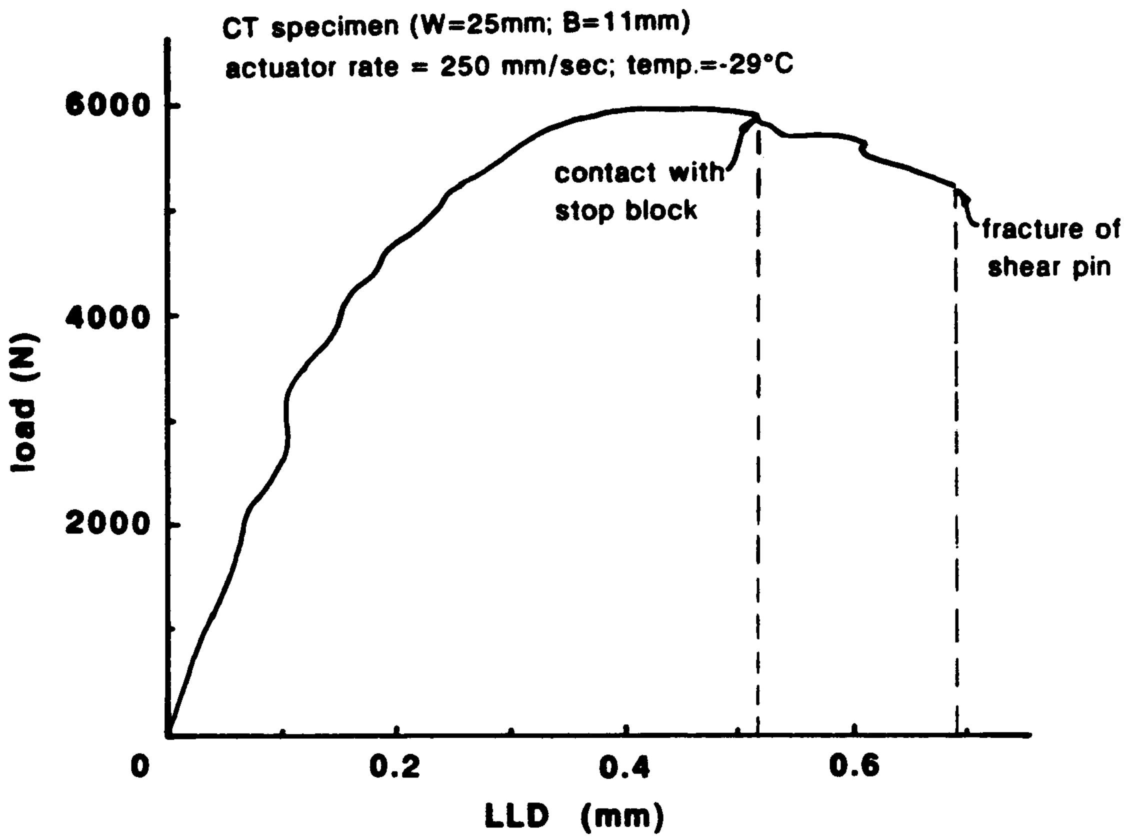


Figure 4. Th.. load - displacement record for an elevated rate fracture toughness test, which shows strain energy can continue to be measured after the stop block has been contacted.