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FRACTURE TOUGHNESS TESTS AND DISPLACEMENT AND CRACK STABILITY ANALYSES OF ROUND BAR BEND SPECIMENS OF LIQUID-PHASE SINTERED TUNGSTEN

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Plane-strain fracture toughness tests were performed using the recently proposed round bar bend test procedure with a liquid-phase sintered tungsten alloy. The tests included a direct comparison of fracture toughness from rectangular and round bend specimens and measurements of load-line compliance using the unloading technique of J-integral fracture tests. Complementary displacement and crack growth stability analyses of the round bar were performed as an extension of recent work in these two areas.

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INTRODUCTION AND OBJECTIVES

Bush (ref 1) was the first to perform comprehensive fracture testing and analysis with the round bar bend specimen to measure fracture toughness of power-generation turbine rotors. Following this work closely, Underwood and Woodward proposed a standard test specimen and wide range stress-intensity factor expression for fracture testing with round bar specimens (ref 2). The work in this report continues the development of the round bend bar for fracture testing. A requirement for reliable fracture testing with a new specimen configuration is direct comparison tests with a proven specimen. This was the primary objective here: the measurement of plane-strain fracture toughness using the standard ASTM method and rectangular bend specimen (ref 3) and the direct comparison of these results with round bar bend results from the same material.

Two additional objectives of the tests and analyses were to investigate the effect of the round configuration on load-line displacement of the specimen and the crack growth stability characteristics of the round specimen. Similar topics of fracture testing have been addressed by Baratta (ref 4) in elastic compliance analysis of three-point loaded beams with various notch configurations and by Baratta and Dunlay (ref 5) in crack stability analysis and tests of brittle materials using three- and four-point loaded beams. Load-line displacement is of general use in fracture testing, particularly now with the common use of unloading compliance to measure crack growth. Crack growth stability is specially important when dealing with brittle materials, such as the tungsten-based material considered here. Furthermore, the configuration of the round bar specimen raises questions about stability, because unlike rectangular specimens, through-thickness dimensions of the round bar change as the crack grows.

EXPERIMENTS

Specimens and Material

The specimen configuration for the round bar fracture tests and analyses is shown in Figure 1. This round bar configuration is well-suited to fracture tests in the L-R orientation shown in the figure, i.e., with the crack plane perpendicular to the longitudinal axis of the bar and crack growth in the radial direction. (Had our interest been with the R-L or C-R orientations, the chevron-notched or disk-shaped specimens could have been used.) This configuration is particularly useful for round bar samples of high strength materials that are difficult to machine, such as the tungsten alloy tested here. The machined flats at the ends of the bar were added to facilitate the test setup and to eliminate the point loads that would occur between the specimen and support rollers with no flat present. The flats were not modeled in the analyses here, nor was this required, since the flats decrease the specimen volume by less than 0.1 percent, in areas remote from the notch. The rectangular specimen configuration used for comparison tests and analyses was the standard bend configuration (ref 3).

The test material was 33-mm diameter bars of a liquid-phase sintered alloy composed of 90 percent tungsten, 7 percent nickel, 3 percent iron, swaged 15 percent reduction in area, and supplied by GTE Products Corporation (Towanda, PA). Nominal values of physical and mechanical properties of interest are density of 19 g/cm^3, elastic modulus, E, of 345 GPa, hardness of 400 HB (Brinell), ultimate tensile strength of 1400 MPa, and plane-strain fracture toughness of 60 MPa m$^{1/2}$. The combination of high strength and low fracture toughness is a clear indication of a relatively brittle material and a possible indication that crack growth stability may affect fracture behavior. Fracture is important for a common application of round bar configurations of this tungsten alloy, i.e., long rod ballistic penetrators (ref 6). The high density of the alloy contributes to the kinetic energy of the penetrator, however, the energy is fully useful only if the penetrator remains intact when subjected to acceleration and target impact loading. Therefore, the fracture toughness and crack growth stability properties of the alloy are important. The low toughness of the material also led to the expected problem of producing fatigue precracks, resulting in the loss of rectangular samples. As discussed later, the results of crack growth stability tests and analyses suggest an explanation for the difficulties in fatigue cracking.

Test Procedures

The pertinent procedures can be discussed in relation to Figures 1 and 2 and Table I. The rectangular and round beam specimens were tested in the general manner shown in Figure 1. The only significant deviation from the usual procedures for fracture testing of bend specimens (ref 3) was the use of bottom surface displacement, d, shown in Figure 1, as opposed to a crack-mouth displacement. A bottom surface displacement has the advantage of allowing both applied J and crack growth measurements, whereas crack-mouth displacement can be used directly only for crack growth. In the tests here, the displacement at the load line, δ, was calculated as

$$\delta = d(S/2X) \tag{1}$$

Recent work (ref 7) has shown that for the configurations in these tests, i.e., $S/2X > 0.95$ and $a/W > 0.5$, Eq. (1) is accurate within 0.4 percent.

Applied load and bottom surface displacement for round and rectangular specimens were measured using a 250-KN servohydraulic machine in displacement control. Figure 2 is a typical plot of each type of specimen, showing predominantly linear behavior, with little indication of stable crack growth or deformation before abrupt failure. However, some differences in the amount of crack growth were noted, as discussed later. Unloadings were performed periodically, as indicated in Figure 2, using a computer-controlled system of the type used for J-integral fracture toughness tests. An automated linear regression routine was applied to the unloading data to obtain the elastic compliance of the specimen for comparison with analytical results.

Following the tests, the compliance of the testing machine was measured with a large, essentially rigid block inserted between the loading heads of the machine with the two setups used in the fracture tests. A specimen was included in the two machine compliance setups, but no bending displacement was allowed. The results are shown in Table I. Note that the rigid block measurements are relatively constant with load, whereas the test setup measurements decrease with increasing load. We believe that the machine compliance measured from the test setup at the higher loads, values of δ_M/P of about 0.0059 and 0.0052 mm/KN, should be used in the crack stability analysis. The values at lower load may be due to threaded connections in the test setup and may not represent stored strain energy in the machine that could affect crack stability.

TABLE I. MACHINE COMPLIANCE MEASUREMENTS WITH VARIOUS TEST ARRANGEMENTS

Applied Load KN	Measured Machine Compliance Using Piston Displacement		
	Rigid Block mm/KN	Rectangular Setup mm/KN	Round Setup mm/KN
10	0.0031	0.0128	0.0189
20	0.0028	0.0079	0.0076
30	0.0027	0.0066	0.0059
40	0.0026	0.0059	0.0052

ANALYSES

It is recognized in fracture testing (ref 8) that even for relatively ductile materials, stable crack growth is an important requirement for accurate measurement of fracture toughness. The presence of crack stability is of even greater importance for fracture toughness tests of brittle materials (ref 9). Consider an extreme case wherein a fracture specimen of brittle material contains an initially blunt starter notch. When the specimen is loaded, it will receive higher strain energy prior to abrupt failure than a specimen with a sharp crack. The higher strain energy will lead to an incorrectly high fracture toughness result. Attempts to introduce a sharp crack by fatigue loading may be unsuccessful unless the specimen and test machine allow stable crack growth. In an unstable system, the loads must be kept low enough to prevent initiation of a crack; attempts to increase the fatigue load result in spontaneous fracture, as experienced in this study. Even if a crack has been successfully placed in a specimen and the fracture toughness test system does not allow stable crack growth, a similar situation, such as the blunt starter notch, will be present to a lesser degree, and an incorrect fracture toughness can ensue.

In order to provide guidelines for round bar tests, a crack stability analysis, which considers both the specimen configuration shown in Figure 1 and the loading system, is presented in the following paragraphs. A prerequisite to crack stability analysis is to determine the load-line compliance of the specimen, discussed first.

Load-Line Compliance

The analysis is based on the work of Paris (ref 10) and is similar to prior work of the present authors (ref 11), therefore only the principal equations are given. The normalized load-line compliance of the idealized cracked round specimen is

$$\delta EB/P = (4/3\pi)(S/D)^3 \, [1+2(1+\mu)/(S/D)^2]$$

$$+ \, 4(S/D)^2 \int_0^{A_n} [\alpha^{3/2}/(1-\alpha^{7/2})] \, [f(\alpha)]^2 \, d\alpha \qquad (2)$$

where μ is Poisson's ratio, taken as 0.3 here; α is normalized crack depth, a/D, for the round specimen; and A_n is normalized crack area of the round beam, given by

$$A_n = A/D^2 = [1/4][\cos^{-1}(1-2\alpha) - 2(1-2\alpha)\{(\alpha(1-\alpha)\})^{1/2}] \qquad (3)$$

where A is the cracked area of the round beam. The function $f(\alpha)$ represents the following wide range expressions that were fitted to experimental and numerical stress intensity results (ref 2) for cracked round beams for various span-to-diameter, S/D, ratios:

$$f(\alpha) = (K/D^{5/2}PS)(1-\alpha)^2/\alpha^{1/2} = 3.75 - 10.93\alpha + 20.05\alpha^2 - 19.93\alpha^3 + 7.56\alpha^4$$

$$4.00 \leq S/D \leq 6.67 \quad ; \quad 0 \leq \alpha \leq 1 \qquad (4)$$

$$f(\alpha) = (K/D^{5/2}PS)(1-\alpha)^2/\alpha^{1/2} = 3.75 - 11.98\alpha + 24.40\alpha^2 - 25.69\alpha^3 + 10.02\alpha^4$$

$$S/D = 3.33 \quad ; \quad 0 \leq \alpha \leq 1 \qquad (5)$$

The integral in Eq. (2) was evaluated numerically over the limits of 0 to A_n. Equation (2) was then programmed into a computer, a stability parameter, Φ, was determined as a function of α and S/D, and the results were used in the following stability formulation.

Crack Growth Stability

Stability considerations are thoroughly presented elsewhere (refs 5,8,9), therefore only the most pertinent formulas are discussed here. Bluhm (ref 9) noted that in no instance was there stability under load control conditions for the beam cases that he examined. Therefore, only displacement control (fixed grip) conditions are considered here. The applicable equation is

$$\Phi = d^2(\delta/P)/dA^2 - [2/(\delta_T/P)][d(\delta/P)/dA]^2 \leq 0 \qquad (6)$$

where Φ is the stability parameter; (δ_T/P) is the total load-point compliance of the combination of test specimen and machine, i.e., $\delta_T/P = \delta/P + \delta_M/P$, where δ_M/P is the machine compliance including ancillary fixtures. Applying Eq. (6) to Eq. (2) leads to the following normalized expression for the crack growth stability of the round bar specimen:

$$\Phi = \frac{2d[f(\alpha)]/d\alpha}{f(\alpha)} + \frac{1+3\alpha}{\alpha(1-\alpha)} - \frac{8(S/D)^2\ \alpha^{3/2}\ [f(\alpha)]^2}{(\delta_T ED/P)(1-\alpha)^{7/2}} \leq 0 \qquad (7)$$

Notice that Eqs. (6) and (7) indicate that Φ must be equal to or less than zero to ensure stability.

As indicated by Eqs. (6) and (7), machine compliance is an important consideration in the design of a stable combination of test specimen and machine. Clausing (ref 8) relates that a normalized compliance, $(\delta_M ED/P)$, of 1.5 is typical of a very stiff loading system, such as a bolt that directly opens a crack, and 600 is typical of a flexible grip arrangement in a tension testing machine. Frame stiffness of many present day testing machines can result in $(\delta_M ED/P)$ values of about 10 to 50. (It is customary to normalize machine compliance using the same values of modulus, E, and specimen size, D or B here, as used for the test specimen compliance. This has no physical significance; it is a mathematical convenience.) Equation (7) was computer programmed to examine the effect of normalized machine compliance from 0 to 100 on stability.

DISCUSSION OF RESULTS

Fracture Toughness Tests

The results of the fracture toughness tests of rectangular and round specimens are shown in Table II. Note that the ranges of measured fracture toughness for the two types of specimen overlap, and the difference between mean values is less than the larger of the standard deviations. These indicate no significant difference between the fracture toughness from the two specimen types. Values of crack growth relative to W or D are shown in Table II, estimated from the amount of load drop that occurred at maximum load compared with the l'.iear extension of the load-displacement plot (see again Figure 2). For example, a 5 percent drop in load corresponds to a 2 percent increase in a/W. The sig ·f,-cantly larger a/D for round specimens compared to rectangular specimens is a clear indication of higher crack growth stability.

TABLE II. COMPARISON OF FRACTURE TOUGHNESS FROM RECTANGULAR AND ROUND SPECIMENS

Rectangular Specimens			Round Bar Specimens		
Crack Length a/W	Fracture Toughness MPa $m^{1/2}$	Crack Growth a/W	Crack Length a/D	Fracture Toughness MPa $m^{1/2}$	Crack Growth a/D
0.500	68.3	0.01	0.519	58.9	0.05
0.514	71.6	0.02	0.533	62.2	0.05
0.610	68.4	0.01	0.534	58.7	0.04
0.618	63.6	0.01	0.633	67.5	0.01
0.664	57.1	0.01	0.636	61.3	0.06
			0.685	60.2	0.01
	mean:	65.8		mean:	61.5
	standard deviation:	5.6		standard deviation:	3.3

Load-Line Compliance Results

A comparison of load-line compliance from the analysis described in Eqs. (2) through (5) with results from the literature is shown in Figure 3 for a wide range of crack depth. Bush's (ref 1) experimental results are shown, and a deep crack limit for the round specimen is given, developed in a manner similar to prior work (ref 2) as follows. Beginning with the expression (ref 12) for opening angle, θ, for a deep crack with applied bending moment, M:

$$\theta EB(W-a)^2 = 15.8\ M \quad (8)$$

and defining $\theta = \delta/D$, $M = PS/4$, and $B = 2D\,(a/D)^{1/2}(1-a/D)^{1/2}$, gives the following deep crack limit:

$$\lim_{a/D\to 1}[(\delta ED/P)(1-a/D)^{5/2}/(S/D)] = 1.975 \qquad (9)$$

The analytical results are in the form of the following polynomial expressions, fitted to the Eq. (2) results over the range $0 \leqslant a/D \leqslant 0.6$ and to the Eq. (9) result for $a/D = 1$

$$(\delta ED/P)(1-a/D)^{5/2} = 19.3 - 48.5\alpha + 57.1\alpha^2 - 21.3\alpha^3 \qquad S/D = 3.33 \qquad (10)$$

$$(\delta ED/P)(1-a/D)^{5/2} = 31.5 - 80.0\alpha + 95.6\alpha^2 - 39.2\alpha^3 \qquad S/D = 4.00 \qquad (11)$$

$$(\delta ED/P)(1-a/D)^{5/2} = 133 - 342\alpha + 379\alpha^2 - 157\alpha^3 \qquad S/D = 6.67 \qquad (12)$$

The agreement between experiment and analysis is good for short cracks and poorer for mid-depth cracks. This could be explained by machine and fixture compliance becoming a significant, albeit unintended, addition to specimen compliance in Bush's tests for deep cracks, considering the lower load range that would have been used for a deeply cracked specimen. Recalling Table I, such an unintended addition to specimen compliance is often possible at low loads.

A comparison of measured load-line compliance from the tests in this report with prior and current analysis is shown in Figure 4. The rectangular specimen results are compared with both the idealized crack analysis (ref 11) and the analysis that takes account of the notch as well as the crack (ref 4). The comparison is quite good. Notice that for total notch-plus-crack depths near the notch depth, i.e., near $a/W = 0.45$, the measured compliance is noticeably higher, as predicted by analysis. The round specimen results are also in good agreement with analysis and also show some indication of higher values for low a/D, as would be expected, if the effect of the notch had been investigated. This is planned for future work.

Crack Stabililty Results

Figures 5 and 6 give the key crack growth stability results of this work. The results of analysis, summarized by Eqs. (6) and (7) for the round specimen, are shown in Figure 5 for a range of span-to-diameter and depth ratios, S/D and S/W, for both specimen types. A threshold of stability parameter, $\alpha_o = (a/D)_o$ or $(a/W)_o$, is plotted as a function of S/D or S/W and $\delta_M ED/P$ or $\delta_M EB/P$, describing values of crack depth relative to specimen size above which crack growth stability is predicted. Notice, as inferred earlier, that large values of $\delta_M ED/P$ or $\delta_M EB/P$ result in decreased stability. The stability curves for the rectangular beam specimen are from a previous study (ref 5).

The most interesting information in Figure 5 in relation to tests performed here is the significantly greater stability of the round compared to the rectangular specimen. Using the machine compliance values discussed earlier, 0.0059 and 0.0052 mm/KN for the rectangular and round specimens, respectively, results in $\delta_M ED/P = 59$ for the round and $\delta_M EB/P = 28$ for the rectangular specimen. The corresponding threshold of stability for the round is $(a/D)_o = 0.51$, lower than the a/D of the test configurations, and for the rectangular $(a/W)_o = 0.58$, within the range of test configurations. This prediction of crack stability for the round tests and instability for some of the rectangular tests was supported by the test results. Recall that it was the rectangular specimens that failed in fatigue cracking and showed significantly less crack growth before abrupt failure.

Another confirmation of the prediction of poorer stability for the rectangular specimens is shown in Figure 6. This is a plot of fracture toughness results and the stability thresholds described in the preceding paragraph. Notice that the two rectangular results, which are clearly in the unstable range, are also among the highest values of fracture toughness. This confirms the earlier suggestion that a condition of unstable crack growth can cause an incorrectly high fracture toughness. If these two values in the unstable range were omitted from the calculation of mean fracture toughness discussed earlier in relation to Table II, a mean for rectangular results would be 63.0 MPa $m^{1/2}$, in better agreement with the mean for round results, 61.5 MPa $m^{1/2}$.

SUMMARY

1. The three-point bend round bar specimen with S/D of 4 produced a measured fracture toughness for a tungsten alloy that was essentially equivalent to the rectangular bar result. The specimen configuration and K expression from prior work and the wide range load-line displacement expression developed here are suitable for general use in fracture testing.

2. A load-line displacement analysis was developed for round bar bend configurations with a/D from 0 to 1 and S/D from 3.33 to 6.67. The analysis was found to be in good agreement with prior measurements from round steel beams with S/D of 3.33 and 6.67, with measurements in this report from round tungsten beams with S/D of 3.88, and with the deep crack limit solution developed here for round beams.

3. A crack growth stability analysis was developed for round beams with S/D from 3.33 to 6.67, a/D from 0.3 to 0.6, and normalized machine compliance, $\delta_M ED/P$, from 0 to 100. More stable crack growth before failure and lower fracture toughness were observed for the combination of tungsten specimen configuration and machine compliance for which stability was predicted.

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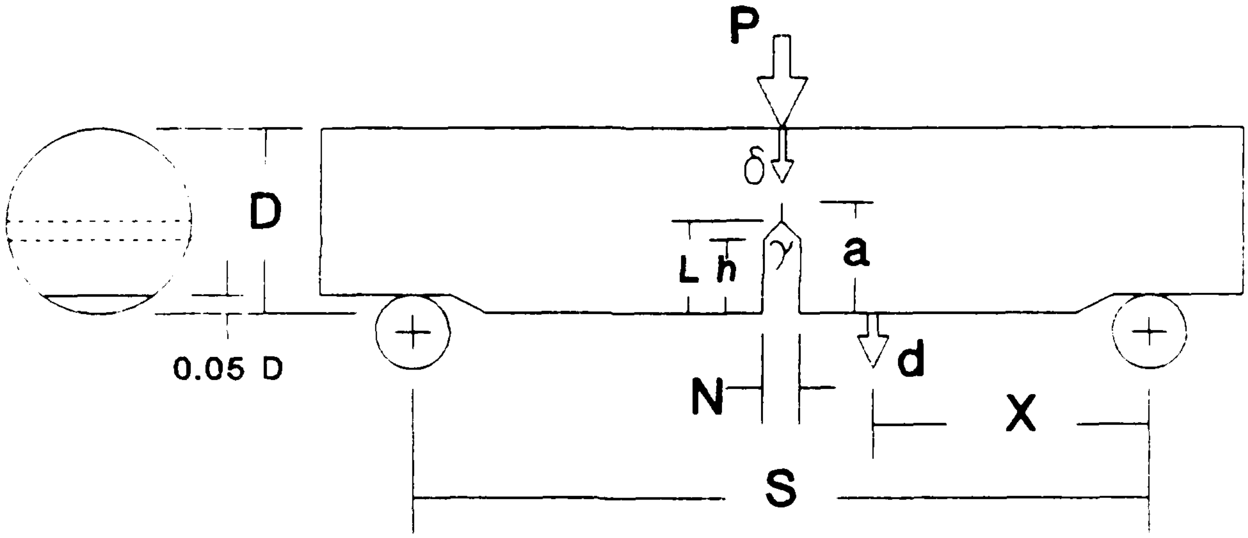

Figure 1. Edge-cracked round bar bend specimen for fracture tests and analyses.

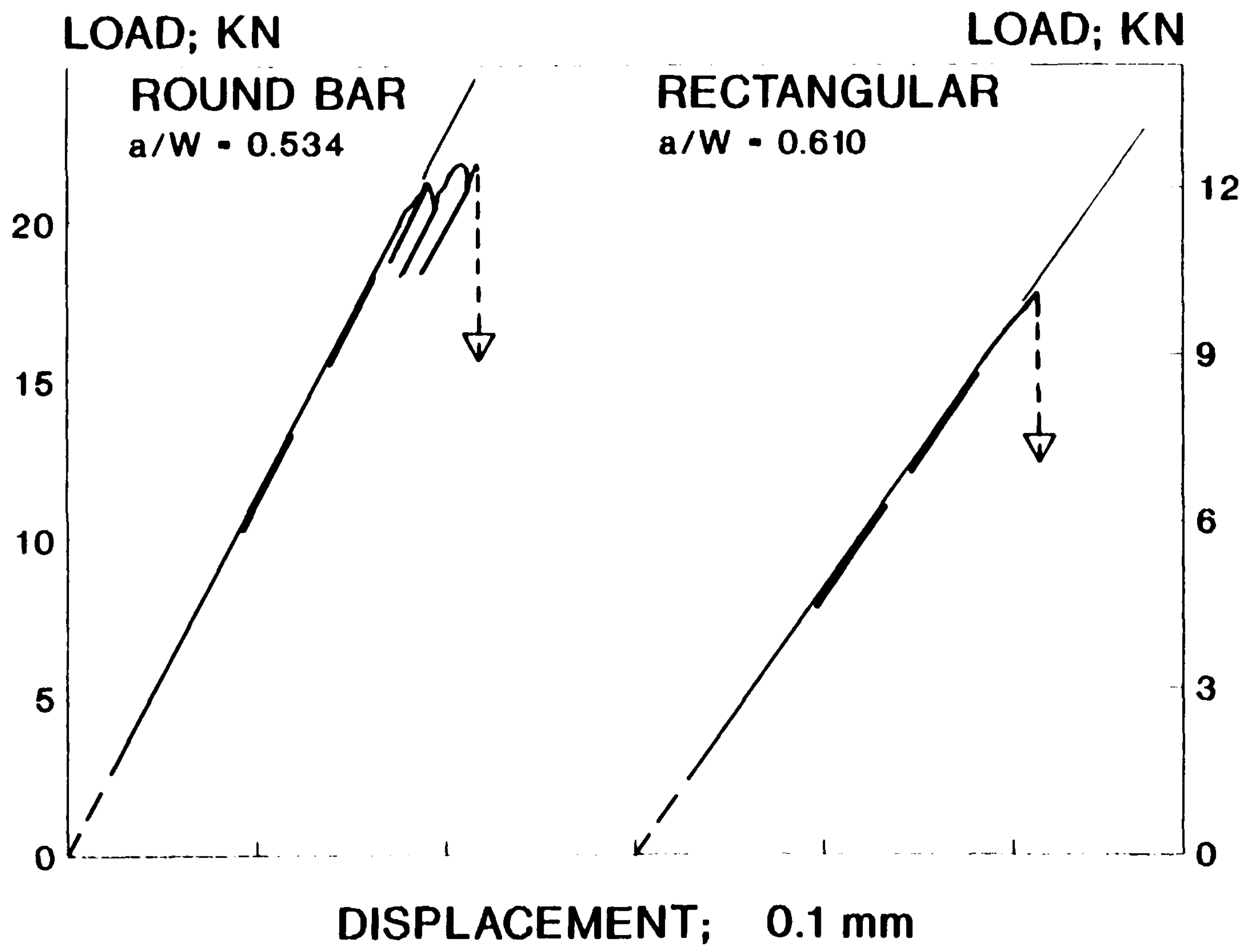

Figure 2. Load displacement behavior of round and rectangular specimens.

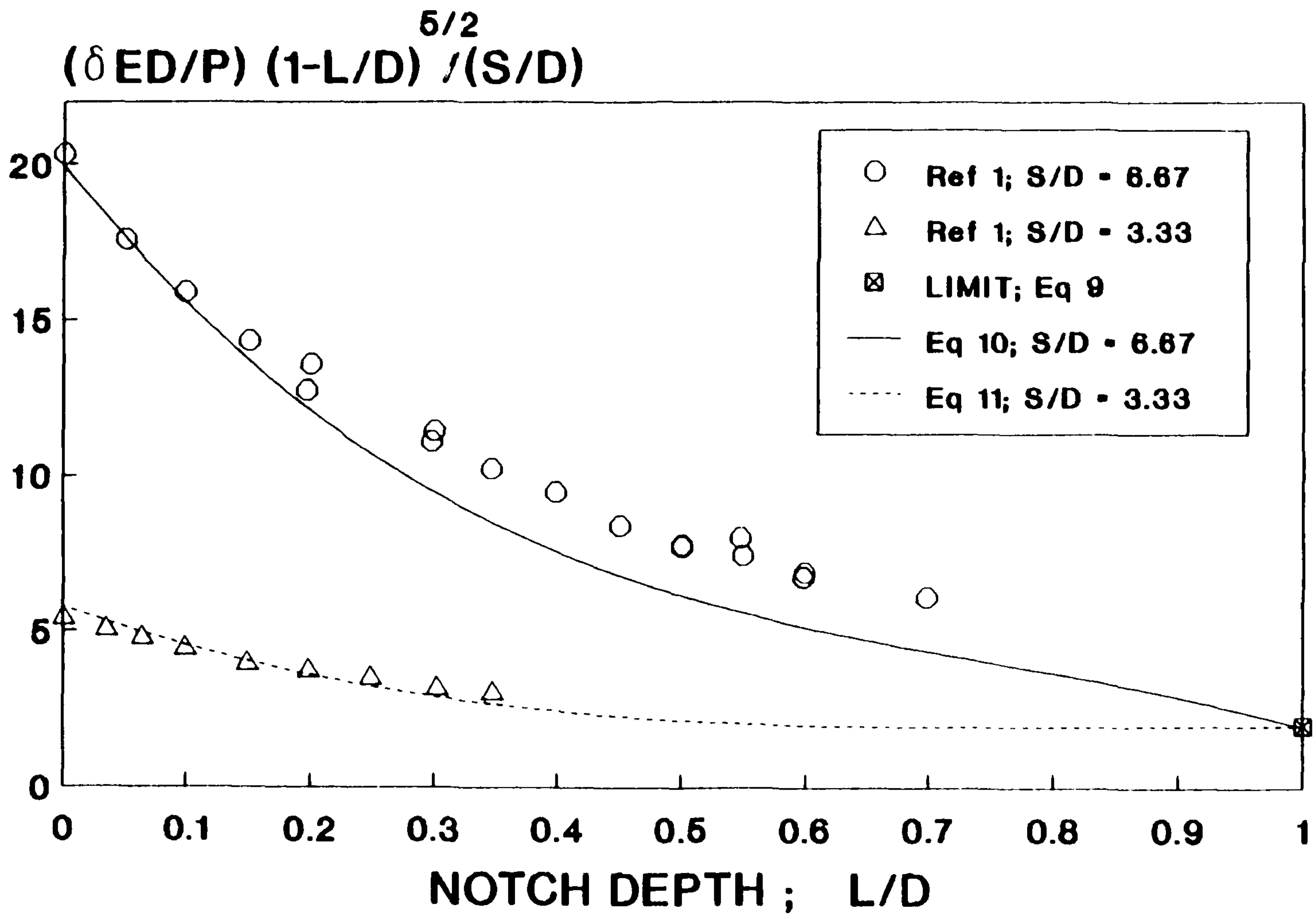

Figure 3. Comparison of load line displacement measurements and analysis.

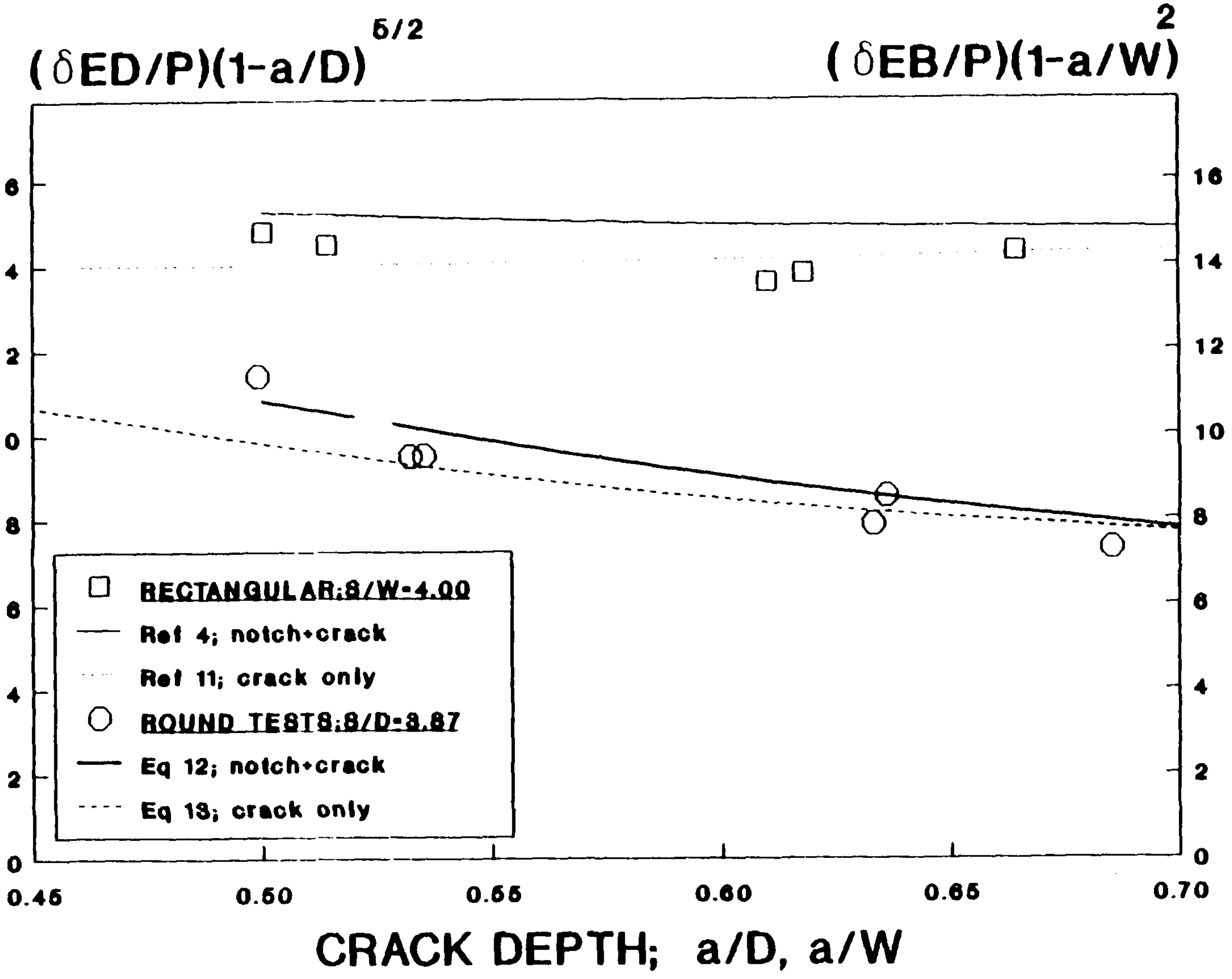

Figure 4. Load line displacement from tungsten specimens and analysis.

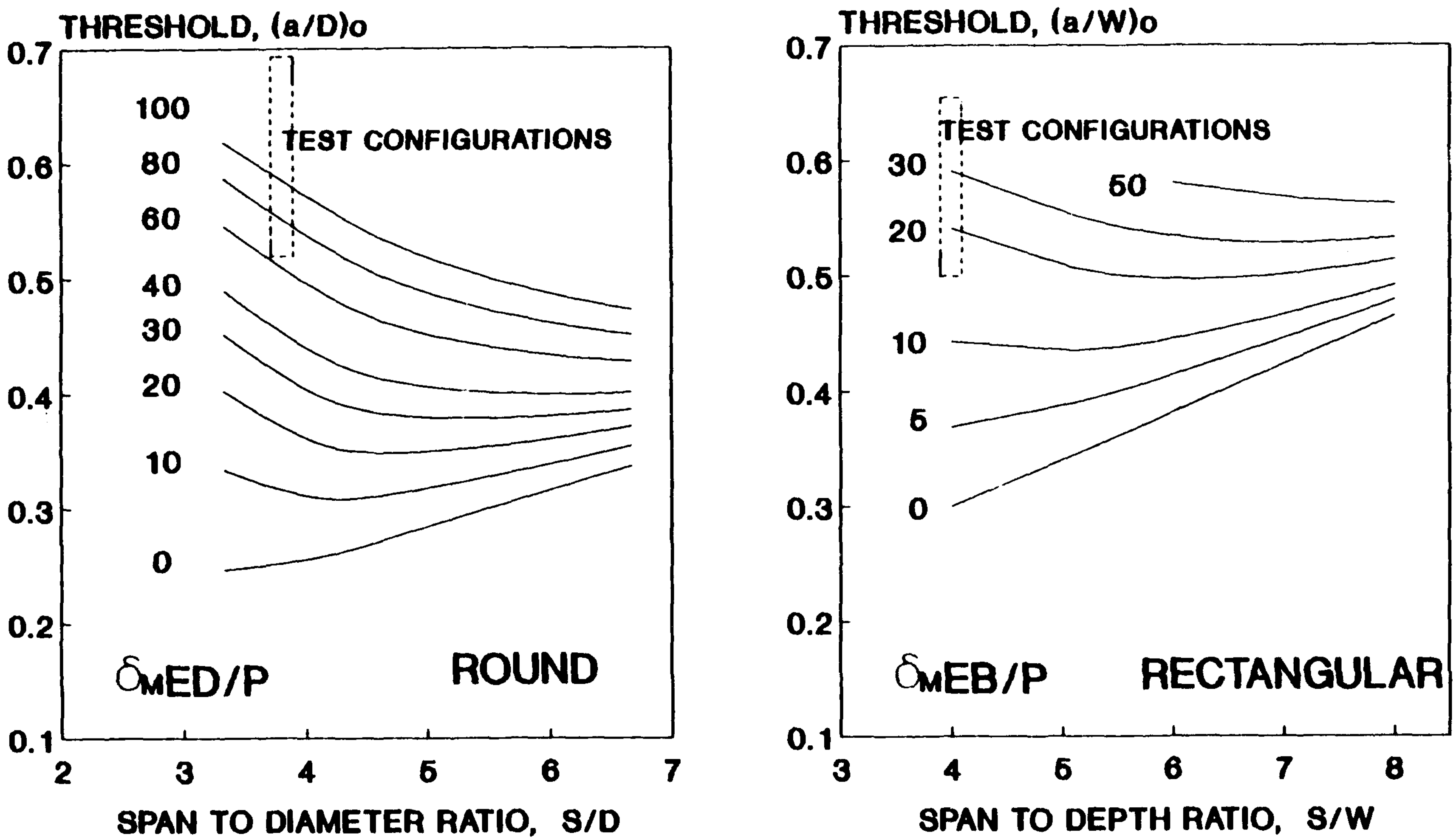

Figure 5. Crack stability thresholds for round and rectangular configurations.

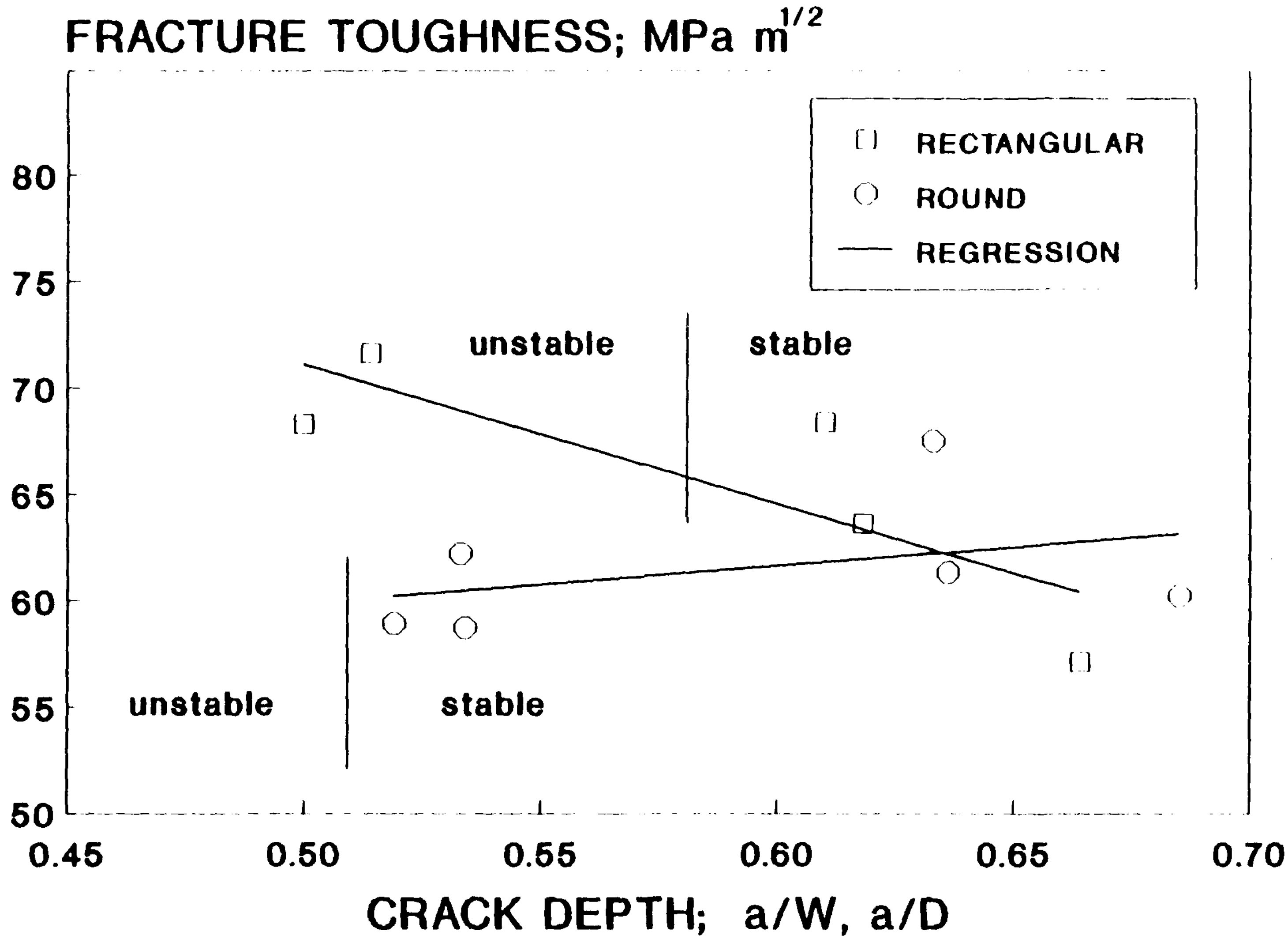

Figure 6. Fracture toughness and stability thresholds for tungsten specimens.

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