TECHNICAL REPORT ARLCB-TR-82010

A SINGLE SPECIMEN J-BASED FRACTURE TOUGHNESS TEST FOR HIGH STRENGTH STEELS

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May 1982

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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AMCMS No. 61110191A0011

DA Project No. 1L161101A9A

PRON No. 1A2231491A1A

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: ARLCB-TR-82010	2. GOVT ACCESSION NO.: AD-A118 674
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): A SINGLE SPECIMEN J-BASED FRACTURE TOUGHNESS TEST FOR HIGH STRENGTH STEELS	5. TYPE OF REPORT & PERIOD COVERED: Final
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): J. A. Kapp and J. H. Underwood	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: US Army Armament Research & Development Command, Benet Weapons Laboratory, DRDAR-LCB-TL, Watervliet, NY 12189	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: AMCMS No. 61110191A0011, DA Project No. 1L161101A91A, PRON No. 1A2231491A1A
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Armament Research & Development Command, Large Caliber Weapon Systems Laboratory, Dover, NJ 07801	12. REPORT DATE: May 1982
	13. NUMBER OF PAGES: 25
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Presented at Fourteenth National Symposium on Fracture Mechanics, UCLA, Los Angeles, CA, 29 June - 1 July 1981.
Published in ASTM Special Technical Publication.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cracks
Toughness
J-Integral
Mechanical Testing
Charpy Specimen
Bending

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A single specimen J-based fracture toughness test has been developed which results in accurate and reliable measurements for a high strength, low alloy steel with several yield strengths. The specimen used is a deeply cracked Charpy specimen tested in slow, three-point bending. A simple plastic stress analysis was performed which identifies a single point on the load-displacement trace at which the J-integral is calculated as an estimate of fracture toughness (K_{Ic}). The method can be applied inexpensively and may be used as a quality control measure of fracture toughness.

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ACKNOWLEDGMENT

The authors wish to thank Mr. J. J. Zalinka for conducting much of the experimental work in this program, Mr. H. Weglarz for specimen preparation, and Mr. A. Hess and Mr. H. Alford for their contributions. Also we wish to thank Ellen Fogarty for preparing the manuscript.

INTRODUCTION

Fracture toughness (K_{Ic}) is a critical material property measurement that is required in order to use fracture mechanics in the design and analysis of structures. Although useful, fracture toughness is often a difficult property to measure because of several testing requirements such as those in ASTM Test Method for Plane Strain Fracture Toughness of Metallic Materials (E-399-81). One of these requirements is the large specimen size which is required when testing relatively ductile materials. Often it is physically impossible to obtain the required specimens from actual structural components. Even if sufficient material is present to obtain the required specimens, the costs of manufacturing such specimens can be prohibitive. The purpose of this study is to use a smaller and more easily manufactured specimen that will provide a measure of fracture toughness comparable to K_{Ic} using J-integral analysis.

The basic criteria for the method described here are: (a) the specimen is easily machined from even relatively thin portions of structural components, (b) the method yields a reliable measure of the fracture toughness comparable with K_{Ic}, and (c) the method is applicable over a range of yield strength and fracture toughness properties. The specimen chosen is similar to the Charpy specimen used in notched bar impact testing; see ASTM Methods for Notched Bar Impact Testing of Metallic Materials (E23-81). The specimen is deeply precracked such that during fracture by slow bending the remaining ligament is subjected to plastic deformation before the onset of crack growth. The method is applied here to steel specimens with 0.1 percent offset yield strengths which vary from 820 MPa to 1230 MPa and with K_{Ic} values which vary from 128 MPa(m)$^{1/2}$ to over 200 MPa(m)$^{1/2}$.

The method described here is intended to be a complement to the strength ratio method described by Succop and Brown[1] as an estimate of K_{Ic}. Succop and Brown proposed that the maximum load from a slow, three-point bend test of a precracked Charpy bar can be used to make an estimate of K_{Ic}. They showed that for moderate deviations from the limited crack-tip plasticity conditions of a K_{Ic} test, the maximum load or the nominal strength from the Charpy bar test correlates well with K_{Ic}. We propose that the J-based method described here can be used over a wide range of crack-tip plasticity conditions, that is, from about the point where the Succop and Brown method no longer applies to a point well into general yielding of the uncracked ligament of the Charpy specimen.

PROCEDURES

The specimen has the same overall dimensions as the Charpy specimen. It was loaded as shown in Figure 1. The specimen was deeply precracked, nominally to $0.6 < a/W < 0.7$, such that the uncracked ligament was subjected to plastic flow prior to crack extension. The deep crack is required for application of the approximate and much simplified J-integral analysis which is now commonly used.[2,3] The deep precrack was not obtainable in all the alloys tested; in

[1] Succop, G. and Brown, W. F., Jr., "Estimation of K_{Ic} From Slow Bend Precracked Charpy Specimen Strength Ratios," Developments in Fracture Mechanics Test Methods Standardization, ASTM STP 632, W. F. Brown, Jr., and J. G. Kaufman, Eds., ASTM, 1977, pp. 179-192.

[2] Rice, J. R., Paris, P. C., and Merkle, J. G., "Some Further Results of J-Integral Analysis and Estimates," Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, ASTM, 1973, pp. 231-245.

[3] Clarke, G. A., Andrews, W. R., Begley, J. A., Donald, J. K., Embley, G. T., Landes, J. D., McCabe, D. E., and Underwood, J. H., "A Procedure for the Determination of Ductile Fracture Toughness Values Using J Integral Techniques," J. of Testing and Evaluation, Vol. 7, No. 1, January 1979, pp. 49-56.

some alloys a crack of depth a/W between 0.5 and 0.6 was used. The method described here is not used to measure J_{Ic} as outlined in Reference 3, but rather to determine the value of J-integral which is the equivalent of the plane strain fracture toughness, K_{Ic}. This means that J must be measured only at the one specified value of crack extension, (Δa), which corresponds to K_{Ic}. Ernst et al[4] analyzed crack extension under large scale crack-tip plasticity conditions. They proposed that the load-displacement trace of a specimen containing a crack which grows under J-controlled conditions can be used to measure both crack extension and the value of J at different values of crack extension. In simplified terms this may be considered as an extension of elastic compliance analysis into the elastic-plastic regime.

The method proposed by Ernst et al[4] has been successfully applied by Joyce et al[5] for compact specimens of HY130 steel. In their study, what they call a "key curve" was developed for the load-displacement characteristics of a single specimen type (compact) for a given material (HY130). Their method involved numerical calculations and was restricted to one specimen type and material. The restrictions arose primarily from material properties. Using the compact

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[3] Clarke, G. A., Andrews, W. R., Begley, J. A., Donald, J. K., Embley, G. T., Landes, J. D., McCabe, D. E., and Underwood, J. H., "A Procedure for the Determination of Ductile Fracture Toughness Values Using J Integral Techniques," J. of Testing and Evaluation, Vol. 7, No. 1, January 1979, pp. 49-56.

[4] Ernst, H., Paris, P. C., Russow, M., and Hutchinson, J. W., "Analysis of Load-Displacement Relationships to Determine J-R Curve and Tearing Instability Material Properties," Fracture Mechanics, ASTM STP 677, C. W. Smith, Ed., ASTM, 1979, pp. 581-599.

[5] Joyce, J. A., Ernst, H., and Paris, P. C., "Direct Evaluation of J-Resistance Curves From Load Displacement Records," Fracture Mechanics: Twelfth Conference, ASTM STP 700, ASTM, 1980, pp. 222-236.

specimen with this material, the uncracked ligament was subject to part elastic, part plastic deformation. The extent of the plasticity controlled the load-displacement record. The plastic deformation was determined by material properties, limiting the applicability of the method. The "key curve" method was shown to be very successful in determining J-R curve for the HY130 material.

We used an approach similar to but simpler than that of References 4 and 5 to determine the point on the load-displacement trace at which to measure J which corresponds to K_{Ic}. The intent of the work was not to generate J-R curves and the simpler use of the approach was justified. If the specimen used is precracked deeply enough, it can be assumed that the remaining ligament is subjected to gross plasticity prior to the onset of crack growth. The maximum load which can be supported by such a ligament may be calculated by assuming rigid plastic material behavior. This load, as will be shown, is a function of the flow stress of the material and the remaining ligament b (b = W-a). As the crack grows, the remaining ligament decreases, and the load which can be supported by the ligament decreases. Thus, if conditions are correct, the amount of load drop after the maximum load should be related to the amount of crack extension. In prior work,[6] on materials similar to those used in this

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[4]Ernst, H., Paris, P. C., Russow, M., and Hutchinson, J. W., "Analysis of Load-Displacement Relationships to Determine J-R Curve and Tearing Instability Material Properties," Fracture Mechanics, ASTM STP 677, C. W. Smith, Ed., ASTM, 1979, pp. 581-599.

[5]Joyce, J. A., Ernst, H., and Paris, P. C., "Direct Evaluation of J-Resistance Curves From Load Displacement Records," Fracture Mechanics: Twelfth Conference, ASTM STP 700, ASTM, 1980, pp. 222-236.

[6]Underwood, J. H., "J_{Ic} Results and Methods With Bend Specimens," Fracture Mechanics, ASTM STP 677, C. W. Smith, Ed., ASTM, 1979, pp. 463-473.

program, the relation between crack extension and load drop was established experimentally. Here we use a plastic analysis to calculate the amount of crack extension associated with a load drop, so that the single specimen J-based test will be more generally useful.

When using a J_{Ic} type test there are certain validity requirements which must be applied to the measured toughness. The major requirement which is applicable to the test method described here is the size requirement.[3] The thickness B, and initial remaining ligament, b, must both be greater than the quantity 25 J/σ_f, where J is the provisional value of J which corresponds to K_{Ic}. If the size requirement is met, then the provisional J measured is a valid measurement of the J-integral.

ANALYSIS

The relationship for the load which can be supported by a fully plastic ligament of depth, b, can be determined by an analysis which is schematically outlined in Figure 2. The loading of the specimen is shown in Figure 2(a). The resultant moment M on a half specimen free body, Figure 2(b), is given as

$$M = PS/4 \qquad (1)$$

This moment must be balanced by the resultant couple, M_s, produced by the stresses. This couple is the sum of the moments of the two forces shown in Figure 2(c), so the moment per unit thickness of the Charpy specimen is:

[3]Clarke, G. A., Andrews, W. R., Begley, J. A., Donald, J. K., Embley, G. T., Landes, J. D., McCabe, D. E., and Underwood, J. H., "A Procedure for the Determination of Ductile Fracture Toughness Values Using J Integral Techniques," J. of Testing and Evaluation, Vol. 7, No. 1, January 1979, pp. 49-56.

$$\frac{M_s}{B} = -\frac{-\sigma_F b}{2} \cdot \frac{b}{4} + \frac{+\sigma_F b}{2} \cdot \frac{b}{4}$$

and

$$M_s = \frac{\sigma_F B b^2}{4} \qquad (2)$$

where σ_F is the flow stress of the material, the average of the ultimate stress and the 0.1 percent offset yield strength. Equation (2) can be compared with the expression[2] for the limit moment of an elastic-perfectly plastic notched specimen in pure bending:

$$M_\ell = 0.36\ Bb^2 \sigma_F \qquad (3)$$

The constant in Eq. (3) is significantly larger than that in Eq. (2). This may be due to an increase in effective flow stress near the notch in the limit solution, whereas no such increased σ_F is included in the derivation of Eq. (2). However, it will be shown below that the constants in Eqs. (2) and (3) do not affect the results and conclusions here. Equating Eqs. (1) and (2) results in an expression which relates the load which can be supported by a fully plastic ligament and the ligament depth

$$P = \frac{\sigma_F B b^2}{S}$$

This may be normalized to obtain an expression in terms of nondimensionalized remaining ligament depth (b/W):

$$P = \frac{\sigma_F B W^2}{(S/W)} \left(\frac{b}{W}\right)^2 \qquad (4)$$

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[2]Rice, J. R., Paris, P. C., and Merkle, J. G., "Some Further Results of J-Integral Analysis and Estimates," Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, ASTM, 1973, pp. 231-245.

From Eq. (4) it is apparent that an increase in crack length, which corresponds to a decrease in b/W, results in a decrease in the load which can be supported. Using Eq. (4) an expression can be developed which relates the relative load drop corresponding to a given amount of crack growth. Immediately prior to crack growth the maximum load P_{max} occurs, and it corresponds to the value of the remaining ligament ahead of the fatigue precrack:

$$P_{max} = \frac{\sigma_F BW}{(S/W)} \left(\frac{b}{W}\right)_o^2 \quad (5)$$

After the crack has grown an amount Δa, the load which the specimen can support, $P_{\Delta a}$, is then related to the decreased remaining ligament $(b/W)_{\Delta a}$ by

$$P_{\Delta a} = \frac{\sigma_F BW}{(S/W)} \left(\frac{b}{W}\right)_{\Delta a}^2 \quad (6)$$

Equations (5) and (6) can be combined to give an expression for the relative load drop which accompanies an amount of crack growth Δa and the associated change in b/W:

$$\frac{P_{\Delta a} - P_{max}}{P_{max}} = \frac{(b/W)_{\Delta a}^2 - (b/W)_o^2}{(b/W)_o^2} \quad (7)$$

Although Eq. (7) is derived assuming the simple stress distribution shown in Figure 2(c), it can be seen that the same result would be obtained if a different stress distribution were used. For example, if Eq. (3), the expression for the limit moment, had been used in place of Eq. (2), the final result in Eq. (7) would have been the same. The constants and all other terms other than ligament terms would vanish. The implications of this are that the test method based on this approach will not be sensitive to details of material yielding or specimen geometry other than ligament size.

Equation (7) can be rearranged to give a parameter which is easily compared with experimental measurements of load drop and crack growth. Expanding both sides of Eq. (7) it is easily shown that

$$\frac{P_{\Delta a}}{P_{max}} = \frac{(b/W)^2_{\Delta a}}{(b/W)^2_0}$$

or

$$(b/W)^2_0 = \frac{P_{max}}{P_{\Delta a}} (b/W)^2_{\Delta a} \qquad (8)$$

This equation gives a relationship between parameters which are a function of material properties and specimen geometry. A plot of Eq. (8) compared with experimental measurements will give an indication of the validity of the simple rigid plastic stress analysis as a measure of crack growth.

MATERIAL

Measurements were taken on the alloy steel which is commonly used in the manufacture of large caliber cannon components, ASTM A723, Grade 2. Four different tempering conditions were tested in this study. The resulting strength and fracture toughness of each condition are given in Table I. The test specimens were obtained from forged cannon components in the circumferential orientation for tensile tests and in the C-R orientation for fracture toughness tests.

TABLE I. MECHANICAL PROPERTIES OF STEELS TESTED

Temper	Yield Strength σ_{ys}, 0.1% MPa	Ultimate Strength MPa	Fracture Toughness Mean $MPa(m)^{1/2}$	Standard Deviation $MPa(m)^{1/2}$	$\frac{2.5}{B}\left(\frac{K}{\sigma_{ys}}\right)^2$
1	820	990	147	12.9	3.2
2	880	970	235	22.7	7.0
3	1050	1150	155	2.1	2.1
4	1230	1320	128	5.7	1.1

Two fracture toughness specimens were obtained for each temper and tested according to ASTM Method E399. However, as shown in Table I, the size requirement of E399 was not met. The ratio of $2.5(K/\sigma_{ys})^2$ to specimen thickness, B was generally more than unity. All other requirements were met. We believe that the fracture toughness values in Table I, although not K_{Ic} values, are the equivalent of K_{Ic}. Prior work[7] with similar materials using both J_{Ic} and K_{Ic} test methods has shown that results from somewhat undersized specimens still give a good measure of K_{Ic}. A possible exception to this in the tests here is the result from the temper 2 material.

[7]Underwood, J. H., "The Equivalence of K_{Ic} and J_{Ic} Fracture Toughness Measurements in Ni-Cr-Mo Steels," Experimental Mechanics, Vol. 18, No. 9, pp. 350-355, September 1978.

CRACK GROWTH AND ASSOCIATED LOAD DROP

To use Eq. (7) to determine the point on the load-displacement trace at which to take the J measurement, the amount of crack growth first must be selected. Appropriate guidance for this selection is the K_{Ic} test procedure. The largest crack growth allowed in the K_{Ic} procedure is two percent, so depending upon the toughness of material and the size of specimen, the crack growth associated with a K_{Ic} value is between zero and two percent. Based on this, a one percent crack growth criteria would be a reasonable selection. Such a selection gains further support from the previous work[7] with materials very similar to those studied here. In that work J calculated at 0.5 mm crack growth was a good measure of K_{Ic} using specimens of about 50 mm crack length, that is about one percent crack growth. Based on the above rationale, one percent crack growth will be used in this work as the criteria for determining the load drop and associated J value which corresponds to K_{Ic}.

The procedure used in the testing was to precrack the sample to a/W of approximately 0.6 to 0.65 and test in slow three-point bending, measuring load versus displacement. After the maximum load was reached during each test the load was allowed to drop substantially, and then the specimen was unloaded before gross fracture had occurred. Figure 3 shows two typical load-displacement traces. The specimens were then heat tinted at 320°C, fractured, and measured for crack growth at the 1/4, 1/2, and 3/4 W points on the fracture surface. The load drop required to cause an average crack growth corresponding to

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[7]Underwood, J. H., "The Equivalence of K_{Ic} and J_{Ic} Fracture Toughness Measurements in Ni-Cr-Mo Steels," Experimental Mechanics, Vol. 18, No. 9, pp. 350-355, September 1978.

one percent of a/W was determined using Eq. (7). This load occurring after P_{max} was found on the load-displacement trace and used to calculate the value of J which corresponds to K_{Ic}.

Figure 4 is a comparison of the experimentally measured parameter $P_{max}(b/W)^2_{\Delta a}/P_{\Delta a}$ and the theoretical prediction of Eq. (8). The agreement is quite good and indicates that the use of Eq. (7) as a measure of crack growth is reasonable. Two further points may be made by Figure 4. First, it seems that Eq. (8) is not sensitive to changes in mechanical properties. For all the materials used in this study, a good estimate of crack growth is obtained when using Eq. (8). Second, the best agreement between theory (Eq. (8)) and the experimental results occurs with the strongest material (temper 4) which also had the shortest crack length. This is opposite from what would be expected if the basic criterion of gross plasticity of remaining ligament plasticity was required. This means that gross plasticity of the remaining ligament is not an important prerequisite for the application of Eq. (8) to deeply precracked Charpy specimens.

RESULTS AND STATISTICAL ANALYSIS

The fracture toughness results from the deeply cracked bend specimens are given in Table II. Shown are the measured precrack depth, $(a/W)_o$, the relative load drop calculated from Eq. (7) using $\Delta a/a_o = 0.01$, and J determined from the load-deflection curve using the area, A, under the curve up to the point of the load drop. J is calculated from

$$J = 2A/Bb_o \tag{9}$$

the expression for three-point bend specimens.[3] The J values are converted to K, using $K = [EJ/(1-\nu^2)]^{1/2}$, for comparison with the fracture toughness values in Table I.

The important comparison of results is between the Table II values of $[EJ/(1-\nu^2)]^{1/2}$ from bend tests and the Table I values of fracture toughness. Statistical analyisis is used to quantify this comparison. The statistics involve considering the types of measurements from each temper as normal distributions with means and standard deviations as measured, and then determining the probability that the means of these two distributions are statistically equivalent. The statistical test used is the same as that of some recent work.[8]

This statistical test is applicable only if it can be shown that the two data sets to be compared are normally distributed. This is accomplished through the application of the Kolmogorov-Smirnov test.[9] This test compares the measured distribution with the theoretical normal distribution having the same mean and standard deviation. If the maximum difference between distributions is less than a certain value which is a function of sample size and confidence level, then the measured data set is normally distributed. All

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[3] Clarke, G. A., Andrews, W. R., Begley, J. A., Donald, J. K., Embley, G. T., Landes, J. D., McCabe, D. E., and Underwood, J. H., "A Procedure for the Determination of Ductile Fracture Toughness Values Using J Integral Techniques," J. of Testing and Evaluation, Vol. 7, No. 1, January 1979, pp. 49-56.

[8] Underwood, J. H. and Kapp, J. A., "Benefits of Overload for Fatigue Cracking at a Notch," Fracture Mechanics: 13th Conference, ASTM STP 743, Richard Roberts, Ed., American Society for Testing and Materials, 1981, pp. 48-62.

[9] Bowker, A. H. and Lieberman, G. T., Engineering Statistics, Prentice-Hall, Inc., Englewood Cliffs, NJ.

TABLE II. RESULTS FROM THE DEEPLY CRACKED BEND TESTS

Temper	Measured $(a/W)_o$	Calculated $\frac{P_{1\%} - P_{max}}{P_{max}}$	Fracture Toughness $[EJ/(1-\nu^2)]^{1/2}$ $MPa(m)^{1/2}$	Table I $MPa(m)^{1/2}$	Probability of Same Mean
1	.664	-.039	162		
	.678	-.042	147		
	.673	-.041	169		
	.670	-.040	163		
		Mean	160	147	0.90
		Std. Deviation	9.6	12.9	
2	.649	-.037	205		
	.670	-.040	192		
	.657	-.038	205		
	.639	-.035	213		
		Mean	204	235	0.80
		Std. Deviation	8.7	22.7	
3	.671	-.040	163		
	.658	-.038	158		
	.655	-.038	141		
	.623	-.033	153		
		Mean	154	155	> 0.95
		Std. Deviation	9.3	2.1	
4	.606	-.031	135		
	.590	-.029	136		
	.552	-.025	131		
	.542	-.024	129		
		Mean	133	128	> 0.95
		Std. Deviation	3.4	5.7	

of the data measured in this study passed the Kalmogorov-Smirnov test. In addition, prior K_{Ic} test programs, such as that of Reference 10, have shown that fracture toughness measurements are generally normally distributed.

To determine the probability that the K-based tests and the J-based deeply cracked bend tests produce a statistically equivalent mean value of fracture toughness, a statistical parameter d is defined:

$$d = \frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}} \qquad (10)$$

where μ_1 and μ_2 are the mean values of the K results and the J results respectively and σ_1 and σ_2 are the standard deviation of the K and J results respectively. Using this parameter and an operating characteristic curve[8] which is a function of sample size and confidence level, the probability that the two tests measure a statistically equivalent mean value of toughness can be determined. Using the values of μ and σ from Tables I and II, this probability is determined using a 99 percent confidence level and listed in Table II.

It is apparent from the probability values that the deeply precracked bend tests described above give a generally good representation of fracture toughness of the materials used in this study. The only data which raises concern is that of temper 2. The decreased probability that the two testing procedures give an equivalent value of toughness for temper 2 can be related to

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[8]Underwood, J. H. and Kapp, J. A., "Benefits of Overload for Fatigue Cracking at a Notch," Fracture Mechanics: 13th Conference, ASTM STP 743, Richard Roberts, Ed., American Society for Testing and Materials, 1981, pp. 48-62.

[10]Underwood, J. H. and Kendall, D. P., "Cooperative Plane Strain Fracture Toughness Tests With C-Shaped Specimens," J. of Testing and Evaluation, Vol. 6, No. 5, September 1978, pp. 296-300.

a specimen size criteria. The size requirement of ASTM Method E399 was more seriously breached in the temper 2 fracture toughness tests than in the other tests, see again Table I. This led to the relatively large standard deviation of the temper 2 fracture toughness tests, that is, 22.7 compared with 235 $MPa(m)^{1/2}$ mean, which is 10 percent. This relative standard deviation is larger than any of the other test sets here and larger than expected for fracture toughness tests.[10]

Another comparison of the two test methods is shown in Figure 5. In this figure, the average values of toughness measured using the K_{Ic} method and the load drop J method are plotted. The error bars indicate the maximum and minimum measurements of toughness using the two methods. If the two methods are exactly equivalent, the plot of the average values for each temper condition should fall on the diagonal line. The statistical analysis described above can be thought of as assigning a numerical probability that the average values of an infinite number of samples tested using each method would indeed fall on the diagonal line. From Figure 5 it is apparent that the fracture toughness is accurately measured with the load drop J method for the temper 3 and temper 4 steels. Additional data gathered from the temper 1 steel would also probably yield an excellent correlation. For the very high toughness material, temper 2, the agreement is poor and it is not clear whether the load drop J technique is applicable for this material.

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[10]Underwood, J. H. and Kendall, D. P., "Cooperative Plane Strain Fracture Toughness Tests With C-Shaped Specimens," J. of Testing and Evaluation, Vol. 6, No. 5, September 1978, pp. 296-300.

At this point, there seems to be a maximum limit of measurement using the load drop technique. The data shows that for steels the load drop method yields good estimates of K_{Ic} values up to about 160 $MPa\sqrt{m}$, but seems to underestimate K_{Ic} values of about 235 $MPa\sqrt{m}$. The average of these two K_{Ic} values (about 200 $MPa\sqrt{m}$) may be considered as a first approximation of the upper limit for this measurement technique.

SUMMARY AND PROPOSAL

Important features of the test procedure are:

a. A deeply precracked, slowly loaded, three-point bend specimen with overall dimensions of a Charpy specimen.

b. Measuring point based on one to two percent crack growth.

c. Measuring point determined by load drop, as calculated from

$$\frac{P_{\Delta a} - P_{max}}{P_{max}} = \frac{(b/W)^2_{\Delta a} - (b/W)^2_o}{(b/W)^2_o} \tag{7}$$

d. J at the load drop point calculated from

$$J = \frac{2A}{b_o B} \tag{9}$$

e. If the size requirement for the specimen is met,

$$B > 25J/\sigma_f$$

$$b_o > 25J/\sigma_f$$

Then the value of J calculated in step d above is an estimate of K_{Ic} by

$$K = \left[\frac{JE}{(1-\nu^2)}\right]^{1/2}$$

If the K value is less than 200 $MPa\sqrt{m}$.

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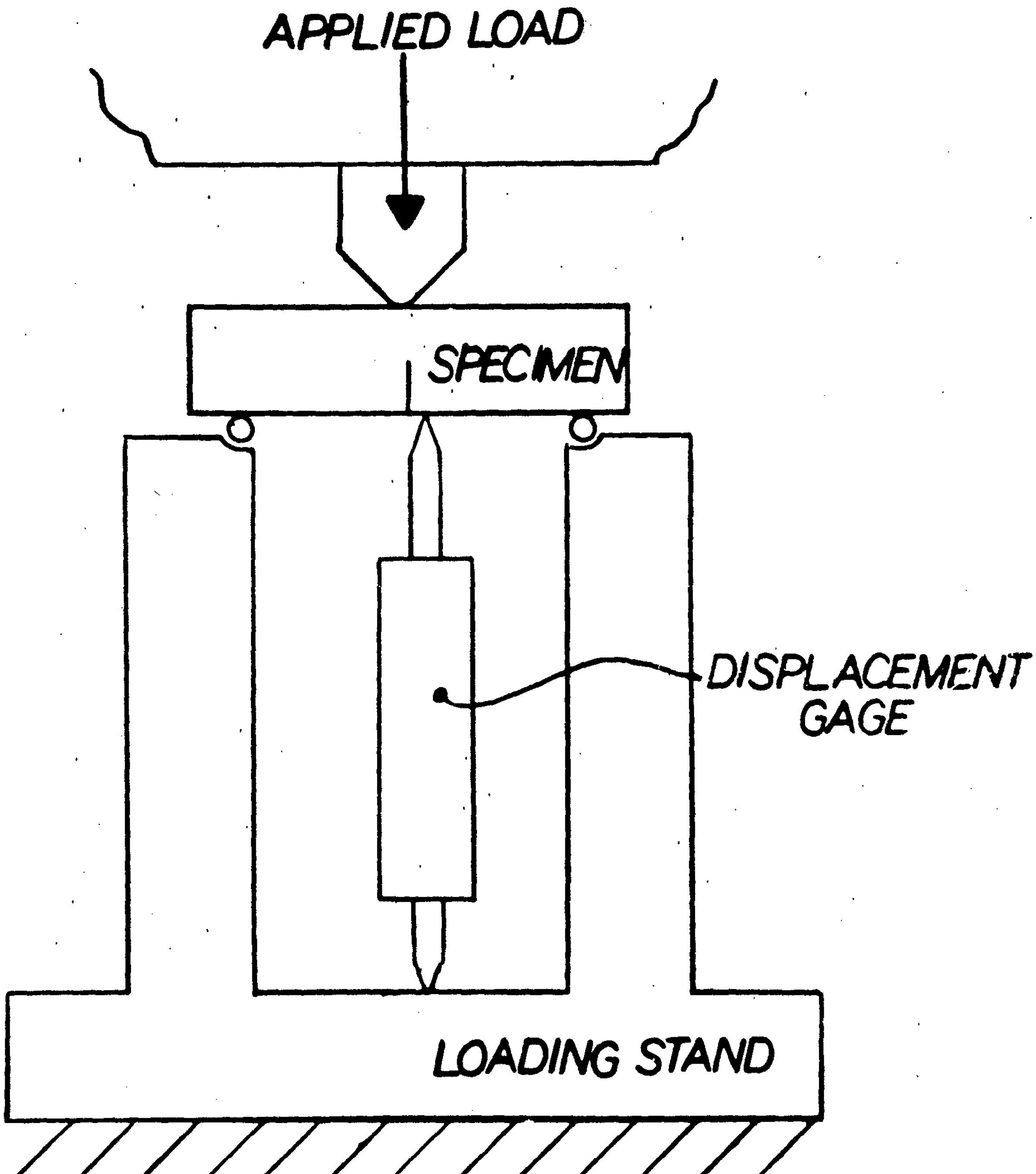

Figure 1. Schematic of Loading Apparatus Used to Measure Toughness With the Load Drop Method.

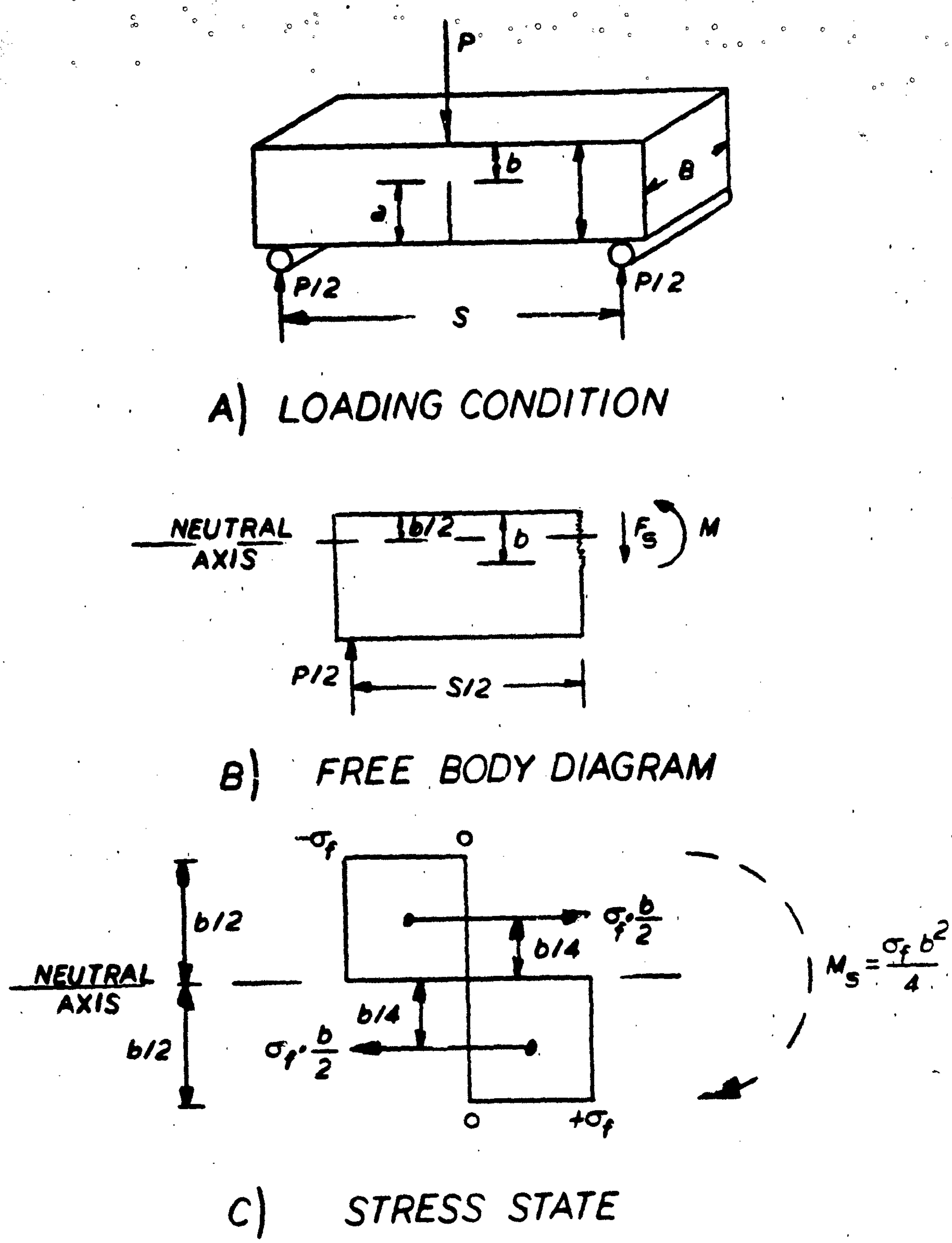

Figure 2. Diagram Used to Derive the Expression Relating Load Drop to Crack Growth.

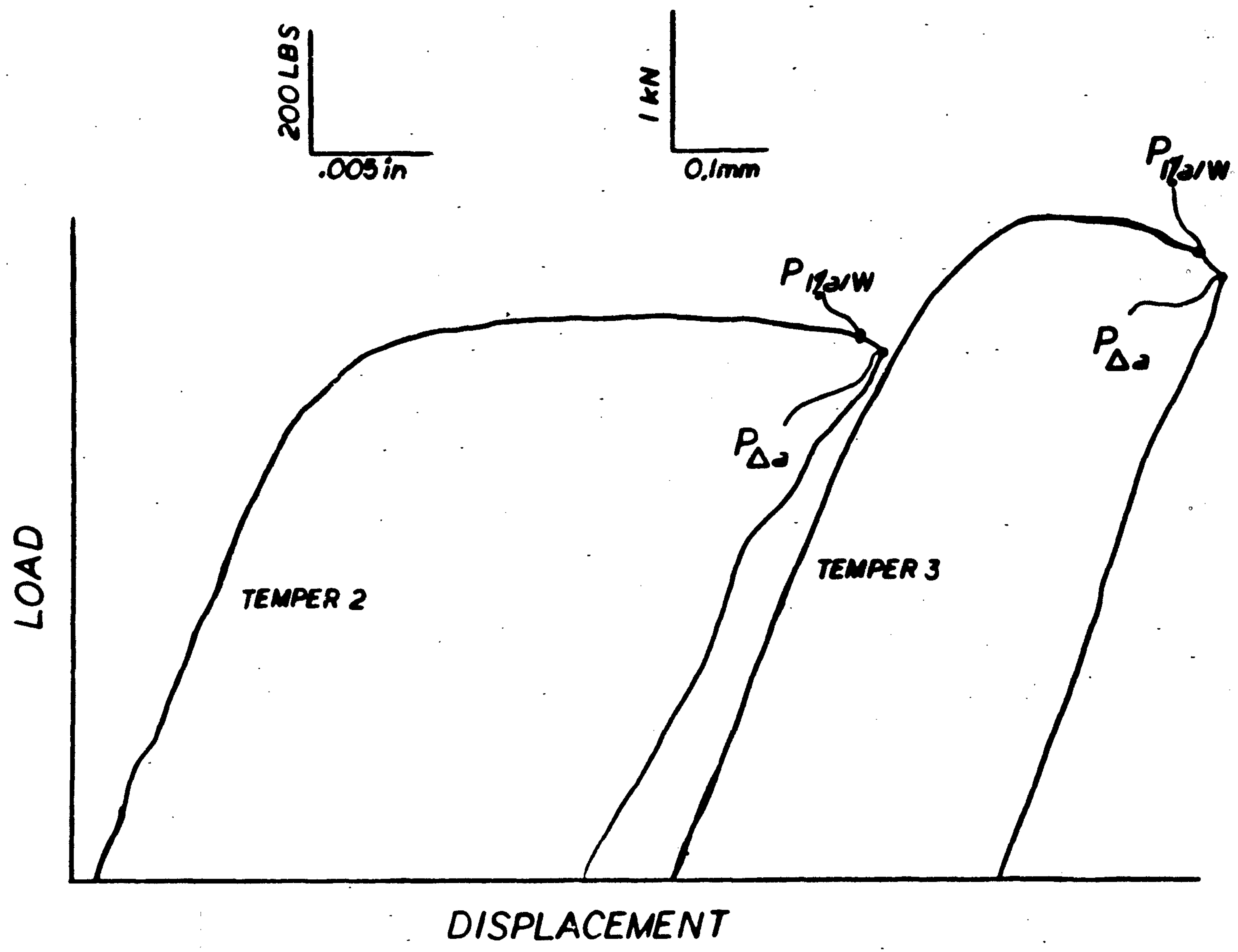

Figure 3. Typical Load-Displacement Traces for Two Different Steels.

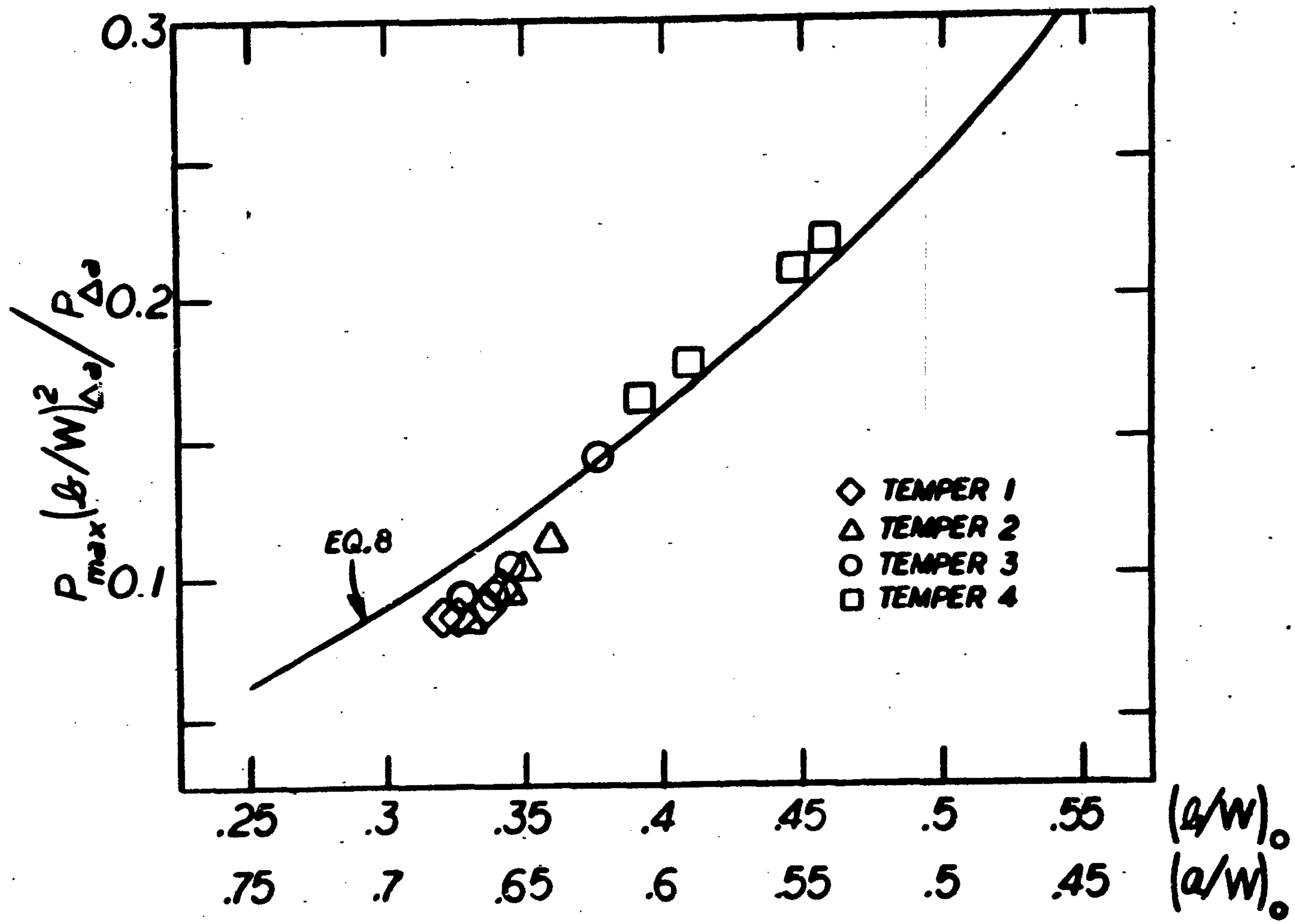

Figure 4. Comparison of Experimentally Measured Crack Growth and that Predicted by Eq. (8).

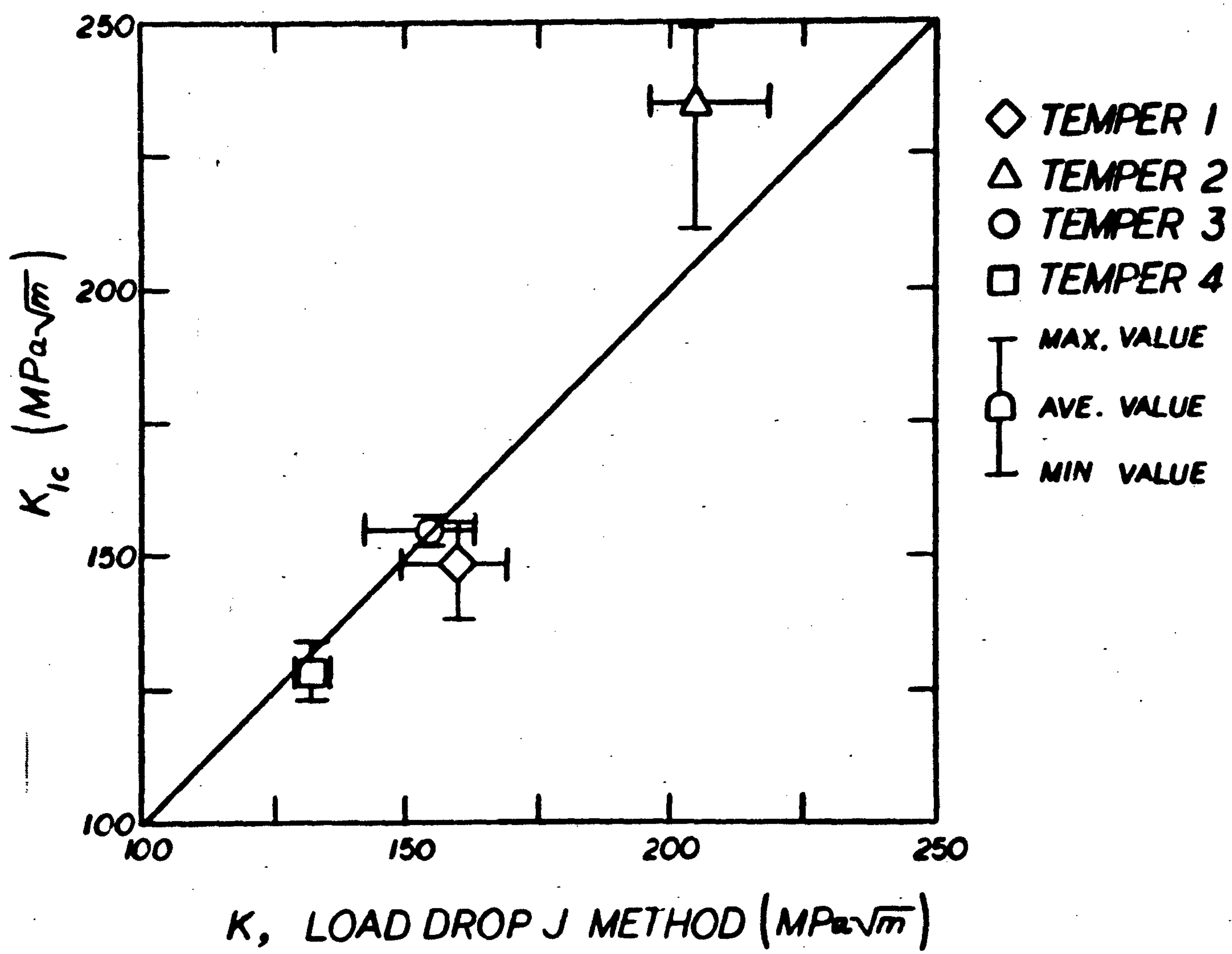

Figure 5. Comparison of Toughness Measurements Using the K_{Ic} and the Load Drop J Methods.

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