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Factors Significant to Precracking of Fracture Specimens

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ABSTRACT

The significance of four controlled variables in the technique used to precrack Charpy specimens is determined by analyses of seven response variables computed from results of slow-bend tests of metallic materials. The variables include crack size, stress-intensity factor at the start of precracking, notch preparation prior to precracking, and material. All four variables are shown here to be significant for more than one of the computed responses. All seven responses, each representing alternative methods for evaluations of fracture toughness, were evaluated for each test. These responses are based either on a single value of load or on energy absorbed in the test. The results can be summarized in three major conclusions: (1) All seven computed responses are linearly related to crack size and the sensitivity to crack size depnds on the choice of response parameter and on the material. (2) Precracking at either very high or very low levels of stress-intensity factor, K_f, are to be avoided. (3) For the three methods of notch preparation, the effects of notch preparation were largely not significant. This work is the result of a study conducted by ASTM Task Group E24.03.03 and members of eight participating laboratories.

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List of Symbols

A	-	Area of uncracked ligament at start of test: A=B(W-a)
A, Aluminum	-	Aluminum alloy 2419-T851 in the aged condition.
a_{25}	-	Crack length at one quarter-thickness location
a_{50}	-	Crack length measured at mid-thickness location
a_{75}	-	Crack length measured at the other quarter-thickness location
$\bar{a}$	-	$(a_{25} + a_{50} + a_{75})/3$ = crack size
$\bar{a}/W$	-	Normalized crack size
B	-	Specimen thickness = 10 mm (0.394 in)
β	-	A coefficient that is a result of a regression analysis
CVN	-	Charpy V notch (test specimen)
CPS	-	Cumulative probability statistic
CTS	-	Compact tension specimen (currently designated C(T)
C	-	Experimental determination of total elastic compliance of specimen (=D1/P1)
C_m	-	Machine compliance
C_s	-	Theoretical elastic specimen compliance
D1	-	Displacement to an arbitrary point "1" in the elastic region.
δ	-	Displacement
E	-	Young's modulus
E_c	-	Energy correction based on specimen compliance and crack length
EDM	-	Electric discharge machining
E_M	-	Energy to maximum load, under the load-displacement trace
E_T	-	Total energy under the load-displacement trace
$E_{T/A}$	-	Total energy divided by area of uncracked ligament.
E'_M	-	Corrected energy to maximum load $E'_M = E_M - E_c$.
K	-	Stress-intensity factor

K_d^*	-	A response, computed from P* and Y*, termed lower-bound or equivalent energy
K_f	-	Stress-intensity factor in fatigue precracking
K_f maximum	-	K_f at the start of precracking in a constant-deflection apparat
K_f ratio	-	K_f maximum/K smallest
K smallest	-	The smallest value of K computed from equations 1, 2, and 3 of this report
K_{Ic}	-	Reference values of fracture toughness obtained from CTS tests, whether valid (E 399) K_{Ic} or invalid K_Q
K_J	-	A response computed from energy to maximum load
K_J'	-	Response K_J corrected for machine compliance of specimen
K_Q	-	A response computed using P_Q, as in ASTM Method E 399
K_{Q-PM}	-	A response computed as for K_Q, except P_M is used in place of P_Q
K_Q'	-	A response computed from total energy absorbed in fracture
μ	-	Poisson's ratio
N	-	The number of observations
ν	-	Residual degrees of freedom
MLR	-	Multiple linear regression
NP	-	Notch preparation
N/A	-	Not applicable
% RD of K	-	Percent relative deviation = $(K - K_{Ic}) \times 100/K_{Ic}$
% RD of R_{sb}	-	Percent relative deviation = $(R_{sb} - \bar{R}_{sb}) \times 100/\bar{R}_{sb}$
P1	-	Load to an arbitrary point "1" in the elastic region
P_M	-	Maximum load
P_Q	-	Load at the 5 percent secant intercept
P*	-	A value of load used to compute equivalent energy

R_{sb}	-	Specimen strength ratio in slow-bend testing
$\bar{R}_{sb}$	-	Mean R_{sb} for each material
S, Steel	-	Steel alloy AL MAR (200) in the maraged condition
S_y	-	Significant differences based on magnitude of test responses
S_s	-	Significant differences based on reproducibility of test responses.
s	-	Standard deviation for replicate responses
s_p	-	Standard deviation pooled for all responses of a material
σ_U	-	Ultimate tensile strength
σ_Y	-	Yield strength
σ_{Y1}	-	σ_Y at the precracking temperature
σ_{Y2}	-	σ_Y at the Charpy test temperature
T, Titanium	-	Titanium alloy Ti-6Al-4V in the annealed condition
W	-	Specimen width = 10.0 mm (0.394 in)
$\bar{Y}$	-	Mean response
Y*	-	A function of $\bar{a}/W$ used to compute K_d^*
y_i	-	An individual test response

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1. Background

A proposal for standardization of a precracked Charpy impact test was made by the Executive Committee of ASTM Committee E24, in January of 1971, and Task Group E24.03.03 was formed to deal with this problem. The task group drafted a preliminary document titled, "Proposed Method for Precrack Charpy Impact and Slow-Bend Testing of Metallic Materials," which required experimental work to determine the significance of variables in the fatigue precracking procedures prescribed in the proposed method. The "best procedures" for fatigue precracking had to be established. Further, the expected variability of test results had to be determined for a multiplicity of laboratories using a prescribed test method.

At the request of the Chairman of Task Group E24.03.03, the authors, from the National Institute of Standards and Technology (NIST), fomerly the National Bureau of Standards (NBS), furnished a proposed statistically designed experiment for determining the significance of four precracking variables on results of tests conducted with fatigue precracked Charpy specimens. This proposal included three levels for each of the four variables (here called factors). The factors and their levels were later modeified at meetings of the Task Group before test specimens were prepared. In addition, the proposal specified two methods of testing, slow-bend and impact; together, these proposed tests comprised what the Task Group called Phase I of their testing program.

This is an analysis of the results of the slow-bend tests conducted for Phase I. At the time that this work was being planned, a report published by the National Materials Advisory Board [3] recommended... "that the fatigue-precracked Charpy-size specimen, tested in slow bending to measure the ratio of specimen strength to either the yield strength or the ultimate tensile strength of the material (ASTM E 399) be utilized, when applicable, for establishing correlation with plane-strain fracture roughness and minimum acceptance standards in quality-control programs. To foster implementation of this recommendation, the Committee urges that the test method be standardized as soon as practicable..." The Phase I test program was distinguished from other extensive research programs [1,2][1] that have used precracked Charpy specimens, as the objective of this program is to establish the effects of precracking variables. The proposed Phase II effort was to be conducted by many laboratories to establish a lab-to-lab variability for precracked Charpy test results.

Charpy test specimens used in this program (shown in Fig. 1) differ from the standard ASTM E 23-66 type A, V-notch Charpy specimen: (1) Charpy specimens for this program (Fig. 1A) contain a fatigue precrack; in this respect they are similar to valid plane-strain facture thoughness specimens (ASTM E 399), while the standard Charpy specimen is not precracked; and (2) the standard V-notch root-radius of .25 mm (0.010 in) is here modified in various ways (Fig. 1B) to facilitate crack initiation under fatigue loading.

This analysis was completed in 1981. While the results of this study and analysis have been made available to various ASTM workers for committee activities, some of this and related information will be published in ASTM STP 1072, Charpy Impact Test - Factors and Variables, where it will be available for use in the development of test methods and in future studies. This internal report contains data and other information not available in the ASTM article.

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[1] Figures in brackets indicate the literature references at the end of this paper.

2. Test Matrix

In the proposed Phase I program, each of three materials are designated to be tested after being precracked in the various ways specified in the proposed test matrix, table 1. These specified precracking variables are notch preparation (NP), stress-intensity factor at the start of precracking (K_f maximum), and crack size ($\bar{a}$). Each precracking variable is controlled at three levels, which are coded 1, 2, and 3 in the proposed matrix. Thus, there are a total of four factors and three levels per factor in the experimental design. In addition, replicate specimens are specified for each test condition. The actual numbers of specimens tested at each condition, given in table 2 to be discussed later, differ slightly from the proposed 2 replicate tests per condition indicated in table 1.

Historically, the proposed test matrix was developed from a matrix suggested by the NIST authors working in cooperation with members of ASTM TG E24.03.03. From that NIST test matrix, proposed matrix of table 1 was developed by the Task Group, which finalized the levels of the factors in the matrix. While the number of test conditions had to be limited for economy, this matrix contains all factors and levels deemed by the task group to be necessary to determine the effects of the variables commonly encountered in fatigue precracking of Charpy specimens.

2.1 Materials

Three materials included in the Phase I program are an aluminum alloy (2419-T851) in the aged condition, a titanium alloy (Ti-6Al-4V) in the annealed condition, and an 18 NiCoMo steel [AL MAR 18 (200)] in the maraged condition. These materials are referred to here as Aluminum, Titanium, and Steel, and they are coded 4, 5, and 6, respectively, for purposes of computer sorting and analysis and for presentations made in the Appendices. They are also coded A, T, and S in some data plots. Their chemical compositions are given in table 3.

The following heat treatments were given prior to precracking: "Aluminum" is the aluminum alloy, as mill treated to the 851 condition. Typical treatment [4] for the 851 condition, in a similar (2219) alloy is: solution treat 535 C (995 F), stretch, and age at 177 C (350 F), 18 h at temperature. "Titanium" is the titanium alloy as solution treated, at 927 C (1700 F), 4 h, furnace cooled 38 C/h (100 F/h) to 315 C (600 F), and air cooled to room temperature. "Steel" is the maraged steel, as solution annealed and then aged at 488 C (910 F), 4 h.

Mechanical properties of the materials are given in tables 4 and 5. Properties listed in table 4 are those used for calculations made in the preparation of this report, after the completion of all slow-bend tests. Table 5 gives nominal properties used for preliminary calculations of allowable stress-intensity factors for fatigue precracking, K_f maximum.

Reference values of fracture toughness for these materials were furnished from tests conducted with the Compact Tension Specimen (CTS). The results of these tests, given in table 4, indicate that not all test results meet the validity requirements of E 399. The tests were conducted in accordance with ASTM Method E 399 [5]; and according to the Method, the results are either valid and are referred to as K_{Ic}, plane-strain fracture toughness, or they are not valid and are referred to as K_Q. Table 4 gives the particular requirement that was not met for each test that failed the E 399 validity requirements. For simplicity in this writing, these reference values of K will be referred to as K_{Ic} values, even though some of the results are actually termed K_Q test results by Method E 399. In this report, these reference values are used to assess the accuracy of the various responses (K values) computed from results of Charpy tests.

For Aluminum, the two reference K_{Ic} values given in table 4 for the CTS tests are averaged to obtain a single reference for all Aluminum Charpy specimens. These two results are 39.3 and 38.4 ksi $(in)^{1/2}$, obtained from specimens of dimensions 1.5 x 3 x 3.6 in, which were taken from a plate sample (designated 411081) that was rolled to 1.5-in thickness. These results are about the same magnitude as results of 38.9 and 38.5 ksi $(in)^{1/2}$ obtained from specimens of dimensions 0.5 x 3 x 6 in, which were taken from the plate sample (designated 411060) that was rolled to 0.5-in thickness and from the same cast as that of plate 411081. Although the Charpy specimens were actually taken from the 0.5-in-thick plate, the reference values obtained from specimens taken from the 1.5-in-thick plate were used as the reference values in this report. This was done because the values of P_M/P_Q for the tests of the 0.5-in-thick plate were relatively high, about 1.7, whereas those from the 1.5-in-thick plate nearly met the E 399 requirement of $P_M/P_Q \leq 1.1$.

For Titanium, the CTS test results represent two specimen orientations, longitudinal (LT) with values of 77.9 and 80.2 ksi $(in)^{1/2}$, which are designated R and L respectively (see table 4), and transverse (TL) with values of 77.4 and 85.5, which are designated W and T respectively. Charpy specimens of Titanium were taken from the broken halves of the 1-3/8-in-thick CTS specimens used to obtain the reference K_{Ic} values. It was noted that these K_{Ic} values vary over a broad range from 77.4 to 85.5, and the difference between these two values is large, being about 14 percent of the smaller one. Further, the smallest value represent a

CTS test result with P_M/P_Q equal to 1.54, and this is a wide departure from the E 399 requirement of $P_M/P_Q \leq 1.1$, and in this regard this CTS is unique among all the specimens tested in this Phase I program. In addition, initial correlations made with the data of CTS and Charpy tests indicated that improved correlations would result from the use of four individual K_{Ic} reference values for Titanium with each CTS result being used as a reference only for the data obtained from Charpy specimens taken from that CTS. Hence, in the analyses presented here, the reference for each Charpy specimen of Titanium is the K_{Ic} result of its parent CTS.

For Steel, three CTS test results are averaged to obtain a single reference value of 120.5 ksi $(in)^{1/2}$ for Steel Charpy specimens. The Charpy specimens were taken from the same plate, at adjacent locations, and in the transverse (TL) orientations. Results of the CTS tests indicate that the E 399 requirement, $B \geq 2.5\ (K_{Ic}/\sigma_Y)^2$, was not met for this material, and this is the only material, among the three tested, that failed the ASTM thickness requirement.

2.2 Laboratory Variabilities

The tasks undertaken by each of eight laboratories that participated in the Phase I program are outlined in table 6. One objective of this program was to conduct the Charpy tests as though only a single laboratory had done the work. In keeping with this objective, only one laboratory can be involved for each step of the procedures of preparation and testing of specimens, and analysis of the data, except for those steps for which ASTM prescribed methods are applicable. In practice, this objective was largely met even though five of the laboratories participated in Charpy related tasks (see table 6). However, some discrepancies did arise. Precracking of Charpy specimens was done at two laboratories due to an unforseen problem. After the specimens of Titanium and Aluminum had been precracked, it was found that although the rough machining of the specimens of the maraging steel had been done in accordance with the applicable ASTM specification, the lengths of these specimens were on the short side of the specification tolerances. These shorter specimens could not be properly precracked in the machine that had been used for specimens of the other two materials. Therefore, a second laboratory precracked the Steel specimens. As a result, not only were different equipment and personnel involved, but slightly different criteria were used for the stress-intensity factor in fatigue precracking. These differences are described later, in Section 2.4.

Other procedures with potential for giving rise to undesirable lab-to-lab procedural effects were generally controlled closely enough so that they are considered to have no significant effects on the test results. Mechanical machining and notching was done at two laboratories, but under the close tolerances of the ASTM specifications for root radius, notch angle, and notch depth. Data reduction from records of the load vs. displacement was done by similar methods at two laboratories, but only after the principals involved had agreed upon a single method for the reduction process.

2.3 Notch-Preparation Factor

The notch-preparation (NP) factor in the experimental design has three levels, as shown in figure 1, which are coded 1, 2, and 3 for purposes of computer sorting and analysis of the data. Each of these levels is a method by which a Charpy V-notch is prepared prior to precracking of the test specimen. Level 1 is a standard 0.25 mm (0.010 in) root-radius V-notch modified by sharpening the root of the notch with a razor blade. Level 2 is a nonstandard V-notch of .125 mm (0.005 in) root-radius. Level 3 is a standard 0.25 mm (0.010 in) root-radius V-notch modified by sharpening the notch root to about 0.05 mm (.002 in) root-radius by electric discharge machining (EDM), using a razor blade as an electrode placed just above the notch in the EDM process.

2.4 Stress-Intensity Factor at Start of Precracking

The stress-intensity factor at the start of precracking (K_f maximum) was controlled at three levels for each material in the proposed test matrix. The three levels are dependent upon properties of the materials, as described below. To compute the proposed levels, first a stress-intensity-factor parameter here called "K smallest" is computed by using three formulae:

$$K_{(1)} = (\sigma_{Y1}/\sigma_{Y2}) \times K_{Ic} \ (\text{ksi (in)}^{1/2}) \qquad (1)$$

$$K_{(2)} = \sigma_{.002} \times E \ (\text{ksi (in)}^{1/2}) \qquad (2)$$

and

$$K_{(3)} = 0.57\ \sigma_{Y1} \ (\text{ksi (in)}^{1/2}), \qquad (3)$$

where σ_{Y1} and σ_{Y2} are static yield stress in ksi at the precracking temperature and at the Charpy slow-bend test temperature, respectively, and E is the elastic modulus in psi. Table 5 shows values used for these constants and results of the K calculations for each of the three materials. The smallest of these calculated K values is called K smallest. Then, loads at the start of precracking are computed to give the following proposed values of K_f maximum (the value at the start of precracking in a constant-deflection machine): K smallest, (2/3)K smallest, and (1/3)K smallest. These K_f maximum values are coded 3, 2, and 1, respectively, for purposes of computer sorting and analysis of data within each material. This is shown in table 7 which gives the fatigue precracking levels, and their codes used for sorting and analysis of data within a material. While three levels (coded 3, 2, and 1) are indicated (in the table) for analyses within each material, a total of 4 levels are indicated for combined materials: Aluminum and Steel have levels 3, 2, and 1, and Titanium has levels 2, 1, and 0. This coding became necessary for combined results because the actual K_f maximum levels used for Titanium are different from (lower than) the proposed K_f maximum levels. The highest actual level for Titanium is 20 ksi $(in)^{1/2}$, which is nearly equal to (2/3)K smallest, the proposed code 2; the next actual level for Titanium is nearly equal to (1/3)K smallest, which is the proposed code 1; and the lowest actual level for titanium is much lower than any other levels used in these tests. Thus, for combined materials, the analysis requires four levels, coded 3, 2, 1, and 0.

Further, as noted in table 7, for Steel the three actual levels are slightly higher than the proposed levels, on average. In addition, for Steel specimens, K_f maximum was measured at the finish of precracking, whereas levels of K_f maximum for Aluminum and Titanium were measured at the start of precracking. In the precracking machines used for this Phase I program, K decreases slightly as crack length increases, so that K_f at the finish of precracking is slightly lower than that at the start. Thus, for a short crack length, K_f at the start of precracking would be slightly greater than K_f "maximum" tabulated for the Steel; and for longer cracks, K_f maximum at the start of precracking is greater still. Thus, actual K_f maximum levels for each material represent different fractions of the K smallest computed for the proposed levels. These fractions are called the K_f ratio and they are greatest for the Steel specimens and least for the Titanium specimens, and they are grouped into 3 levels for each material and into 4 levels for combined materials.

2.5 Crack Size Factor

The test matrix gives three levels for the crack-size factor ($\bar{a}$) used in calculations. These levels of $\bar{a}$ are coded as follows:

Code 1: $\bar{a}$ = 2.5 to 3.6 mm (0.097 to 0.140 in)

Code 2: $\bar{a}$ = 3.6 to 4.6 mm (0.1405 to 0.180 in)

Code 3: $\bar{a}$ = 4.6 to 6.1 mm (0.1805 to 0.242 in)

The lower bound for Code 1 was established as follows. After testing had been completed, it was observed that a crack was never initiated in some specimens fatigue cycled at the lowest level of K_f maximum; further, during a preliminary screening of the data, results for specimens with $\bar{a}$ less than 2.48 mm (0.097 in) were found to be more highly variable and in this respect inconsistent with the data for specimens with $\bar{a}$ between 2.48 and 6.15 mm (0.097 and 0.242 in). Thus a lower limit on $\bar{a}$ and 2.48 mm (0.097 in) was set for purposes of this analysis. Data for specimens below this limit are not included here. No upper limit was warranted for $\bar{a}$.

2.6 Actual Number of Tests Conducted

The actual number of tests conducted for each test condition is given in table 2. The two replicate specimens specified in the proposed test matrix were actually tested except for selected cases, especially those involving K_f code 1, the lowest stress-intensity level (K smallest/3). The K_f code 1 tests actually conducted include only about half of the proposed tests; of the 9 replicate tests proposed for each material, actual replicate results include only one for Aluminum, three for Titanium and eight for Steel. These deficiencies are reportedly due to difficulties commonly encountered in the process of precracking at very low K levels in tough materials. Further, a total of 54 specimens were proposed for tests of each material, and while 51 specimens of the Steel were tested, the number of specimens tested for the other materials was lower--43 Aluminum and 44 Titanium. The deficiencies in the numbers of tests for each of these materials are mainly in the K_f code 1 level, and the analysis of the results for K_f code 1 are adversely affected by these deficiencies.

3. Test Procedures

Precracked Charpy specimens were tested in three-point bend, using a bend test fixture with the geometry and dimensions recommended in ASTM Designation E 23-72 for Charpy impact testing. No movable support pins are used in this fixture, which uses two anvil blocks to provide support at a fixed span. The cross-head speed was 2.5 mm/min (0.10 in/min). Load and displacement were measured and plotted. The load was taken from the load cell of the test machine and the displacement was measured using a transducer (LVDT) placed between the top and bottom plates of the bend test fixture, as shown in figure 2. Therefore, while the measured displacement represents the displacement of the specimen, the measurement is affected by the compliance of the test machine.

After each slow-bend test, the test response was computed using the raw data obtained from the broken halves of the Charpy specimen and the load-displacement test records. If the specimen was not fractured into two pieces during the test, this was done using liquid nitrogen coolant after the test. Load P, displacement δ, and energy absorption E (area under the P-δ plot) were measured using a digitizer to trace along the P-δ plot of the test record. From the raw data, various fracture toughness test responses were computed. These responses are here designated K_Q', K_{Q-PM}, K_Q, K_J', K_J, K_d^*, and R_{sb}, and are computed by methods described in section 4 of this report. As is shown in figure 3, each response is based on one of three principal measurements, total energy (E_T), energy to maximum load (E_M or E_M') or a single value of load (P_M or P_Q).

To compute the response K_Q', the total energy E_T (fig. 3A) is measured. E_T is taken to be the area under the curve from the start of test to a load equal to $P_M/10$, where P_M is the maximum load. Measurement of energy absorption beyond this level of load was impractical for two reasons, some of the specimens were not completely fractured into two halves during the test and most of the test records had a very broad tail area which could not be recorded without sacrificing accuracy in the record of the more important initial loading behavior. To compute the responses K_J, K_J', and K_d^* (fig. 3B), several measurements were taken: maximum load P_M, compliance D1/P1, and energy to maximum load, E_M. The responses R_{sb}, K_{Q-PM}, and K_Q (fig. 3C) require measurement of either the load P_M, or the load P_Q measured by the 5 percent secant method described in Method E 399.

Computations of the above responses also require a measure of the area (A) of the uncracked ligament at the start of the test. This area is obtained from the relationship $A=B(W-\bar{a})$, where the nominal specimen width B and thickness W each are set equal to 10 mm (0.394 in); the crack size factor $\bar{a}$ is an average of the a_{25}, a_{50}, and a_{75} crack length measurements taken, respectively, at the 1/4-, 1/2-, and 3/4-thickness (B) locations on the broken halves of the slow-bend tested Charpy specimens. This ligament is seen in figure 1A as the distance from the front of the fatigue crack to the back boundary of the specimen.

Hence, raw data taken for each Charpy specimen include P_Q, P_M, E_M, E_T, $\bar{a}$, a_{25}, a_{50}, a_{75}, and D1/P1. These data are given in Appendix I for all slow-bend test results that were included in this analysis.

For all aluminum and titanium specimens, and for most steel specimens, the load-displacement plots were observed to be of the type (general shape) shown in figure 3, in which there is no indication of a cleavage initiation event. For some Steel specimens the plots were bimodal as shown in figure 4, indicating a cleavage fracture with rapid machine unloading. During the unloading of the first mode of the bimodal type, the energy of the test machine is released to the specimen and it was not recorded on the test record. Thus, while the area under each of the two modes is included in the measurement of E_T, this energy of unloading, which contributes to the fracture process, is not included in this measured value. The bimodal load-displacement plot is observed only for steel specimens with crack size less than 3.56 mm (0.140 in), i.e. small crack lengths. The E_T values used in this analysis were not corrected to take machine unloading into account; as the analysis had been nearly completed when this was discovered, time constraints precluded this correction.

4. Calculation of Response from Charpy Test Results

Raw data taken in precracked slow-bend Charpy tests are not directly used to assess material properties. Rather, data are converted to responses of fracture toughness, designated by the symbol K, or specimen strength ratio, R_{sb}. These responses are calculated by various methods given below. The computed K and R_{sb} results are given in Appendix Table II for all specimens included in this analysis.

Relationships used to compute responses of K are:

$$K_Q = (P_Q S/B\ W^{3/2})\ f(a/W), \qquad (4)$$

where S = 1.574 and

$$f(a/W) = 3(\bar{a}/W)^{1/2} \frac{[1.99-(\bar{a}/W)(1-\bar{a}/W)(2.15-3.93\ \bar{a}/W\ \ 2.7\ \bar{a}^2/W^2)]}{2(1+2\bar{a}/W)(1-\bar{a}/W)^{3/2}}$$

after ASTM Method E 399 [5],

$$K_{Q-PM} = (P_M S/B\ W^{3/2})\ f(a/W), \qquad (5)$$

which is the same as the equation for K_Q but maximum load P_M, rather than P_Q, is used;

$$K_Q' = [0.5\ E\ E_T/A\ (1-\mu^2)]^{1/2}, \text{ after Ronald [6]}, \qquad (6)$$

where:

E = Young's modulus;

E_T = total energy under the load-deflection trace;

A = area of uncracked ligament at the start of the test ($= B(W - \bar{a})$); and

μ = Poisson's ratio.

$$K_J = [2\ E\ E_M/A\ (1-\mu^2)]^{1/2}, \text{ after Rice [7]}, \qquad (7)$$

where E_M = energy to maximum load, under the load-deflection trace.

$$K'_J = [2\ E\ E'_M\ /A(1-\mu^2)]^{1/2}, \text{ after Rice [7]}, \qquad (8)$$

where E'_M is E_M corrected for the compliance of the test machine: $E'_M = E_M - P_M^2\ C_m/2$; where C_m is machine compliance, after EPRI procedures [8,9]; $C_m = C - C_s$, with C and C_s, respectively, representing experimental and specimen (theoretical) compliance values. Measured values of C are given as D1/P1 in Appendix Table IC.

$$K^*_d = \frac{6\ Y^*\ (\bar{a})^{1/2}\ P^*}{B\ W}, \qquad (9)$$

where

$$Y^* = 1.93-3.07(\bar{a}/W) + 14.53(\bar{a}/W)^2 - 25(a/W)^3 + 25.8(a/W)^4$$

$$P^* = [2\ E'_M\ /C_s]^{1/2}.$$

It is noted that K^*_d can also be computed using P^* in place of P_Q in Equation 4. The lower bound (or equivalent-energy) procedure (K^*_d) arises from concepts developed by Witt [10].

Responses of strength ratio in slow-bend testing, R_{sb}, were computed using the equation:

$$R_{sb} = 6\ P_M\ W\ /B\ (W-\bar{a})^2\sigma_Y, \qquad (10)$$

after Method E 399 [5].

Responses computed using equations (4) through (10) are used here to determine statistically whether or not the level for each of the four factors significantly affects the test result. The <u>accuracy</u> of a Charpy test response is assessed, as described in Section 5.1.3 for each of the various fracture toughness measures of having the symbol K. This is done using an appropriate reference value of K_{Ic} for each material. The reproducibility is assessed, as described in Section 5.1.2, using replicate responses.

5. Statistical Tests

The controlled variables, called factors in this analysis, are notch preparation (NP), fatigue-load at the start of precracking (K_f maximum), and original crack size ($\bar{a}$) and material. The goals of this experiment do not include between material differences. Material-to-material differences are known to exist and in this analysis this variable is not considered as a factor in the analysis. In the proposed test matrix, each factor is tested at three levels only; however, for the factors $\bar{a}$ and K_f maximum, many more than three levels were actually tested. A variety of analytical methods are used here to determine whether or not statistically significant difference exists among the levels of a factor. These include (1) the Kruskal-Wallis (KW) test, (2) multiple linear regression (MLR) analysis, and (3) graphical analysis of variance. The results of both the KW test and the MLR analysis is a Cumulative Probability Value (CPV) which corresponds to a percent point of the null distribution. The two tests are not identical and were run because they are sensitive to different aspects of the same problem. To determine whether a factor is significant, the MLR analysis is conducted using the individual responses. The KW test used ranks of these responses and each factor is subdivided into three levels to test whether the levels are significant. These differences are expected to give rise to differences in the CPV results for the two tests.

In this analysis, when either of these tests indicates a factor or its levels to be significant, then graphical analysis is used to further describe the effect.

5.1 Kruskal-Wallis Test

One procedure used here to carry out the test of significance is based on the Kruskal-Wallis [11] test statistic, H. The Kruskal-Wallis test statistic H can be shown to be equivalent to the usual 1-way analysis of variance statistics, with the observations within a given treatment (or level) replaced by their ranks. (To rank the data, the minimum observation of the set is replaced by a 1, the next larger observation is replaced by a 2, etc.) This transformation to ranks allows one to validly carry out the usual analysis of variance (ANOVA) test for equivalence of means without regard to the actual distribution of the data. In statistical terms, the test procedure is essentially a distribution-free analysis of variance.

The H test statistic is used in this analysis, instead of the usual ANOVA, because it is a distribution-free test and so the validity of the conclusions is not dependent on the distribution of the data. In particular, inasmuch as the usual ANOVA assumes the data to be normally distributed, and inasmuch as inspection of the data reveals that such a normality assumption is not likely to be valid in this case, then the application of a distribution-free test appears to be the simplest and most reasonable way to proceed.

Under the null hypothesis of no effect on the result by the various levels of a factor, the null distribution for H can be determined strictly from theoretical considerations. The test statistic H is then calculated from the data and compared with this theoretical null distribution of H. Calculated values of H which fall out in the extreme regions of the null distribution are deemed to be indicative of a false null hypothesis--thus, the levels within a factor are concluded to be significantly different. Calculated values of H which occur in the "middle" or "body" of the null distribution are deemed to be typical and they give no evidence that the null hypothesis is false. Thus, the levels within a factor are concluded to be not significantly different from one another.

Associated with any given value of the Kruskal-Wallis test statistic, H, is a cumulative probability value (CPV). The CPV is arrived at from a given value for the H statistic in the following manner: In forming the null hypothesis H_o that all levels of a factor yield an equivalent response, it follows that when H_o is true, the H statistic has a distribution which can be theoretically determined. To be specific, when the null hypothesis is true, the distribution of the H statistic has been found to be very closely approximated by a χ^2 distribution. Thus, for a given value of the H statistic, the cumulative probability value (CPV) associated with this H value can be found by a simple table look-up in the appropriate χ^2 table. The resulting probability value, which is noted from the table, is the area (= probability) under the null distribution density function from the observed point (i.e., from the H value) all the way back to $-\infty$. If the null hypothesis H_o is true, one would expect cumulative probability values (CPVs) generally between 0.0 and 0.90. If H_o is false, one would hope to obtain CPVs larger than 0.90. In the present analysis, all cases with CPV > 0.90 will be discussed and the values are expressed in percentage points (i.e., 90 percent rather than 0.90).

If the null hypothesis H_o of no difference between levels of a given factor is true, then the distribution of the H statistic is theoretically determinable. And so (if H_o is true), the observed value of H should behave like a single random drawing from the of the theoretical distribution of H. The "body" of such a distribution is that region between the 0 percent point and the 90 percent point--all values of H which fall in this region will yield CPVs between 0.0 and 0.90. Values of H which fall out of the "most likely region" are rare and imply that the validity of H_0 is not supported by the data. These larger values of H beyond the 90 percent point will, of course, yield CPVs larger than 0.90.

This CPV is reported here as the result of a test for the equality of the levels within a factor. The CPV is rather simply related to the probability of erroneously concluding that the difference between levels is significant. If this value is significant at the 10 percent level, only 10 percent of the time will it be erroneous to conclude that a significant difference exists.

For example, when a factor has a reported CPV of 95 percent there is a 5 percent chance of erroneously rejecting the null hypothesis when, in fact, it is true; thus, at a probability value of 95 percent, the difference between the levels of a factor is said to be significant at the 5 percent level. It is noted that significance levels commonly used for hypothesis testing are 1, 5, or 10.

5.1.1 Significance

For each factor, X, it is of interest to test whether the various levels of X give the same result or a significantly different result. If the different levels do not (within random error) give the same value, the factor is said to be statistically significant. In this report, a test of significance is applied independently to data sets representing each of the materials tested and to data representing all materials (of Phase I) combined into a single set. The result of the test of significance is a determination of whether the levels of a factor are significantly different.

The parameters used to conduct the KW statistical test are the standard deviation for replicate responses, s, the individual test responses, y_i, and the mean response, $\bar{Y}$. Responses derived from these three parameters are specimen strength ratio R_{sb}, and percent relative deviation (%RD) from reference K_{IC} values are given for each of several measures of fracture toughness (Section 4) designated K_Q', K_{Q-PM}, K_Q, K_J', K_J, and K_d^*.

When the test of significance indicates that significant differences exist among the responses for the various levels of a factor, the question becomes which level is best. For the responses given above, low values of s and |%RD| indicate, respectively, better reproducibility and more accuracy. Thus, they are considered better than high values of s and |%RD|; therefore, the best level can be determined for computed responses of K by selection of the level with the lowest values of either s or |%RD|. However, for the computed values of specimen strength ratio, R_{sb}, the best level can be determined only from the reproducibility parameter s, because no reference values of R_{sb} (from which to make a determination of accuracy) are available for this analysis. Hence, for R_{sb} responses, the parameters y_i and $\bar{Y}$ are used only to determine of the <u>significance</u> of differences (in the R_{sb} responses) among the levels of each factor, and the question as to which level is most accurate cannot be addressed without reference values of R_{sb}.

The requirement of replicate testing (see table 1) was not met for every combination of levels and factors given in the test matrix (table 2). In addition, reference data are not available for all of the calculated test results, as reference values of R_{sb} are not available. Thus, the analysis is somewhat incomplete whenever these requirements for replicates and reference values were not met.

5.1.2 Reproducibility

Reproducibility of the test results is estimated from replicate responses. Let y_i denote the individual response for a group of replicate specimens. A mean response, $\bar{Y}$, and a standard deviation, s, are computed for each set of replicates in accordance with the formulae:

$$\bar{Y} = \sum_{1}^{N} (y_i)/N, \qquad (11)$$

and

$$s = [\sum_{1}^{N} (y_i - \bar{Y})^2/(N-1)]^{1/2}, \qquad (12)$$

where N = the number of responses in the group (see Table 2). For the test of significance, a CPV is computed from a data set for each factor. The set includes the standard deviation, s, responses and their corresponding levels for one of the factors.

In this way, reproducibility evaluations are made for each material and for data <u>combined</u> for more than one material. The response parameter in each case is the value of s, converted to rank <u>within</u> a material. For combined data, this same <u>rank</u> (of s <u>within</u> <u>a</u> <u>material</u>) is the response parameter. The variance of data for each material to be combined is different, i.e., the pooled s for all responses of a material differ for the various materials evaluated. In the test of significance, each s response is assigned a rank that depends upon performance within one of the materials, so that the effects of differences among the variances of the three materials are effectively eliminated, when the CPV is computed.

5.1.3 Accuracy

The test of significance is an estimate of the accuracy of the responses for each level of a factor whenever the CPV is obtained from computed estimates of K for which reference K_{Ic} values are available. The estimator of accuracy used here is called the percent relative deviation (%RD). This estimator of accuracy is based upon the difference between a value of fracture toughness, K, computed by one of the described methods (Section 4) used for precracked Charpy specimens, and the reference value (K_{Ic}) computed in accordance with ASTM Method E 399 [5] for large compact tension specimens. The %RD is this difference expressed as a percentage of K_{Ic}.

The %RD has an average in studies of this type. It can sometimes be an absolute measure that can be used to compare directly the results of one material (with one level of K_{Ic}) with those of another material (with another level of K_{Ic}); in these instances it would be a measure of the accuracy of the predicted response. The formula for relative deviation is

$$\%RD = (K - K_{Ic})\ 100/K_{Ic}. \qquad (13)$$

Thus, the absolute value of relative deviation is a measure of the departure of the computed K from the reference K_{Ic}, and responses of lower absolute values of %RD are considered to be better in accuracy.

It is noted that when %RD is negative, K is smaller than K_{Ic}. Further, the test of significance used on this analysis will not yield the same result for the algebraic value of %RD and for the absolute value of %RD. In this report, tests of significance are conducted using the algebraic value of a response rather than the absolute value. This is done because most of the responses evaluated were found to be linearly related to crack length and information would be lost to the test if the absolute values were used.

The test of significance is conducted independently for each of two response parameters: y_i, the individual response, and $\bar{Y}$, the mean response for replicates. Both of the tests (one on the individual observation y_i and another on the average $\bar{Y}$ of the data over replications within a level) were conducted so as to assure that the conclusions of the analysis were not dependent on a single approach. This follows a general principle of data analysis which states that perturbations in the analysis should be introduced whenever possible so as to assess the sensitivity of the conclusion to various facets of the analysis. The ultimate objective is to arrive at conclusions which are simple manifestations of the data "speaking for themselves" and devoid of any implicit bias introduced by the method of analysis. This objective is best attained by the aforementioned analytic perturbations--approach-dependent results will yield different conclusions for different perturbations; approach-independent results will yield substantially the same conclusions regardless of the particular perturbation.

The accuracy of responses for combined materials is given a test of significance in a manner similar to that described earlier for the reproducibility responses, except that both replicated and nonreplicated responses are included in the data set and two tests of significance are made. The response for one test is the rank of y_i within a material and the response for the other is the rank of $\bar{Y}$ within a material.

5.2 Multiple Linear Regression

A procedure based on linear regression may also be used to complement the Kruskal-Wallis analysis. It is important to carry out alternative analyses (such as the regression procedure discussed in this section and the graphical procedure to be discussed in the following section) so as to assure that conclusions are not approach-dependent. Conclusions which do not hold up over all three different approaches would lead one to suspect their validity; alternatively, a consistency of conclusions over the three separate approaches is highly supportive of their validity.

The first step in the regression approach consisted of fitting the response versus $\bar{a}$ as described by the model:

$$y = \beta_0 + \beta_1 \bar{a}. \qquad (14)$$

Due to results from the Kruskall-Wallis test, $\bar{a}$ was chosen as the first factor of interest. After this linear fit was performed, the residual standard deviation was computed and noted. At this point, there exist various tests that could be applied to determine if $\bar{a}$ itself is significant. The simplest such test is to note whether the slope β_1 is significantly nonzero. A second test is to compare the 1-factor residual standard deviation with the residual standard deviation gotten by fitting the model:

$$y = \beta_0 + e. \tag{15}$$

If a significant reduction has occurred, then $\bar{a}$ is interpreted as being significant.

The next step was to augment the 1-factor model to a 2-factor model as follows:

$$y = \beta_0 + \beta_1 \bar{a} + \beta_2 K_f. \tag{16}$$

The K_f factor was chosen again from Kruskall-Wallis test results. The residual standard deviation for this 2-factor model was computed. The appropriate test of significance was then carried out to determine if a significant reduction occurred in the residual standard deviation in going from the 1-factor model to the 2-factor model. Such a significant reduction would be interpreted as the second factor (K_f) being significant.

The final step was to similarly augment the 2-factor model to a 3-factor model:

$$y = \beta_0 + \beta_1 \bar{a} + \beta_2 K_f + \beta_3 NP. \tag{17}$$

As before, the residual standard deviation was computed and compared to the 2-factor residual standard deviation. A significant reduction would imply the significance of the notch preparation factor.

5.3 Graphical Analysis

The graphical approach is a valuable complement to the Kruskall-Wallis and regression procedures. The rationale behind the graphics approach is multifold: First of all, it allows one to use the eye's built-in pattern recognition capabilities to confirm or explain significance or nonsignificance of a factor. Secondly, the graphical approach is not sensitive to one particular aspect of the data set, but rather incorporates the entire data set--each point individually--and so it uncovers not only what we suspect, but also what we may not suspect. A third point is that outliers are most easily flagged via a graphical approach. Outliers stand out on a plot and are easily noticeable. Subsequently, they may be confirmed as such by subsequent rigorous statistical tests. A fourth advantage of the graphical approach is that it is assumption free--the validation of conclusions and suspicions unearthed via graphics are not dependent on some underlying statistical assumptions, because, by and large, no assumptions are made in employing a graphical analysis. Fifth, the use of graphics avoids the potential problem of reducing a large data set to a few statistics--such few statistics must necessarily be sensitive to only certain aspects of the data and will be insensitive to many other aspects of the data. Such statistical selectivity has the net result that some information is emphasized, but most information in the data set is filtered out and ignored. Statistics for summary purposes has its place, but for analysis purposes, a properly constructed plot will frequently be more informative. The final advantage of the graphical approach is that of communication. Whereas the use of the Kruskall-Wallis and regression procedures of the analysis may not be fully understood by some researcher, a properly constructed plot to emphasize the significance of a factor is easily understood by all.

All in all, the graphics approach is for many reasons a valuable one--its application to the Charpy data served as a useful complement to the Kruskall-Wallis and linear regression approaches.

6. Results

The results indicate that: (1) All seven computed responses are linearly related to crack size and the sensitivity to crack size varies with the choice of response parameter and with material. (2) Precracking at either very high or very low levels of stress-intensity factor, K_f, are to be avoided. (3) For the three methods of notch preparation used in this study, no significant effects (of notch preparation) on the responses were observed.

In the presentation to follow, anomalies in the test data are described before these results are developed. The anomalies include departures from the proposed experimental design. Reasons are given for elimination of selected test data from this analysis. The method of analysis using the KW test of significance is then further described by application to the problem of determining whether the levels of three factors are significantly different for the response R_{sb}. The results of the KW test are then presented for all other responses. The presentation describes results for R_{sb} in detail and results for various responses of K more succinctly. Next, sections are devoted to the results for each of the factors, crack size K_f maximum, and notch preparation. Finally, the sensitivity to crack size is discussed for the responses.

6.1 Anomalies in the Data

This analysis of the Phase I slow-bend test data led to conclusions that some of the data submitted for analysis should not be included in determinations of the effects of the levels of the factors. Before discussion of the test results, the data excluded from the analyses are mentioned here.

A preliminary analysis of the data indicated that responses computed for test specimens with crack size less than 2.46 mm (0.097 in) should be excluded from the analysis because the variability of these responses was greater than that for specimens with larger crack sizes. These excluded specimens include some that were reported to have crack size of 2.00 mm (0.079 in) and thus were acknowledged by the experimentalist to have been uncracked after the completion of the precracking process. Others had reported crack sizes up to 2.18 mm (0.086 in). It was concluded that these excluded data would have confounded the test results. Therefore, specimens with crack sizes less than 2.46 mm (0.097 in) were excluded from the analysis. It is noted that the depth of the machined notch is about 2.0 mm, and this is about 0.5 mm less than the cut-off established for the present work. Thus, a minimum of 0.5 mm of fatigue crack growth was established here as a limit below which variability of the response increased greatly. From this experience, it is recommended that a minimum crack extension equal to 0.5 mm (a CVN crack size equal to about 2.5 mm) may be required as a practical measure to assure that fatigue crack initiation is properly detected and that the crack front has developed across the entire front of the V notch of a Charpy specimen.

In addition, during a preliminary analysis of data, one specimen of Aluminum and one of Steel behaved as outliers and the discrepancies could not be resolved with the experimentalist, so these two specimens were omitted.

Data for Steel specimens with the smallest crack size factor ($\bar{a}$ code 1) were not included in the analysis for the response K_Q'. For reasons given under Test Procedures, the total energy, E_T, for many of these specimens was in error. The response K_Q' is the only response that is based on total energy. Therefore, K_Q' is the only response for which it was necessary to omit the data for Steel specimens of $\bar{a}$ code 1.

Titanium data were derived from four sets of Charpy specimens, taken from each of four compact tension specimens (CTS). See table 4. Charpy specimens taken from one of the four CTS, the one coded W, were anomalous in several respects and were omitted from determinations of the significance of and effects of the levels of the factors. Apparently, the code W Charpy specimens were not randomized before being selected for precracking, as they were all precracked at a single level of K_f maximum. This is shown in figure 5, which is a plot of the computed R_{sb} response as a function of K_f maximum. The plot characters (R, T, L, and W) represent the CTS specimen from which the Charpy specimens were taken. All W specimens are shown to have been precracked at K_f code 3, the highest level of K_f maximum in this plot. None of the other Titanium specimens were precracked at this level. In addition, it is seen that for R_{sb} data, the mean and the variance of these code W results are significantly different (smaller than) those for the R, T, and L data, which are plotted at lower levels of K_f maximum, codes 1 and 2; large differences (between mean and between variance) were also observed for most of the other computed responses of K. Further, as indicated in table 5, the CTS coded W is the only Titanium CTS that failed the validity requirements of ASTM Method E 399, and this CTS has the lowest fracture toughness (77.4 ksi $(in)^{1/2}$) among the four CTS of Titanium tested. It was concluded that for Titanium, the code W specimens and therefore the Code 3, K_f maximum level should be excluded here, in determinations of the significance of the levels of a factor.

In developing an understanding of the results for the factor K_f maximum, the reader is asked to bear in mind that, contrary to the original experimental design with its three proposed K_f ratios, a wide range of actual K_f ratios (K_f maximum/K smallest) were used in this test program. This range is illustrated in figure 6, which is a plot of the computed responses %RD of K_J' as a function of K_f ratio. Steel specimens are precracked over a wide range of ratios within each of three proposed "discrete" levels of the factor K_f maximum. The highest K_f ratio used for Steel is about 1.3 $Ksi(in)^{1/2}$, a level well above the proposed Code 3 level of 1.0. These ratios for Steel are measured at the finish of precracking (see table 7). Discrete levels of the ratio are shown for Aluminum (0.33, 0.67, and 1.0) and for Titanium (0.20, and 0.40), and these ratios were measured at the start of precracking. Due principally to brinelling at the load points of the specimen, the actual K_f maximum at the finish is expected to be slightly lower than these indicated levels for Aluminum and Titanium. Thus, the range of stress-intensity ratios used in precracking the three materials varies from less than 0.20 to more than 1.3, and the levels for only two of the materials are discrete and are measured at the start of precracking.

6.2 <u>Results of KW Test of Significance for R_{sb} Responses</u>

The CPV results of the KW tests of significance conducted for the R_{sb} responses are presented as table 8 and described here to facilitate reader understanding of the method of this analysis. Included are the results for Aluminum, all Titanium (including the Code W specimens), Titanium (including only the R, T, and L specimens), and Steel. In addition, results for the combined materials, Aluminum, Titanium (R,T,W,&L), and Steel are presented.

In summary, these cumulative probability results indicate that for the factor NP, the level of the factor is not significant for any of the three materials; for the factor K_f maximum, the level is significant for steel and possibly significant for Titanium; and the factor $\bar{a}$ is significant for all three materials tested. In general, the combined results tend to reflect any significant effect that is found for one or more of the individual materials.

The conclusion that the level of the factor NP does not significantly affect the R_{sb} responses for any of the three materials tested is supported by results given in table 8. The highest cumulative probabilities are 69% for the individual response (y_i), 61% for the mean response ($\bar{Y}$) and 78% for the reproducibility parameter (s). Thus, the highest value in the analysis of the factor NP, is 86%. This indicates that even if the null hypothesis is true (that the factor NP for Steel has no effect on test result R_{sb}), we would on the average erroneously reject that hypothesis 14% of the time. Stated another way, on the average when the null hypothesis is true, then 14% of the time the calculated test statistic will exceed the tabulated 86% point of the null distribution for the factor NP, using the results for reproducibility of R_{sb} responses for Steel. Inasmuch as commonly used significance levels for hypothesis testing are 1, 5, and 10%, then it is concluded that the three levels of the factor NP are not significantly different from one another on the basis of either the level of the response, y_i or $\bar{Y}$, or the reproducibility of the response, s. Thus it is concluded, on the basis of a distribution-free analysis of variance, that the levels of the factor NP do not significantly affect the R_{sb} response for the materials tested.

The conclusion that the level of the factor K_f maximum is significant for Steel and possibly significant for Titanium is obtained from the CPV given in table 8. For Steel, the response parameters y_i and $\bar{Y}$ are, respectively, 98% and 96%, indicating that the effect on the response R_{sb} is significant at the 5% confidence level. The CPV for the reproducibility parameter s is only 25%; thus, reproducibility of R_{sb} responses for Steel is considered to be not affected significantly by the level of the factor K_f maximum.

For Titanium, only 2 levels of K_f maximum are tested for the RTL specimens used in the KW test of significance. Their CPV results are 50% for y_i, 21% for $\bar{Y}$, and 90% for s. The y_i and $\bar{Y}$ results clearly indicate that the response is not affected significantly by the level of the factor K_f maximum, but the value of 90% for s is marginal, being significant at only the 10% confidence level. The possible effect of the level of K_f maximum on the reproducibility of R_{sb} responses therefore requires clarification from a more thorough analysis, which is presented later.

When Code W specimens of Titanium are included in the analysis of either "all Titanium" data or combined data for the three materials, the conclusions given above for Titanium are contradicted, and this points up the impropriety of the use of the Code W data. For all Titanium data, the CPV exceeds 94 percent for each of the parameters, y_i, $\bar{Y}$, and s. These data supplement what was said earlier concerning the exclusion of Code W specimens from the Phase I program and this analysis. For the combined data set, the CPVs for the parameters y_i and $\bar{Y}$ exceed 90% in support of the trend for steel.

6.3 Results of KW Test of Significance for All Responses

The results of the KW tests conducted for each of the responses R_{sb}, K'_Q, K_{Q-PM}, K_Q, K'_J, K_J, and K^*_d are presented as Appendix Tables III through V for the factors $\bar{a}$, K_f maximum, and NP, respectively. In these tables are given the results for each of the materials and for the combined materials. The Code W data for Titanium are excluded from the analyses of the Titanium (RTL) data, from the analyses given for Combined Materials and from the findings of this report of the Phase I program.

In general, the results of the KW tests of significance indicate that

(1) The level of the crack-size factor $\bar{a}$ is significant for all three materials and for almost every computed response. This is evident from the results of both the individual response parameter y_i and from the mean response parameter $\bar{Y}$.

(2) The level of the stress-intensity factor used in precracking, K_f maximum, is significant for one or more responses for each material, but the significance levels are generally not as high as for the crack-size factor.

(3) The level of the notch preparation factor NP is not significant.

(4) For selected cases, the reproducibility parameter is significant for the factors $\bar{a}$ and K_f maximum.

6.4. Effects of Crack Size and Material

Responses computed from slow-bend tests of precracked Charpy specimens are shown to be linearly related to crack size. With increases in normalized crack size, responses of R_{sb} increase and responses of K decrease. The relationship between response and crack size depends on the choice of response parameter and on the material. In this section, these relationships will be illustrated. In Section 6.7, the sensitivity of the response to crack size will be examined as a function of response parameter and material.

The predominant effect of crack size on the test responses is illustrated by selected plots presented as figures 7 through 12. In general, the responses of K (or %RD of K) decrease roughly linearly with increases in normalized crack size, as shown in figure 7, which is a plot of the responses of %RD of K_J' for Aluminum specimens. The plot characters (1, 2, and 3) used here represent the levels of the factor K_f maximum to be discussed later. Figure 8 is similar to figure 7, except that the data is for the response R_{sb} and a regression line is shown to illustrate the expected value of response R_{sb} with increases in normalized crack size. The effect of the response parameter is illustrated further in figure 9, a plot of the regression results for Aluminum for each of the seven responses of %RD as functions of normalized crack size. Further, in table 9, results of regression analyses used for these plots are given, for all three materials. The function %RD of R_{sb} used in figure 9 and table 9 was computed using an arbitrary reference chosen to be the mean R_{sb} response, $\bar{R}_{sb}$, computed for each material. Thus, each R_{sb} response was converted to a %RD of R_{sb} so that the results of regression analyses of R_{sb} responses could be expressed in terms that would facilitate comparison with the %RD of K values (see Eq. 13) used in analyses of all other responses computed from Charpy test results. This conversion is especially useful in the analysis of sensitivity to crack size. Figure 9 and table 9 each illustrate that both the slope and the magnitude of the response are functions of the response parameter. In the figure, R_{sb} is the only response with a positive slope. Further, the magnitudes of the responses of K are shown to decrease roughly in the order K_J, K_J', K_d^*, K_Q', K_{Q-PM}, and K_Q. However, the magnitude is dependent on the material; and the order indicated above for Aluminum is, to some extent, a function of material, as well as crack size. The sensitivity of the response to crack size is discussed in Section 6.7.

The effect of material is illustrated in figures 10 through 12 and in table 9. From the regression results, given in the figures and in the table, it is seen that at any crack length, the magnitude of the expected response (%RD of K or R_{sb}) is much greater for Steel than for Aluminum or Titanium, and this effect is especially marked for all of the K responses. This result opens to question the validity of the reference value of K_{Ic} used for this Steel. As was shown earlier among the CTS results used to obtain K_{Ic} reference values (table 4), the Steel failed to meet the thickness requirement, whereas the Aluminum and the Titanium both passed this requirement. Hence, this K_{Ic} for Steel is unique among the K_{Ic} reference values used in this analysis.

6.5 Effect of K_f maximum

The results, as summarized in table 10, indicate that precracking at levels of K_f maximum outside the range of 0.4 to 0.9 times K smallest is to be avoided, as either the magnitude or the variability of computed responses of K or R_{sb} may be greater than that for responses for specimens precracked within this range. These observed effects of the level of K_f maximum are somewhat dependent on the response parameter and are generally dependent on crack-size factor. For example, R_{sb} is the only response with greater variability at high K_f ratio. Furthermore, the results are based on limited data and they may be dependent on the material, as each material was not tested over the same range of K_f ratios (K_f maximum/K smallest), and data are sparse for some combinations of coded $\bar{a}$ and K_f levels. The range of K_f ratios for these tests are 0.33 to 1.0 for Aluminum, 0.20 to 0.40 for Titanium, and 0.33 to 1.3 for Steel. Thus, while conclusions of this analysis are presumed to be generally applicable to all materials tested, this presumption could not be completely tested with the available data.

A summary of significant results, for all seven responses and for the three materials, is given in table 10. A CPV is shown for the F test of the relevant MLR analysis and for each of the relevant parameters (y_i, $\bar{Y}$ and s) of the KW test. The CPV is given for each significant result and for a few others, included for comparison. In addition, some symbols are presented in this table, to represent the significance. The symbols S_y and S_s represent those cases in which the K_f ratio significantly affects the magnitude and reproducibility, respectively, of the response. The symbol "?" is used in selected cases to indicate a questionably significant result. For each case in which one of these symbols is indicated, in either Column A for the magnitude of the response, or Column C for the reproducibility of the response, graphical analysis was conducted to further establish, illustrate, and describe the effect. The combined results of these methods of analysis gives a final result indicated in Column B (for the effect of K_f on the magnitude of the response) or in Column D (for that of the reproducibility). Results are illustrated in figures 13 through 16.

6.5.1 Aluminum

Results for aluminum specimens indicate that for $\bar{a}$ codes 1 and 2, at a K_f ratio less than 0.4 the magnitude of the response is greater than at higher K_f ratios. As is indicated in table 10 column B, the magnitudes for all responses except R_{sb}, K_Q, and K_Q' are significant. This effect of a low K_f ratio is illustrated in a plot given as figure 13, in which data for %RD of K_J' are plotted against the K_f ratio. The plot characters represent coded crack length. For each crack size shown, the response for specimens precracked at a ratio of 1.0 is similar to that at a ratio of 0.67, but for specimens precracked at a ratio of 0.33 the magnitude of the response increases for $\bar{a}$ codes 1 and 2. This plot typifies and represents four of the five significant responses for Aluminum specimens; these are K_{Q-PM}, K_J', K_J, and K_d^*. A graphical analysis for the other significant response, K_Q, indicates that this effect is perhaps significant but only for $\bar{a}$ code 1. For $\bar{a}$ code 2 specimens, responses of K_Q for specimens precracked at a K_f ratio of 1.0 have greater magnitude than those precracked at ratios of either 0.67 or 0.33. Thus, for Aluminum specimens, K_Q responses are unique among the seven responses, and the other significant responses behaved as shown in figure 13.

6.5.2 Titanium

Results for titanium specimens indicate that the factor K_f maximum is significant for all seven responses and on the basis of limited available data for six of these responses and for $\bar{a}$ codes 1 and 2 only, it is concluded that responses for specimens precracked at a very low K_f ratio of 0.20 may have greater variability than the variability for specimens precracked at a ratio of 0.40. These findings are summarized in table 10 columns C and D. For Titanium specimens, data is available only for two levels of the K_f ratio and at the lowest level (0.20) the data are sparse for specimens of $\bar{a}$ code 1 and very sparse for those of $\bar{a}$ code 3. Thus, the conclusions are somewhat tentative.

The results indicate that for $\bar{a}$ code 2 at a K_f ratio of 0.20, responses are more variable than at a K_f ratio of 0.40. This is true for five of the responses, including R_{sb}, K_{Q-PM}, K_J, K_J', and K_d^*, and for each of these responses it appears that the effect may be significant even for specimens of $\bar{a}$ code 1, for which the data are sparse. For a sixth response K_Q', this effect clearly is significant only for $\bar{a}$ code 2. The result for the seventh response K_Q is significant but markedly different from that of the other responses. At a K_f ratio of 0.20, the magnitude of K_Q responses is <u>smaller</u> for $\bar{a}$ codes 1, 2, and 3, and the variability is greater for $\bar{a}$ code 2 specimens but smaller for $\bar{a}$ code 1 specimens. Thus, K_Q responses behave uniquely (in both S_s and S_y of table 10) amongst these seven responses. The unique behavior observed for the response parameter K_Q for both the Aluminum and the Titanium specimens, as discussed in this section, give the authors pause and we note that in a previous work [14], the parameter K_Q (based on the same 5% secant intercept used in the present work) was found to be an inappropriate parameter for evaluations of fracture toughness in sub-sized specimens of a heat of 4340 steel at a yield strength of 180 ksi. It is concluded that K_Q may be an inappropriate parameter for evaluations of the fracture toughness using Charpy tests conducted under conditions used in this study. These conditions give a load-displacement trace of the type shown in figure 3, in which there is no indication of a cleavage initiation event.

The general behavior described for the other significant responses is illustrated in figure 14, a plot of data for response %RD of K_J' versus the K_f ratio. In the figure, the increased variability at a ratio of 0.20 is clearly evident for code 2, it is less clear for code 1, and for code 3 the data are too sparse for an assessment of an effect. This illustration is consistent with the KW test result of table 10 column C, which indicates that the CPV for the reproducibility parameter s of the KW test equals 96% for these coded data. Thus, it is concluded that, on the basis of the available data for Titanium specimens of $\bar{a}$ codes 1 and 2, responses for specimens precracked at a very low K_f ratio of 0.20 have greater variance than those for specimens precracked at a ratio of 0.40.

6.5.3 Steel

Steel specimens were precracked at K_f ratios of from 0.33 to 1.3 (see table 7). However, only a limited number of specimens were precracked at a ratio of less than 0.4. Hence, the results for Steel are used here for conclusions concerning the general trends for ratios above 0.4. In general, the data for steel specimens indicate that the magnitude of each of the seven responses tends to increase with increases in the K_f ratio. This effect is most marked for Steel specimens of $\bar{a}$ code 2 and it indicates that precracking at K_f ratios above 0.9 is to be avoided. In addition, for R_{sb} variability of responses may increase at either high or low levels of the K_f ratio.

The general tendency for increases in the response with increases in the K_f ratio is illustrated by figure 15, a plot for Steel specimens showing data and a regression line for responses of R_{sb} versus the K_f ratio. Table 10 indicates the magnitude of the response is significant. Although the reproducibility parameter in the KW test (column C) does not indicate a significant effect, it is apparant from this plot of R_{sb} data that for $\bar{a}$ codes 2 and 3, variability is decidedly smaller at intermediate levels of the K_f ratio. Thus, it is concluded that both the magnitude and the variability of response R_{sb} may be significantly affected by the level of K_f ratio for Steel specimens.

The marked effect of K_f ratio on the responses of %RD of K observed for $\bar{a}$ code 2 specimens is illustrated in figure 16, a plot of coded-crack-length data for response K_{Q-PM} versus K_f ratio. Linear regression lines for each of the three coded crack lengths are shown in order to facilitate comparisons of the effects of the K_f ratio for each coded crack size. Significance tests (table 10) indicate S_y (K_f maximum has a signficant effect on the response magnitude) for both the KW tests and the MLR analyses, except for responses based on energy to maximum load (K_J, K_J', and K_d^*), for which only the MLR analyses lead to a significant effect of K_f maximum. Graphical analyses for these three responses indicate a significant behavior only for $\bar{a}$ codes 1 and 2. It is noted that for response K_Q', data are not available for Steel specimens of $\bar{a}$ code 1, and the observed effects for the available data ($\bar{a}$ codes 2 and 3) are similar to the effects illustrated in figure 16 for K_{Q-PM}. Thus, it is concluded that the magnitude of each of the seven responses tends to increase with increases in the K_f ratio for Steel specimens. This effect is most marked for Steel specimens of $\bar{a}$ code 2 and it is an indication that precracking at K_f ratios above 0.9 is to be avoided. In addition, it was shown that for response R_{sb}, variability of the response may increase at either high or low levels of the K_f ratio, and this is another indication that these extreme K_f levels are to be avoided.

6.6 Effects of Notch Preparation

Significant effects of the level of NP on the responses were observed only for Steel specimens, for three responses R_{sb}, K_{Q-PM} and K'_Q. These effects were supported by results of MLR and graphical analyses, but they went largely undetected by the KW test for significant differences among coded levels of the factor NP. The results indicate that for a hard material, such as the margaging steel used in the Phase I program, razor scratching before precracking may lead to increases in either the variability or the magnitude of the response.

The KW test results, given as Appendix Table V, indicate that at the 10 percent confidence level the only potentially significant responses are K'_Q for Titanium (R, T, and L) specimens and K_{Q-PM} for Steel specimens. In this table, for Titanium, y_i is 92 percent for K'_Q responses, and for the Steel, s is 96 percent for K_{Q-PM}. Graphical and MLR analyses of the Titanium data indicated that there is no effect of NP on the magnitudes of the responses of K'_Q for Titanium. This eliminates Titanium from further consideration for effects of notch preparation. However, results of graphical and MLR analyses conducted with the data for Steel indicate that NP is significant for responses R_{sb}, K_{Q-PM}, and K'_Q. These NP results are summarized in table 11, which also gives some results for responses K'_J and K^*_d, two responses for which significant effects of NP were not found.

The observed significant effect of NP for Steel specimens is illustrated in figure 17, a plot of %RD of K_{Q-PM} vs $\bar{a}/W$. Results in table 11 indicate that, statistically, K_{Q-PM} responses are affected more greatly than the other two significant responses, R_{sb} and K'_Q. Figure 17 illustrates an effect observed in plots for all three responses, R_{sb}, K_{Q-PM}, and K'_Q: Variability of responses for NP code 1 is greater than that for codes 2 or 3.

Figure 17 also illustrates two effects observed only for responses R_{sb} and K_{Q-PM}: (1) the mean and median responses for NP code 1 are greater than those for codes 2 or 3, and (2) there exists along the top of the trend band (of each plot) a set of NP code 1 data, with no data there for the other NP codes. Not illustrated in this plot is the observed effect of NP on the magnitudes of the responses of K_Q': The K_Q' responses are generally smallest for data of NP code 1, and there are NP code 1 data at the <u>bottom</u> of the plot of for K_Q'. Thus, for NP code 1, while the magnitudes of responses of selected specimens are greater for response of R_{sb} and K_{Q-PM}, they are smaller for K_Q' responses; further, NP code 1 responses for R_{sb}, K_{Q-PM}, and K_Q' are more variable than those for NP codes 2 and 3. Clearly, selected test results of Np-code-1 steel specimens are signficantly contributing to the variability and magnitude of results for responses R_{sb}, K_{Q-PM}, and K_Q' for steel.

Our interpretation of these findings is that some Steel specimens of NP code 1 (razor scratched) were somehow improperly prepared for the precracking process. The net result of this improper preparation is that something (perhaps an uneven crack front or perhaps cold work) occurred in the test specimen during precracking. As a result of this, (1) responses that are a function of maximum load (R_{sb} and K_{Q-PM}) have greater than expected magnitude, (2) the response that is a function of total energy absorbed (K_Q') has smaller magnitude, and (3) those that are a function of either P_Q or energy to maximum load do not appear to be affected by NP. Because these effects of NP were not observed for the softer materials, Aluminum and Titanium, it is further speculated that, in general, the observed effect of NP occurred in this Steel because it is a difficult material to scratch with a razor blade, especially after the blade begins to become dull, as it might after being used to scratch several hard steel specimens.

The results given above are believed to be unaffected by the previously discussed effect of the level of K_f maximum on the responses for Steel. This was assured by graphical analyses in which the responses for K_f code 3 were tagged and counted for each NP and $\bar{a}$ code subdivision. Thus, it is concluded that razor scratching before precracking may lead to increases in either the variability or the magnitude of the reponse for a hard material, such as the maraging steel used in the Phase I program.

6.7 <u>Sensitivity of Response to Crack Size.</u>

In this section, the sensitivity of the response to crack size is shown to be a function of the choice of response parameter and of the material. The response parameters most sensitive to crack size are K_J and K_J', both of which are based on energy to maximum load. Among the three materials tested, Steel is most sensitive to crack size and Aluminum is least sensitive to crack size.

Comparisons of the sensitivity of response parameter R_{sb} with that of one of the responses based on %RD of K is facilitated here in tables 9 and 12 and in figure 9, by the conversion of data for response R_{sb} to percent relative deviation (%RD of R_{sb}) from an arbitrary reference, the mean R_{sb} for each material, as discussed in Section 6.4. Table 12 contains selected data from table 9. These are data needed to compare the relative sensitivities (of all seven responses) to crack size. Two numbers are given for each combination of response parameter and material. The first of these is the slope, in the relationship between %RD of response and crack size (eq. 14), and the second is the residual standard deviation obtained from the fit to equation 14.

The indicated slopes and residuals lead to the conclusion that responses based either on a single value of load, including R_{sb}, K_Q, and K_{Q-PM}, or on a total energy, K'_Q, are less sensitive to crack size, in comparison with the sensitivities of responses based on an energy to maximum load. The slopes for responses that are based on either a load or total energy are comparatively small. They vary from 0.04 to 0.11. On the other hand, slopes for responses K_J and K'_J are particularly large, ranging from 0.20 to 0.43. Slopes for response K^*_d are intermediate in magnitude ranging from 0.11 to 0.18. Thus, responses based on energy to maximum load are more sensitive. This is illustrated by regression results for aluminum given as figure 9. In addition, residuals (table 12) for responses based either on a single value of load or on total energy are generally smaller and range from 2.4 to 6.1, whereas residuals for responses based on energy to maximum load are larger and range from 5.3 to 8.7. Thus, it is concluded that, among the seven responses, K_J and K'_J are most sensitive to crack size, K^*_d is intermediate in sensitivity to crack size, and responses based on either a single value of load or total energy are least sensitive to crack size and are generally similar to one another in sensitivity to crack size.

The relative sensitivity to crack size is measured by the absolute magnitude of the slope given as β_1 in table 9. These data indicate that

(1) The three materials tested are similar, but minor differences are present.

(2) The Steel is most sensitive to crack size.

(3) The Titanium and the Aluminum have similar sensitivities to crack size.

Table 12 shows the similarities between slopes for most responses of aluminum and those of titanium, and it shows that the slope for most responses is greater for the Steel than for the other materials, with the exception of responses R_{sb} and K'_Q for which slopes are nearly equal for each of the three materials.

Table 12 indicates that the residual standard deviation for six of the seven responses is smaller for Aluminum than for either of the other two materials. This is an indication that Aluminum is least variable.

7. Conclusions

7.1 Responses computed from slow-bend tests of precracked Charpy specimens are shown to be linearly related to crack size.

7.1.1 With an increase in crack size, the response of R_{sb} increases and the K responses decrease.

7.1.2 At fixed crack size, the magnitude of the %RD of K, for each of six responses, is much greater for the Steel tested than that for the Aluminum or the Titanium, a result that opens to question the validity of the reference value of K_{Ic} used for the Steel.

7.2 The sensitivity of the response to crack size is a function of both the choice of response parameter and of the material.

7.2.1 Among the seven response parameters evaluated here, K_J and K_J' are most sensitive to crack size, K_d^* is intermediate, and responses based on either total energy (K_Q') or a single value of load, (K_{Q-PM}, K_Q and R_{sb}) are least sensitive and are similar to one another in sensitivity to crack size.

7.2.2 Among the three materials tested, sensitivity to crack size is greatest for the Steel and least for the Aluminum.

7.3 Preliminary screening of the data used for this analysis led to the conclusion that a lower bound of crack size equal to about 2.5 mm (0.098 in) may be required as a practical measure to assure that fatigue crack initiation is properly detected and that it has developed across the entire front of the V notch of a Charpy specimen.

7.4 Precracking at levels of K_f maximum outside the range of from 0.4 to 0.9 times K smallest is to be avoided, as either the magnitude or the variability of computed responses of K or R_{sb} may be greater than that for responses for specimens precracked within this range.

7.4.1 Available data for the Aluminum and the Titanium tested indicate that precracking at levels below a K_f ratio of about 0.4 is to be avoided, as either the magnitude or the variability of the response may be increased.

7.4.2 Indications that precracking at a low K_f ratio may increase the magnitude of the response were obtained from results of tests of Aluminum specimens. At a K_f ratio less than 0.4, the magnitude of the response is greater for crack sizes of $\bar{a}$ codes 1 and 2. This was observed for four of five significant responses K_{Q-PM}, K_J', K_J and K_d^*. For the fifth significant response, K_Q, the magnitude is greater only for $\bar{a}$ code 1.

7.4.3 Indications that precracking at low K_f ratio may increase the variability of the response were obtained from Titanium and Steel specimens. Results for Titanium specimens indicate that the factor K_f maximum is significant for all seven responses. On the basis of limited data available for six of these responses and for $\bar{a}$ codes 1 and 2 only, it is concluded that responses for specimens precracked at a very low K_f ratio of 0.20 may have greater variability than those for specimens precracked at a ratio of 0.40. Variability of R_{sb} responses for $\bar{a}$ codes 2 and 3 of Steel specimens is decidedly smaller at intermediate levels of the K_f ratio.

7.4.4 Results for the Steel specimens indicate that the magnitude of the response generally tends to increase with an increase in the K_f ratio over the range of ratios of from 0.33 to 1.3. This effect is most marked for specimens of $\bar{a}$ code 2, and it is an indication that pre-cracking at very high K_f ratios above 0.9 is to be avoided.

7.5 Among the three levels of notch preparation tested, no signficant effects of the level of NP on the response were observed, except for steel. The results indicate that for materials similar to those used inthe Phase I program, similar responses are to be expected from a standard notch that is either razor scratched or EDM sharpened or from a sharply (non-standard) machined notch. The results suggest that for hard specimens (like the steel used here) razor scratching may not be appropriate because hard specimens may be difficult to scratch uniformly.

7.6 The results indicate that the response K_Q based on a 5-percent-secant intercept may be inappropriate for characterization of fracture toughness using precracked Charpy tests conducted under conditions used in this study.

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Table 1

Proposed Test Matrix

Coded Levels of Factors			Proposed Number of Tests Per Material
NP	K_f	$\bar{a}$	Al, Ti, Steel
1	1	1	2
1	1	2	2
1	1	3	2
1	2	1	2
1	2	2	2
1	2	3	2
1	3	1	2
1	3	2	2
1	3	3	2
2	1	1	2
2	1	2	2
2	1	3	2
2	2	1	2
2	2	2	2
2	2	3	2
2	3	1	2
2	3	2	2
2	3	3	2
3	1	1	2
3	1	2	2
3	1	3	2
3	2	1	2
3	2	2	2
3	2	3	2
3	3	1	2
3	3	2	2
3	3	3	2
			54

Table 2

Actual Numbers of Tests Conducted for Each Level of the Factors
and for Each Material.

K_f* code	NP code	$\bar{a}$ code = 1			$\bar{a}$ code = 2			$\bar{a}$ code = 3			Sum for all $\bar{a}$ levels			
		0.097"<$\bar{a}$<.140			0.140≤$\bar{a}$≤0.180			0.180<$\bar{a}$<0.242					All Ti**	
		Al	Ti	Steel	Al	Ti	Steel	Al	Ti	Steel	Al	Ti**	RTL	Steel
	1	1	0	1	1	2	2	0	1	3	2	3	3	6
1	2	1	2	2	0	1	2	1	1	2	2	4	4	6
	3	1	1	2	2	2	2	0	0	2	3	3	3	6
	1	2	2	2	2	2	1	2	2	3	6	6	6	6
2	2	2	2	1	2	2	1	2	2	2	6	6	6	4
	3	2	3	2	1	1	2	3	2	2	6	6	6	6
	1	2	2	1	2	1	3	2	1	1	6	4	0	5
3	2	2	3	2	2	2	2	2	1	2	6	6	0	6
	3	2	4	2	1	0	2	3	2	2	6	6	0	6
								TOTALS			43	44	28	51

* See Table 7 for codes used in computer analysis.
**Data used in the analyses for Titanium include R, T, and L specimens and exclude all Charpy specimens prepared from a CTS specimen that was designated W.

Table 3

Chemical Composition
(Percent by Weight)

Material	Al	C	Co	Cr	Cu	Fe	H	Mg	Mn	Mo	N	Ni	O	Si	Ti	V	Zn	Zr
Aluminum Al-2419-T851 Sample 411081, Lot 216251	bal	-	-	0.00	6.14	.08	-	.02	.28	-	-	0.00	-	.06	.06	.11	.01	.15
Titanium Ti-6Al-4V Heat G50860-76	5.9	.028	-	-	-	.13	.006	-	-	-	.011	-	.09	-	bal	4.0	-	-
Steel AL MAR 18 (200) Heat 83514-1	-	.011	7.7	<.10	-	bal	<1ppm	-	.02	3.95	.001	17.8	6ppm	-	.20	-	-	.01

Table 4

MECHANICAL PROPERTIES AND RESULTS OF TESTS OF COMPACT TENSION SPECIMENS (CTS) TESTED BY METHOD ASTM E 399

Material and Orientation	Properties From Tensile Tests σ_Y (ksi)	σ_U (ksi)	Plot characters	CTS Fracture Toughness K_{Ic} or K_Q (ksi(in)$^{1/2}$)	CTS Thickness (in)	$2.5(K_{Ic}/\sigma_Y)^2$ E-399 Minimum Thickness Requirement	Handbook Properties: Elastic Mod. E x10^6 (psi)	Poisson's Ratio
4 Aluminum, aged			A					
Al-2419-T851						1.43		
Longitudinal	52	67		39.3$^{(a)}$, 38.4$^{(b)}$	1.500	1.36	10.5	.33
Titanium, annealed			T					
Ti-6Al-4V								
Longitudinal	112	125	R ≡	77.9	1.375	1.28	16.2	.30
			L ≡	80.2				
Transverse	120	128	W ≡	77.4$^{(c)}$	1.375	1.26	16.2	.30
			T ≡	85.5				
Steel, maraged			S					
AL MAR 18 (200)								
Transverse	203	223		120.5$^{(d)}$ ave. of 3 tests	0.750	.875	30.0	.33

Departure from E-399 Requirements

(a) $P_M/P_Q = 1.12$*

(b) $P_M/P_Q = 1.14$*

(c) $P_M/P_Q = 1.54$* -- These specimens were eliminated from this analysis.

(d) Fails thickness requirements -- computed K from Charpy specimens of this material were generally greater than this value.

*Fails: E-399 requires $P_M/P_Q \leq 1.1$

Table 5

Determination of K Smallest

MATERIAL & ASSUMED PROPERTIES	CRITERIA (See Eqs. 1, 2, and 3)		
	$K_{(1)} =$	$K_{(3)} =$	$K_{(2)} =$
	$K_{Ic} \frac{\sigma_{Y_1}}{\sigma_{Y_2}}$ *	$.57\sigma_Y$	$.002E$
Aluminum			
$\sigma_{Y1} = 60$ ksi $= \sigma_{Y2}$ $K_{Ic} = 40$ ksi(in)1/2 $E = 10 \times 10^3$ ksi	40	34	<u>20</u>
Titanium			
$\sigma_{Y1} = 100$ ksi $= \sigma_{Y2}$ $K_{Ic} = 80$ ksi(in)1/2 $E = 16.5 \times 10^3$ ksi	80	57	<u>33</u>
Steel			
$\sigma_{Y1} = 200$ ksi $= \sigma_{Y2}$ KIc = 100+ $E = 30 \times 10^3$ ksi	100+	114	<u>60</u>

* σ_{Y1} is the static yield strength at the precracking temperature and σ_{Y2} is the static (slow bend) yield strength at the test temperature.

Table 6

Preparation and Testing of Specimens and Preparation of Raw Data.

(Numbers given in parentheses represent participating laboratory and principal participant.)

Material (Source)	Tests of and Results from Compact Tension Specimens	Mechanical Machining and Notching of Charpy Specimens	Charpy Notch Sharpening	Precracking	Testing, and Preparation of Load Displacement Plots	Reduction of Data Taken From Charpy: Test Specimens	Reduction of Data Taken From Charpy: Plots of load vs Time or Deflection
Aluminum (1)	(1)	.010" radius (8)	razor scratched (4)	(4)	(6)	(6)	(6,7)
		.005" radius (8)	N/A	(4)	(6)	(6)	(6,7)
		.010" radius (8)	EDM (8)	(4)	(6)	(6)	(6,7)
Titanium (6)	(6)	.010" radius (5)	razor scratched (4)	(4)	(6)	(6)	(6,7)
		.005" radius (5)	N/A	(4)	(6)	(6)	(6,7)
		.010" radius (5)	EDM (8)	(4)	(6)	(6)	(6,7)
Steel (2)	(3)	.010" radius (8)	razor scratched (4)	(6)	(6)	(6)	(6)
		.005" radius (8)	N/A	(6)	(6)	(6)	(6)
		.010" radius (8)	EDM (8)	(6)	(6)	(6)	(6)

Participating Laboratories and principal participants:

(1) Alcoa; R. E. Davies
(2) Allegheny Ludlum (Coatesville); S. Fisher
(3) NASA Marshall Space Flight Center; M. W. Brennecke
(4) Effects Technology, Inc.; W. Server presently at Fracture Control Corp.
(5) Army Materials and Mechanics Research Center (AMMRC); C. Curll
(6) Air Force Materials Laboratory (Wright Patterson); T. Ronald
(7) National Bureau of Standards; C. Interrante
(8) The Timken Company; A. Burnett.

Table 7

Fatigue Precracking Levels, and Their Codes for Purposes of Data Analysis

Material Code	$K_{smallest}$ (1) (ksi (in)$^{1/2}$)	Proposed K_f maximum (ksi (in)$^{1/2}$)	Proposed K_f Ratio (2)	Actual K_f maximum (ksi (in)$^{1/2}$)	Actual K_f Ratio (2)	Codes for Computer: Within a material	Codes for Computer: For combined materials
Aluminum, 4	20						
Level 3		20.0	1.00	20.0	1.0	3	3
Level 2		13.3	0.67	13.3	0.67	2	2
Level 1		6.67	0.33	6.7	0.33	1	1
Titanium, 5	33						
Level 3		33.0	1.00	20.0	0.61	3	2
Level 2		22.0	0.67	13.3	0.40	2	1
Level 1		11.0	0.33	6.7	0.20	1	0
Steel, 6	60						
Level 3		60.0	1.00	(>55-70)	(>0.91-1.3)**	3	3
Level 2		40.0	0.67	(>35-55)	(>0.58-0.91)**	2	2
Level 1		20.0	0.33	(20-35)	(0.33-0.58)**	1	1

1 See Eq. 1, 2, 3.

**These represent values at the finish of precracking. K_f at the start would be slightly greater.

2
$$K_f \text{ Ratio} = \frac{K_f \text{ maximum}}{K_{smallest}}$$

Table 8

Kruskal-Wallis Test of Significance and Cumulative Probability Values for Response R_{sb}.

Type of Statistic	Response Parameter	N	Material	Cumulative Probability NP	K_f	Value for a
Single Material						
Individual Responses	y_i	43	Aluminum	68.9	56.9	>99.9
Mean Responses	Y	24	Aluminum	61.2	52.8	99.4
Reproducibility	s	17	Aluminum	51.3	70.7	96.8
Individual Responses	y_i	44	Titanium, all	22.5	100.0**	93.4
Mean Responses	Y	24	Titanium, all	7.3	>99.9	41.9
Reproducibility	s	16	Titanium, all	57.2	94.3	69.8
Individual Responses	y_i	28	T RTL only	57.5	49.8	96.9
Mean Responses	Y	16	T RTL only	25.0	20.9	95.1
Reproducibility	s	11	T RTL only	40.9	89.8	37.2
Individual responses	y_i	51	Steel	63.5	98.5	99.9
Mean responses	Y	27	Steel	35.3	96.0	99.6
Reproducibility	s	21	Steel	77.8	25.5	75.5
Combined Materials						
Individual Responses	Rank* of y_i	122	A, T(all), & S	61.3	99.3	100.0**
Mean Responses	Rank* of Y	67	A, T(all), & S	92. 7	99.2	>99.9
Reproducibility	Rank* of s	48	A, T(all), & S	53.5	3.5	99.5

*Rank is assigned within the response for a material

$$R_{sb} = 6P_m W/B(W-\bar{a})^2 \sigma_Y$$

** >99.9995

Table 9. Results of Regression Analyses Conducted for Each of Three Materials and for All Computed Responses.

Mat.		Observed Responses[2] Min.	Max.	$Y = \beta_1\bar{a} + \beta_o$ Slope β_1	Y-Int. β_o	$\bar{a}$ at K_{Ic} (mils)	Std. Dev. Pooled	Residual	Deg. of Freedom ν
4	RSB	1.83	2.20	0.0013	1.77	-1400.18	0.24	0.08	41
5	RSB	1.83	2.39	0.0011	1.86	-1625.20	0.15	0.12	26
6	RSB	1.96	2.35	0.0011	1.89	-1658.58	0.05	0.07	49
4	% RD of RSB	-7.35	11.47	0.0638	-10.64	166.74	-	3.87	41
5	% RD of RSB	-18.65	16.42	0.0560	-9.05	161.79	-	5.77	26
6	% RD of RSB	-6.09	20.32	0.0586	-10.02	171.08	-	3.67	49
4	% RD of KQ'	-13.65	2.47	-0.0739	6.46	87.35	2.73	2.39	41
5	% RD of KQ'	-14.09	8.73	-0.0665	7.93	119.28	5.78	5.94	26
6	% RD of KQ'>140[1]	9.86	42.47	-0.0660	37.62	-570.00	-	6.14	34
4	% RD of KQ-PM	-32.37	-14.42	-0.0730	-11.06	-151.57	3.14	3.03	41
5	% RD of KQ-PM	-27.75	-2.13	-0.0911	1.02	11.24	5.39	4.70	26
6	% RD of KQ-PM	-11.10	9.90	-0.1145	19.14	167.26	2.62	3.07	49
4	% RD of KQ	-37.81	-19.68	-0.0400	-22.43	-561.17	3.60	3.95	41
5	% RD of KQ	-33.51	-10.87	-0.0963	-3.99	-41.47	2.76	4.95	26
6	% RD of KQ	-21.99	0.34	-0.1021	7.69	75.33	3.06	4.09	49
4	% RD of KJ'	-19.63	28.19	-0.2191	40.06	182.78	6.23	6.23	41
5	% RD of KJ'	-10.48	31.89	-0.2026	41.06	202.65	9.89	8.67	26
6	% RD of KJ'	15.65	67.33	-0.3111	91.26	293.32	6.08	7.08	49
4	% RD of KJ	-10.79	38.85	-0.2505	52.04	207.75	6.02	5.28	41
5	% RD of KJ	-8.53	35.43	-0.2472	50.69	205.06	9.42	8.15	26
6	% RD of KJ	24.82	89.83	-0.4343	127.05	292.51	5.96	6.91	49
4	% RD of Kd*	-23.92	13.33	-0.1124	12.32	109.59	5.73	5.82	41
5	% RD of Kd*	-15.51	16.70	-0.0982	15.45	157.37	8.28	7.60	26
6	% RD of Kd*	9.33	45.04	-0.1774	55.82	314.65	5.31	6.10	49

[1]Only specimens with $\bar{a} > 140$ mils are included in the analysis.

[2]Given as an R_{sb} response or as a % RD of a K response.

Table 10. Summary of Results for the Factor K_f maximum.

Material	Response	CPV from KW Test N	CPV from KW Test y_i	CPV from KW Test Y	CPV from MLR F test	CPV from MLR ν	Column A Combined Results of KW Test and MLR Analysis	Column B Combined Results of Column A and Graphical Analysis	Column C Significant CPV for reproducibility parameter s of the KW test	Column D Result of Column C plus graphical analysis
		Tests for Significant Differences in the Magnitude of Test Response							Tests for Significant Differences in the Reproducibility of Test Responses	
4	R_{sb}	43	-	-	-	40	-	-	-	-
	K'_Q	43	-	-	-	40	-	-	-	-
	K_{Q-PM}	43	98	95	(71)	40	?	S_y	-	-
	K_Q	43	(84)	(64)	(86)	40	?	?	-	-
	K'_J	43	96	88	91	40	S_y	S_y	-	-
	K_J	43	95	88	95	40	S_y	S_y	-	-
	K^*_d	43	96	85	(86)	40	?	S_y	-	-
5	R_{sb}	28	-	-	-	25	-	-	90	S_s
	K'_Q	28	-	-	-	25	-	-	90	?
	K_{Q-PM}	28	-	-	-	25	-	-	96	S_s
	K_Q	28	96	92	>99	25	S_y	S_y	(85)	S_s
	K'_J	28	-	-	-	25	-	-	96	S_s
	K_J	28	-	-	-	25	-	-	99	S_s
	K^*_d	28	-	-	-	25	-	-	96	S_s
6	R_{sb}	51	99	96	>99	48	S_y	S_y	-	S_s
	K'_Q	36	NC	NC	94	33	S_y	S_y	NC	-
	K_{Q-PM}	51	95	(70)	>99	48	S_y	S_y	-	-
	K_Q	51	97	(70)	98	48	S_y	S_y	-	-
	K'_J	51	(54)	(32)	94	48	?	S_y	-	-
	K_J	51	(38)	(13)	91	48	?	S_y	91	-
	K^*_d	51	(70)	(51)	94	48	?	S_y	-	-

Symbol	Meaning
NC	Not computed.
?	Significance of effect of K_f maximum is open to question.
S_s	K_f maximum has a significant effect on the reproducibility s of the response.
-	K_f maximum does not have a significant effect.
S_y	K_f maximum has a significant effect on the response magnitude.
()	Not significant, but included for comparisons.

Table 11. Effects of Notch Preparation on Results for Steel Specimens.

Response	CPV From KW Test(1)			CPV from MLR Analysis	Findings from Graphical Analysis
	y_i	Y	s		
R_{sb}	70	40	86	95	For NP code 1, both variability, and magnitudes of mean and median responses, are greater than those for codes 2 and 3.
K_{Q-PM}	30	18	96	97	Same as R_{sb} (above).
K_Q'	80	72	37	94	For N P code 1, variability is greater than, and magnitudes of mean and median responses are less than, those for NP codes 2 and 3.
K_J'	6	8	58	88	No significant effects of NP.
K_d^*	18	26	78	89	No significant effects of NP.

(1) Taken from Appendix Table V.

Table 12. Sensitivity of Responses to Crack Size.

	Material	R_{sb}	K'_Q	$K_{Q\text{-}PM}$	K_Q	K'_J	K_J	K^*_d
		Regression results for %RD**, taken from table 9.						
Slope β_1								
	A	0.064	-0.074	-0.073	-0.040	-0.22	-0.25	-0.11
	T	0.056	-0.067	-0.091	-0.096	-0.20	-0.25	-0.10
	S	0.059	-0.066	-0.115	-0.102	-0.31	-0.43	-0.18
Residual Standard Deviation								
	A	3.9	2.4	3.0	4.0	6.2	5.3	5.8
	T	5.8	5.9	4.7	5.0	8.7	8.2	7.6
	S	3.7	6.1	3.1	4.1	7.1	6.9	6.1

** $\%RD = \beta_1 \bar{a} + \beta_0$.

Fig. A

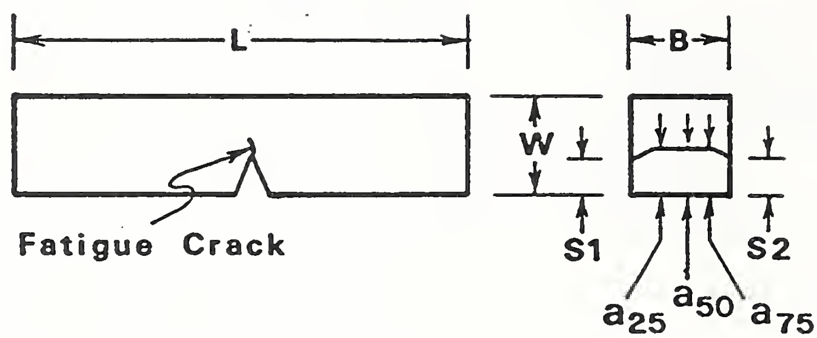
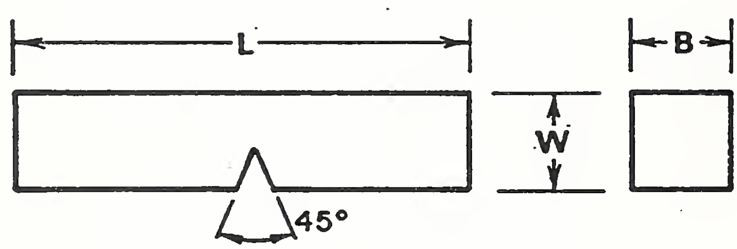
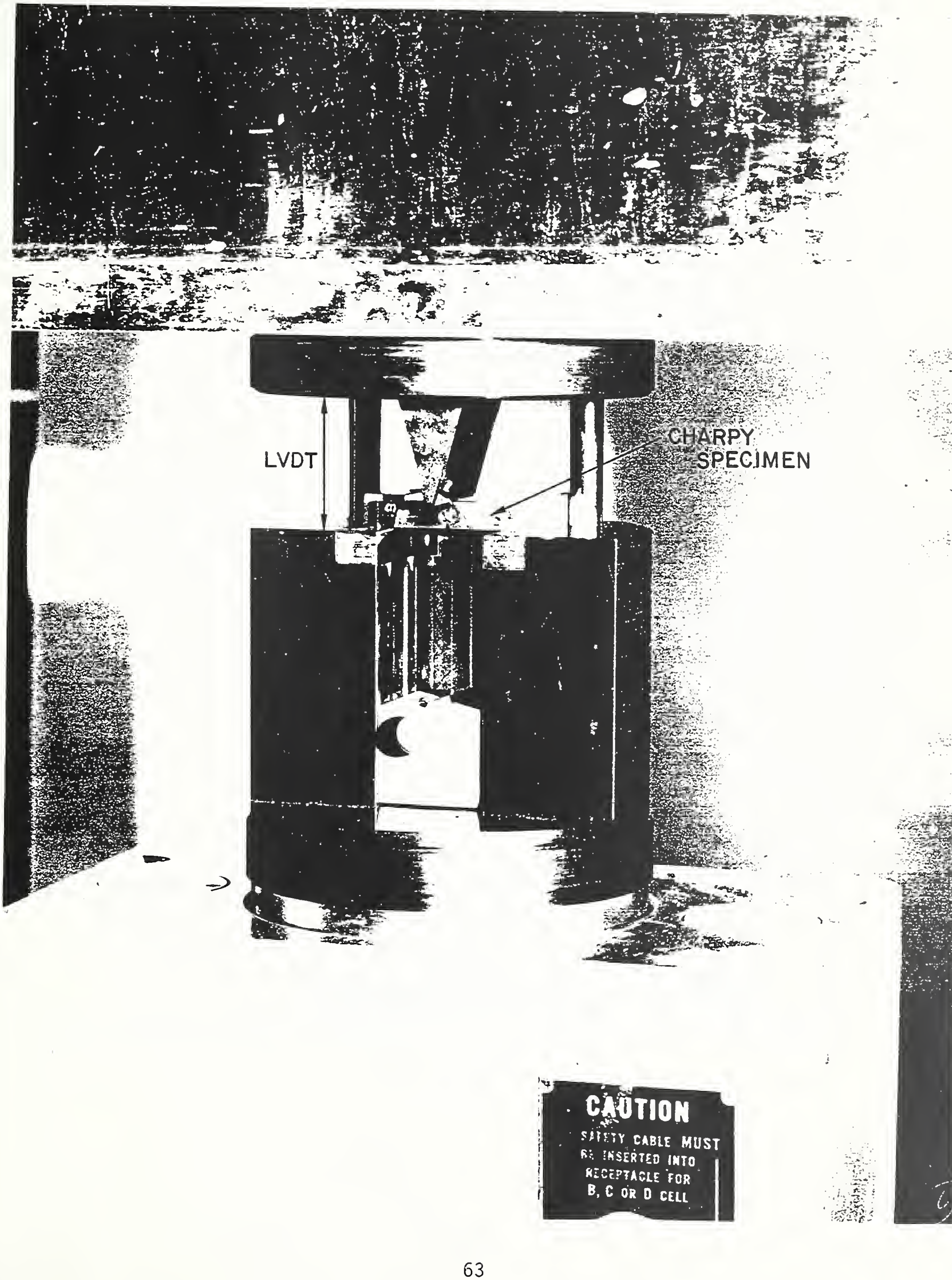


Fig. B



Machined Root Radius (mm)	(in)	Notch Preparation Code	Special Preparation	Final Root Radius
.250	.010	1	razor scratch	~ .05 mm (.002 in)
.125	.005	2	none	.125 mm (.005 in)
.250	.010	3	EDM with razor electrode	~ .05 mm (.002 in)


LVDT
CHARPY SPECIMEN
CAUTION
SAFETY CABLE MUST
BE INSERTED INTO
RECEPTACLE FOR
B, C OR D CELL

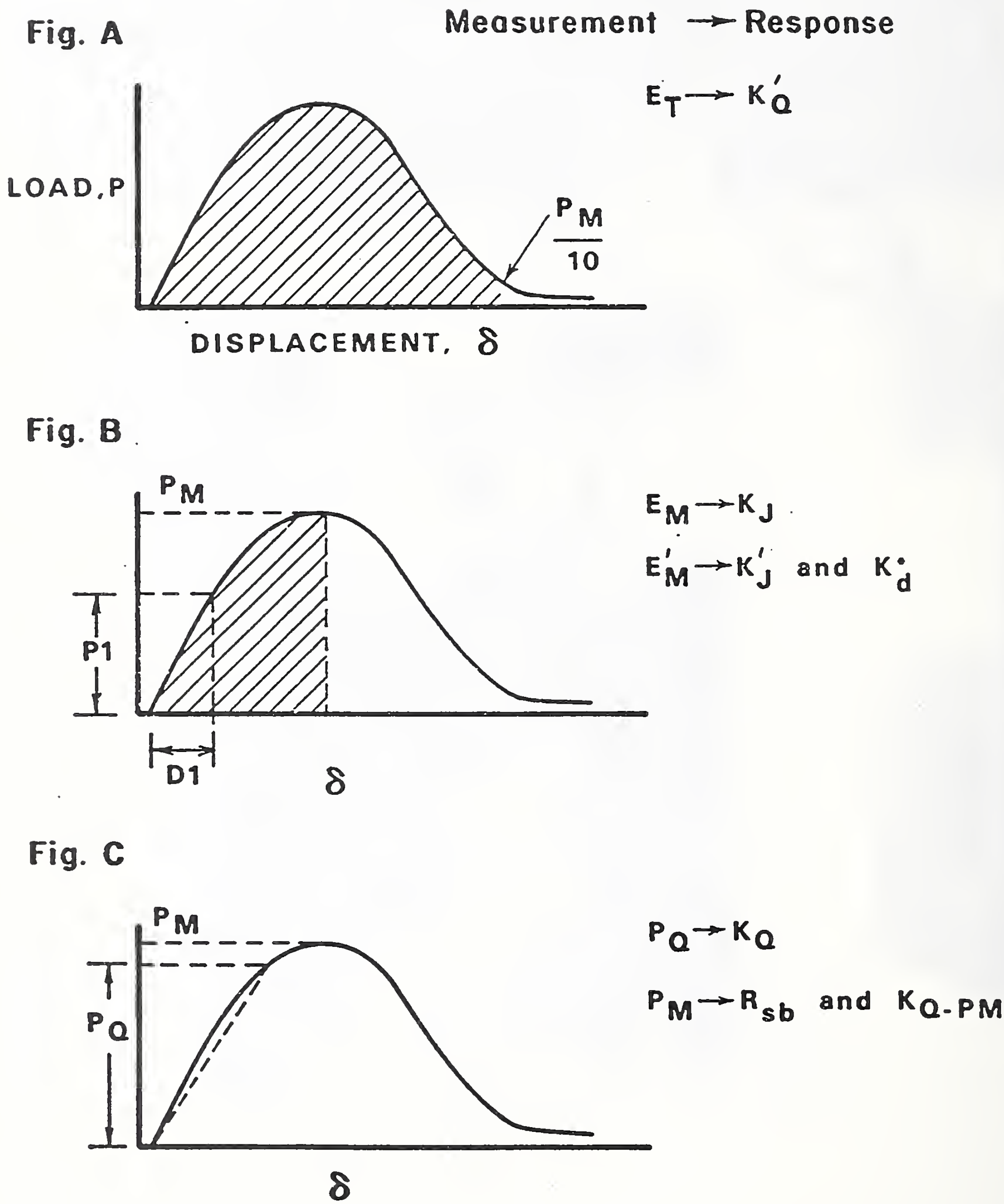


Fig. A
Measurement → Response
E_T → K'_Q
LOAD, P
P_M / 10
DISPLACEMENT, δ
Fig. B
P_M
E_M → K_J
E'_M → K'_J and K˙_d
P1
D1
δ
Fig. C
P_M
P_Q → K_Q
P_M → R_sb and K_Q-PM
P_Q
δ

Fig. 3

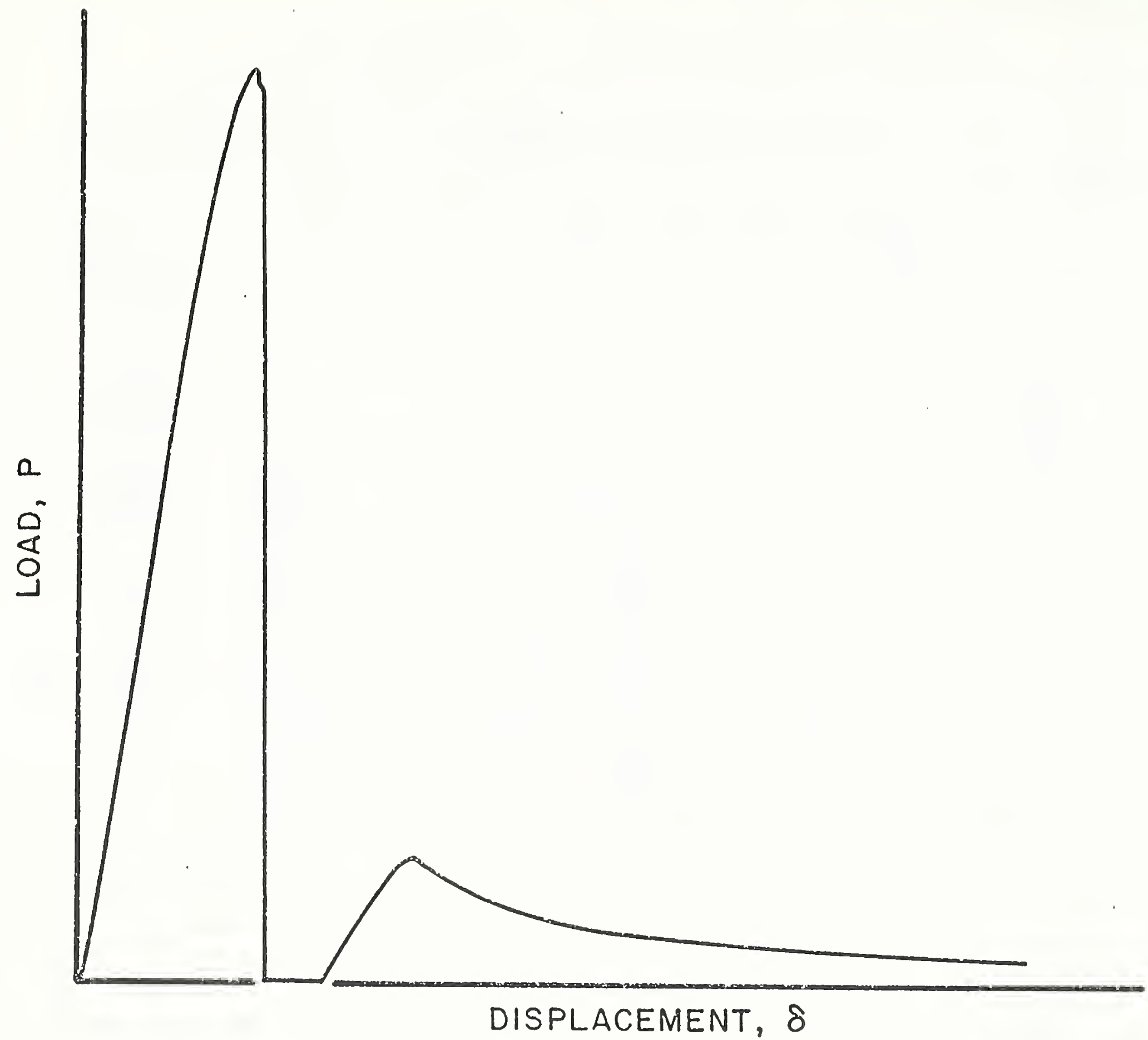
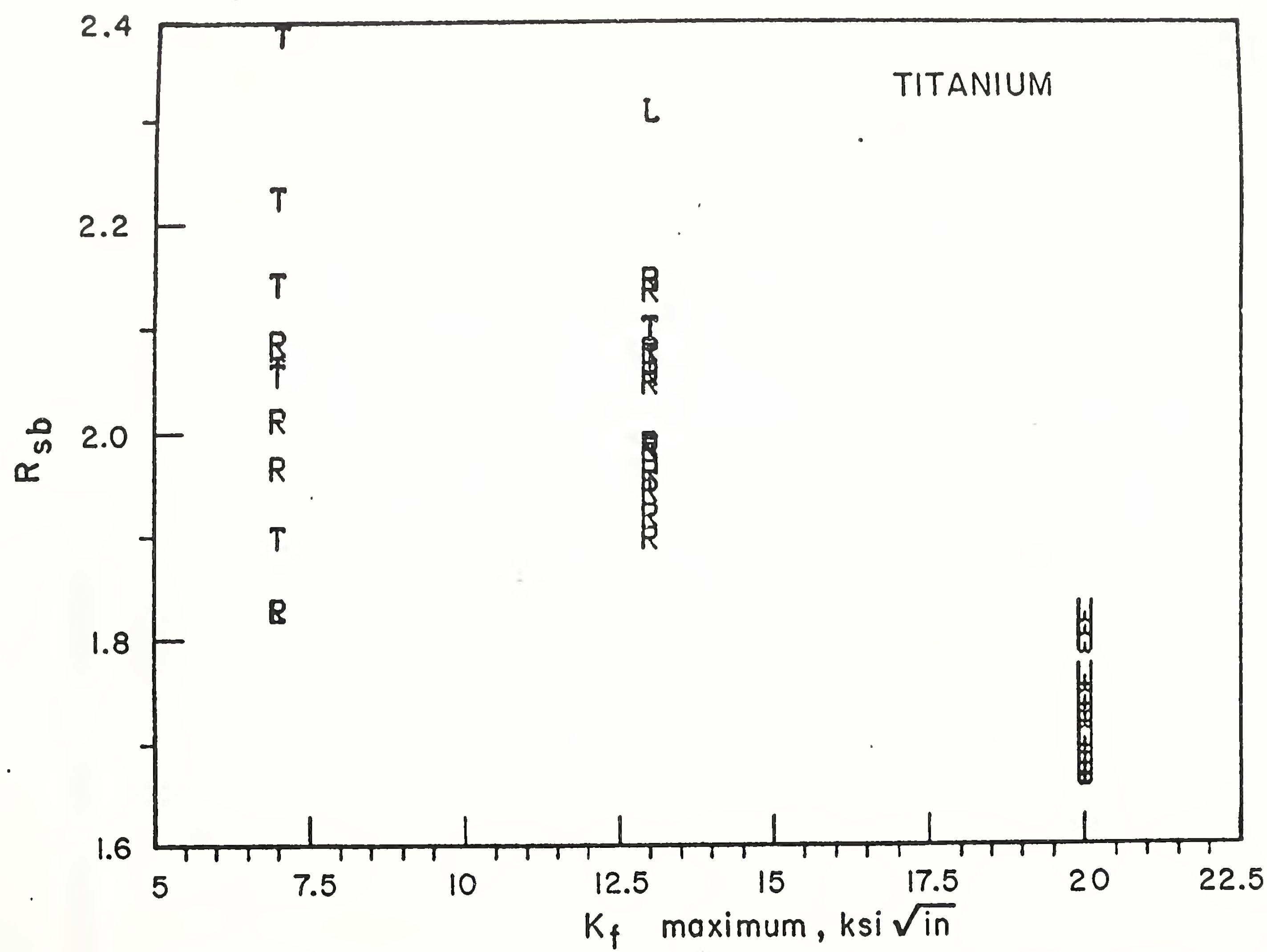


Fig. 4



PLOT CHARACTERS REPRESENT DESIGNATION OF CTS FROM WHICH CVN SPECIMENS WERE TAKEN

Fig. 5

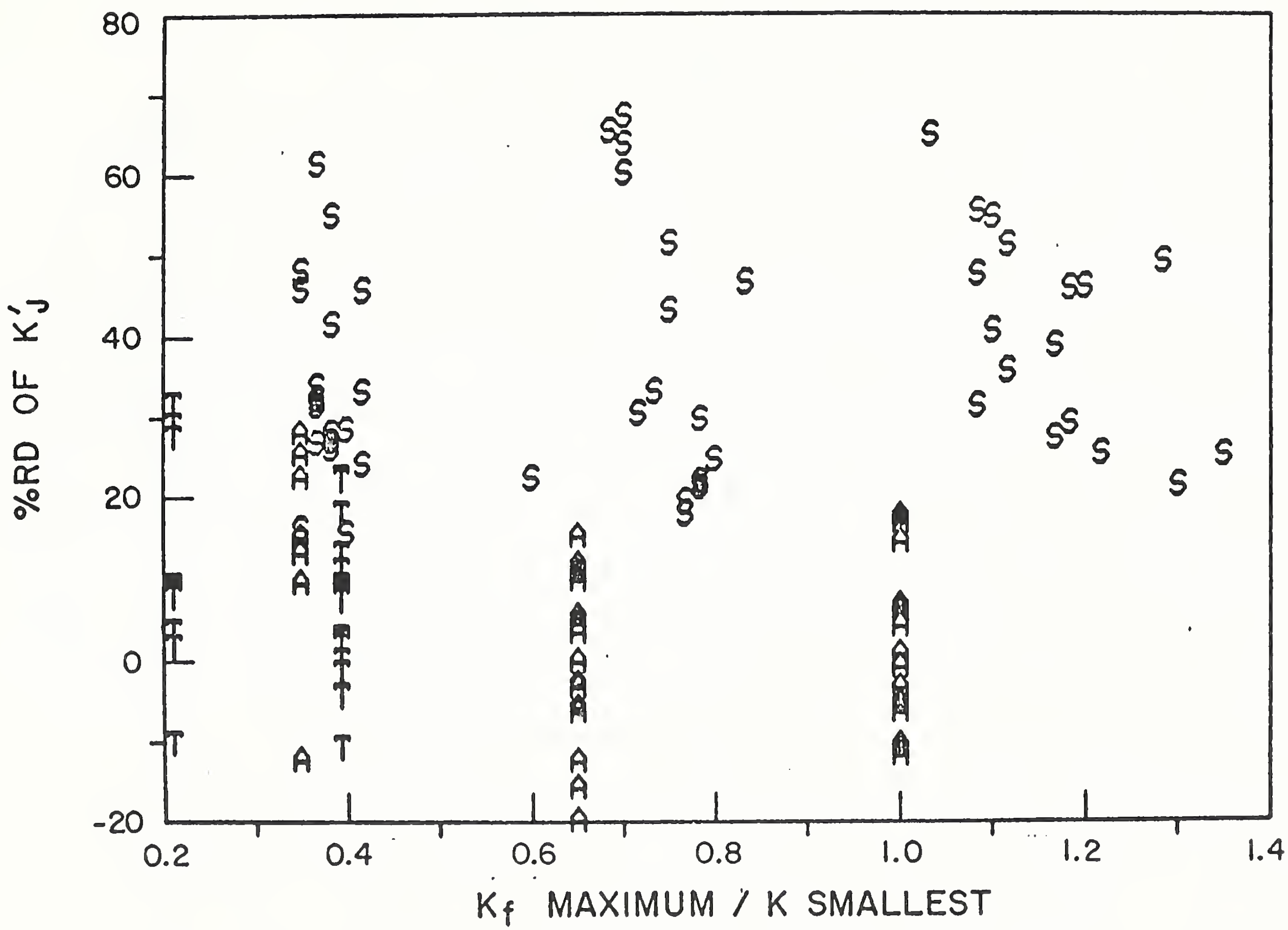
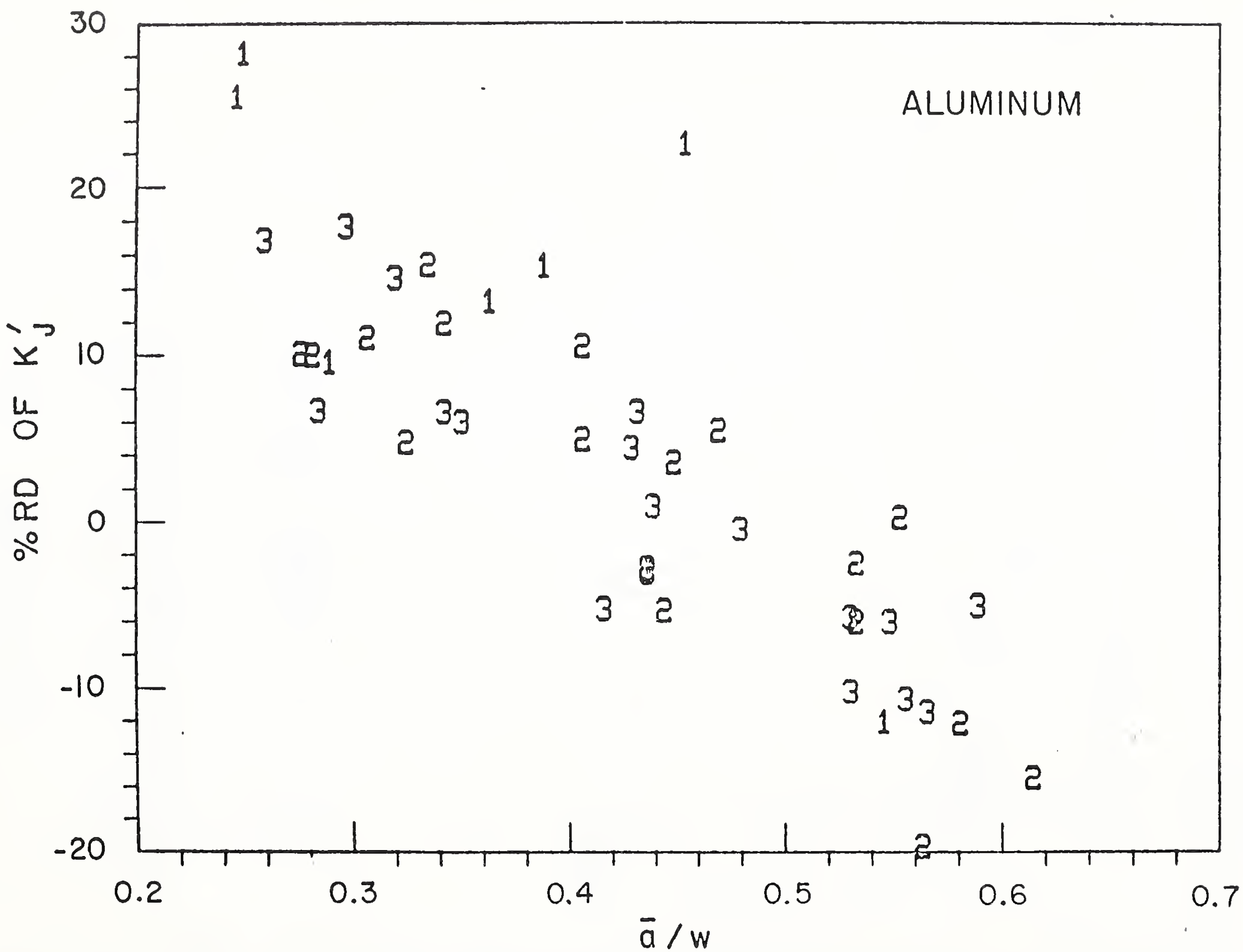

80
60
40
20
0
-20
%RD OF K'J
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Kf MAXIMUM / K SMALLEST
PLOT CHARACTERS REPRESENT ALUMINUM, TITANIUM, AND STEEL

Fig. 6



PLOT CHARACTERS REPRESENT CODED K_f

Fig. 7

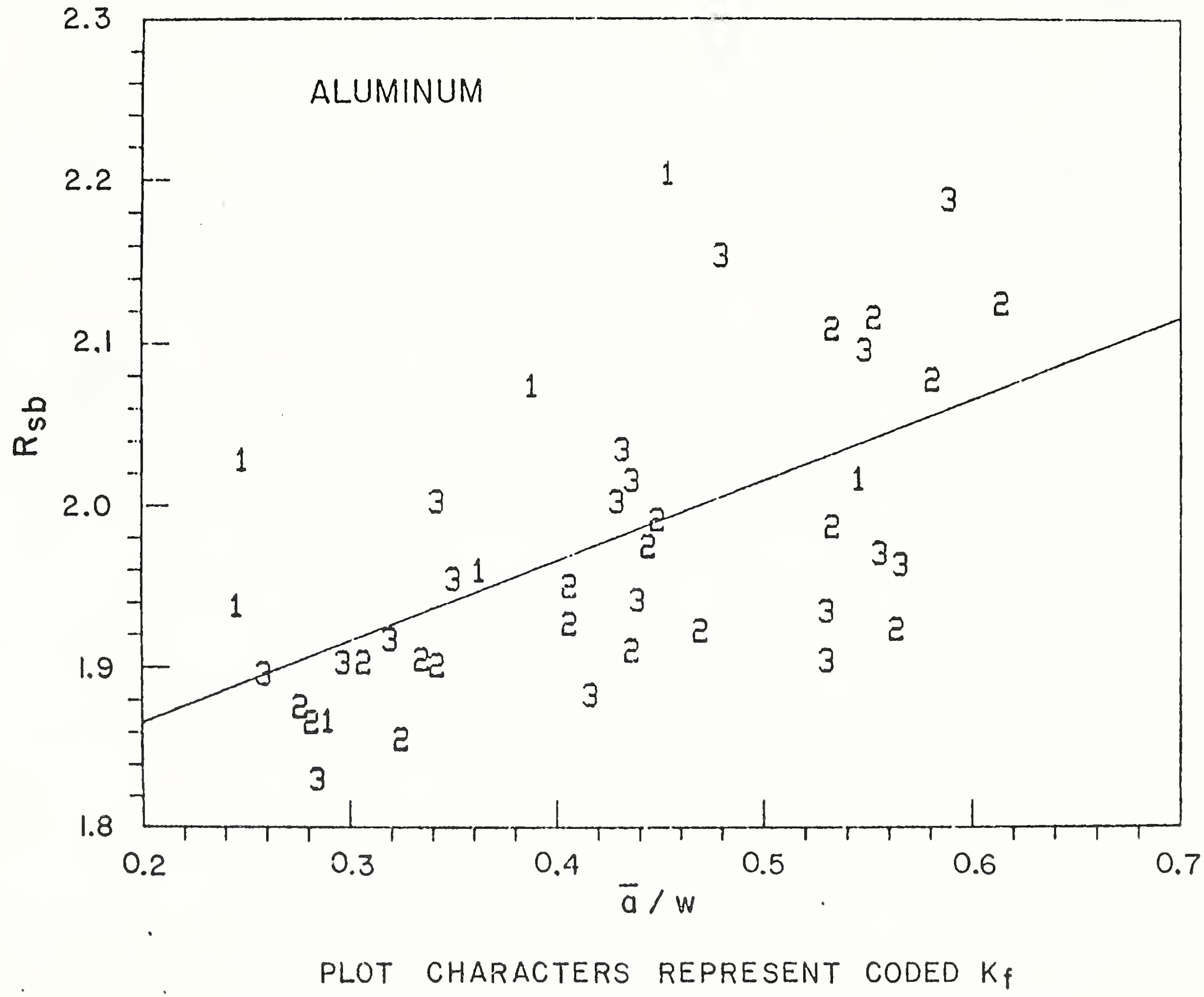

ALUMINUM
2.3
2.2
2.1
2.0
1.9
1.8
R_{sb}
0.2
0.3
0.4
0.5
0.6
0.7
$\bar{a}$ / w
PLOT CHARACTERS REPRESENT CODED K_f

Fig. 8

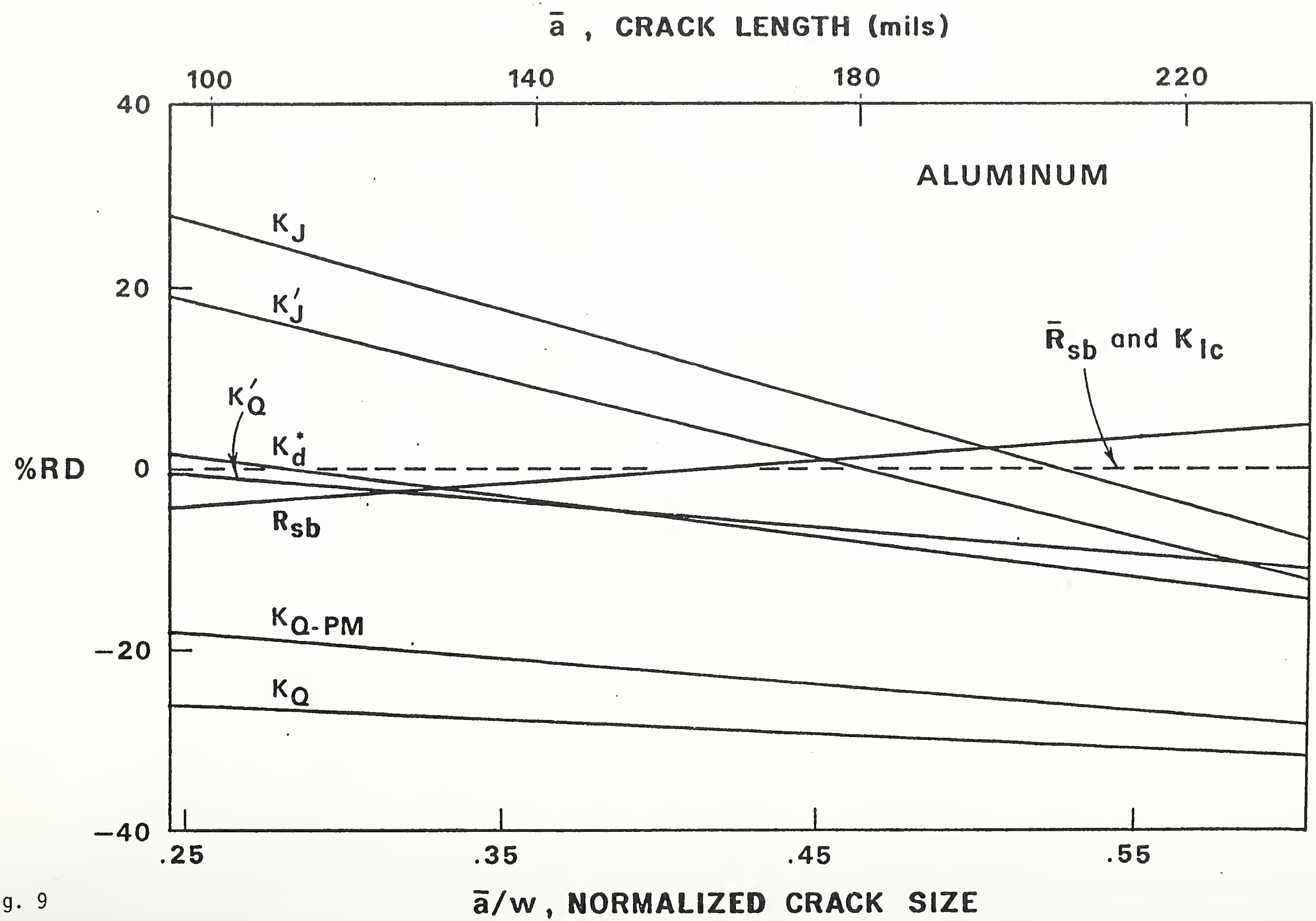

ā , CRACK LENGTH (mils)
100
140
180
220
40
20
0
−20
−40
%RD
ALUMINUM
K_J
K'_J
K'_Q
K*_d
R_sb
R̄_sb and K_Ic
K_Q-PM
K_Q
.25
.35
.45
.55
ā/w , NORMALIZED CRACK SIZE

Fig. 9

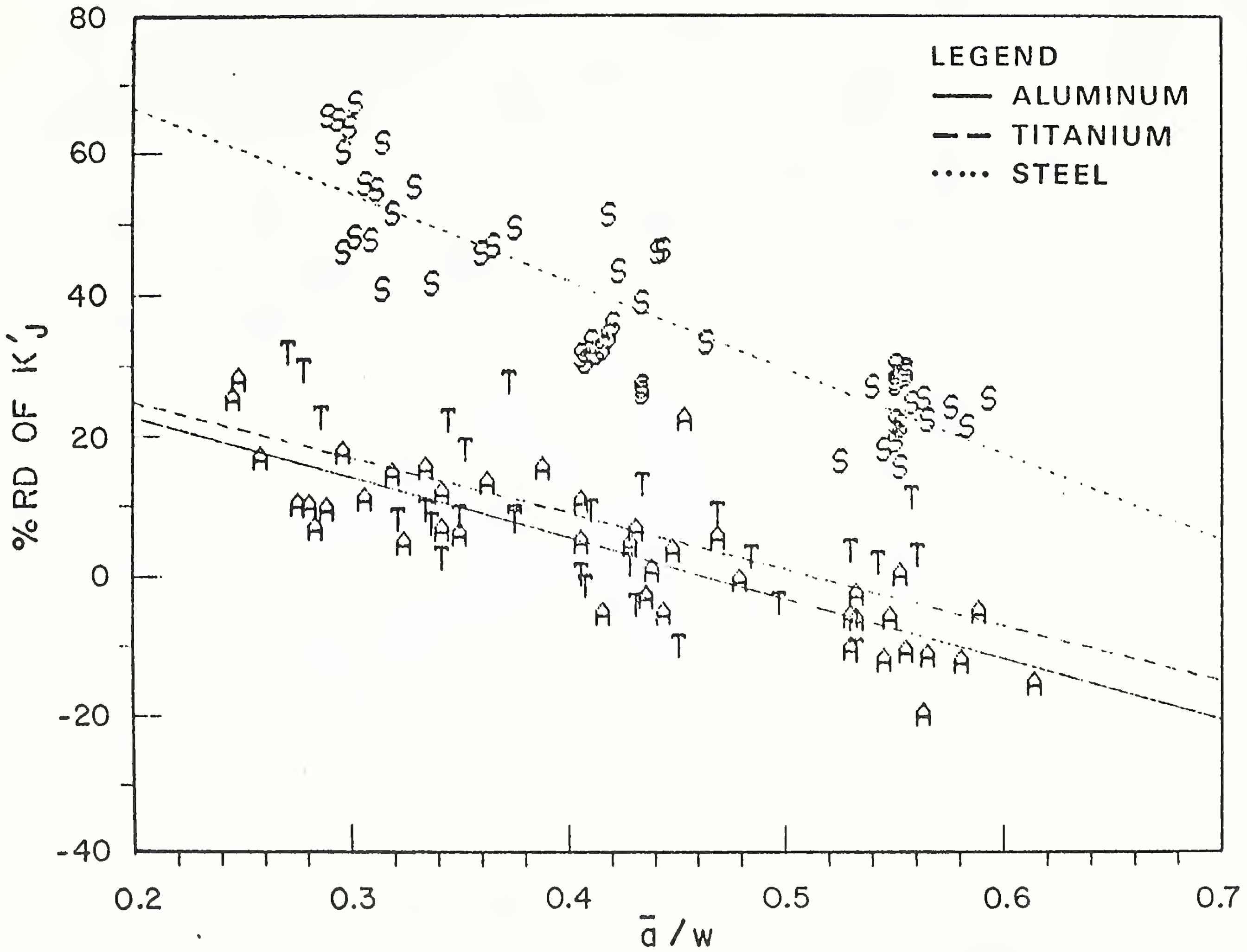

LEGEND
ALUMINUM
TITANIUM
STEEL
% RD OF K'J
ā / w
80
60
40
20
0
-20
-40
0.2
0.3
0.4
0.5
0.6
0.7

Fig. 10

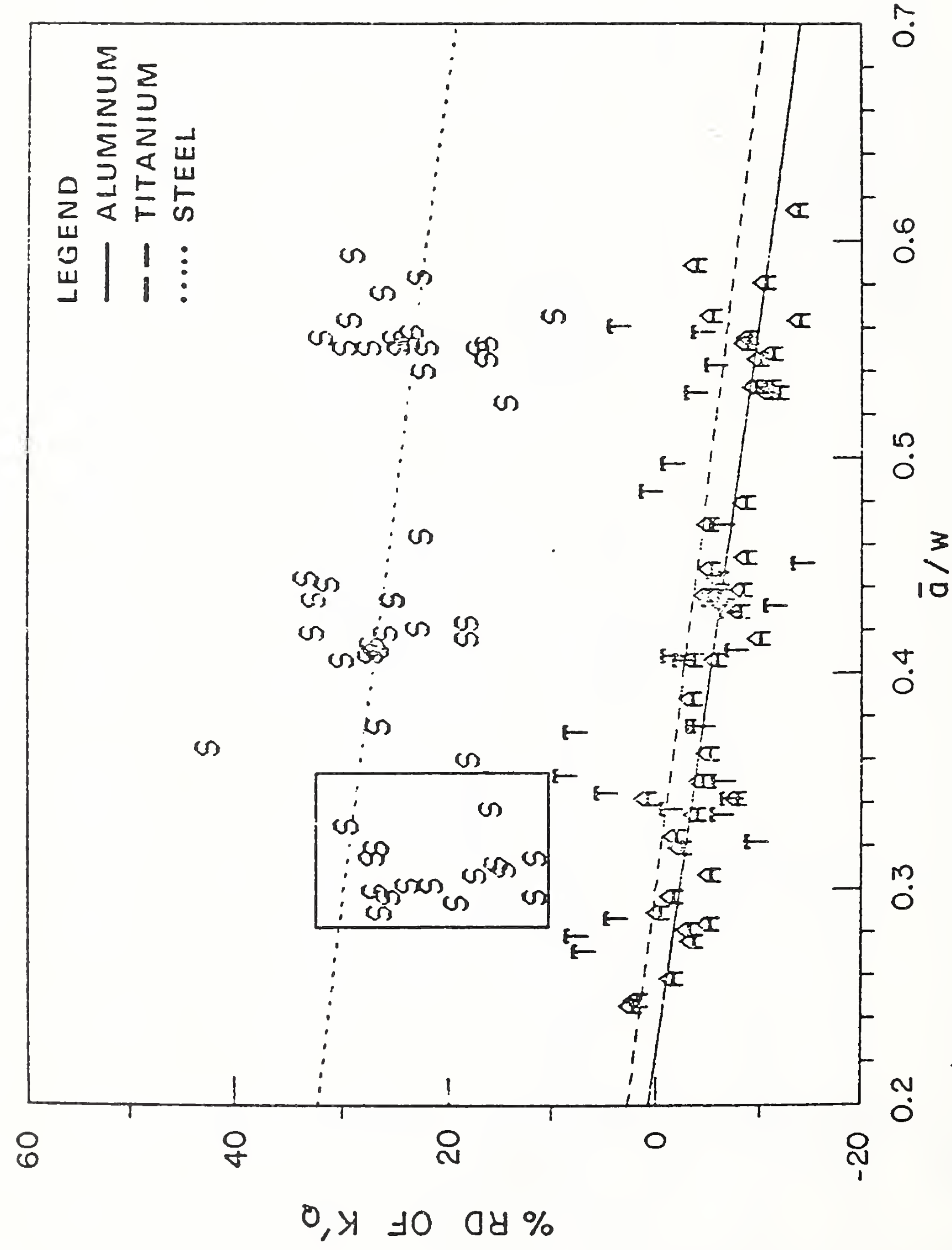

LEGEND
ALUMINUM
TITANIUM
STEEL
ā/w
% RD OF K'Q
60
40
20
0
-20
0.2
0.3
0.4
0.5
0.6
0.7

Fig. 11

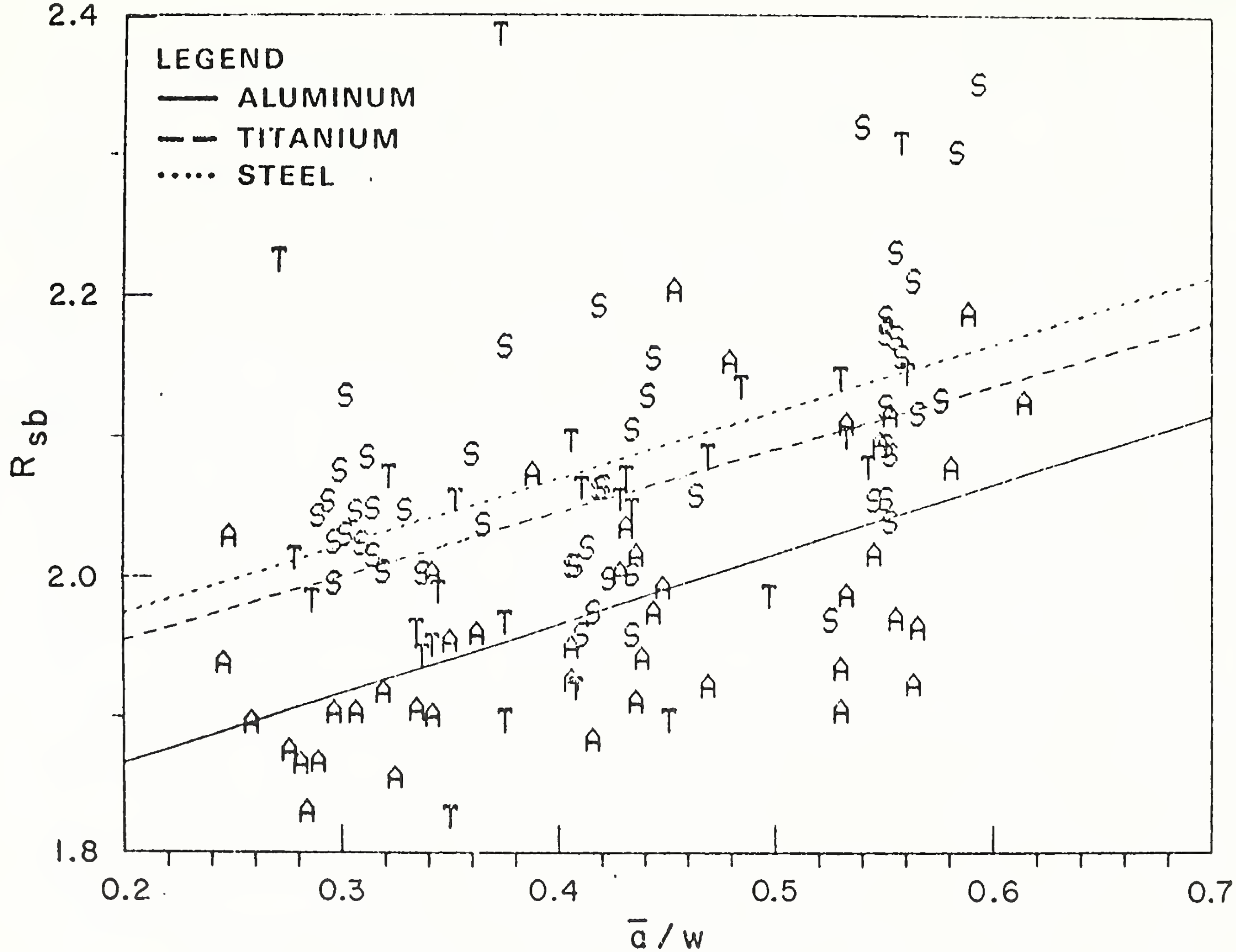
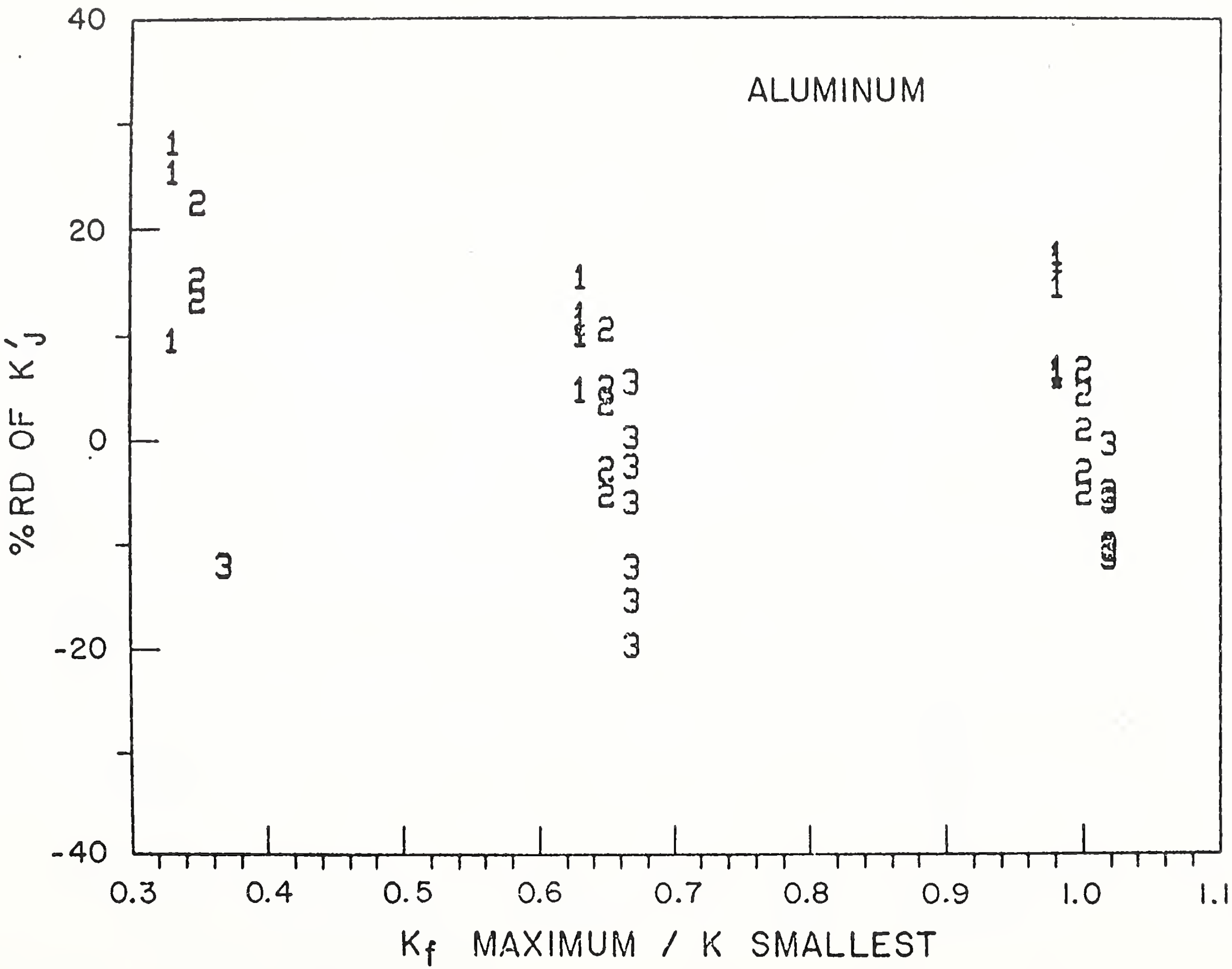
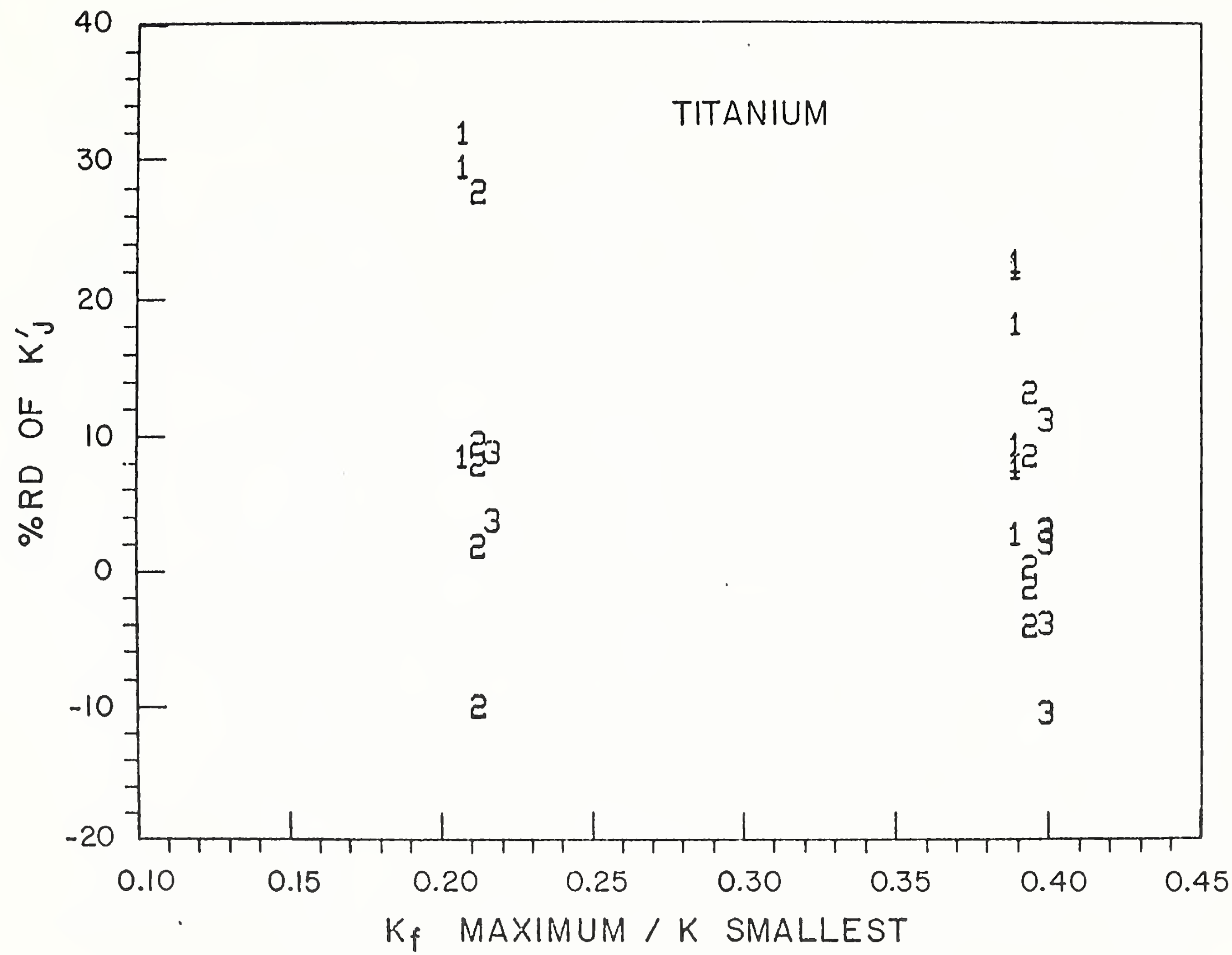

LEGEND
ALUMINUM
TITANIUM
STEEL
R sb
2.4
2.2
2.0
1.8
0.2
0.3
0.4
0.5
0.6
0.7
a / w

Fig. 12



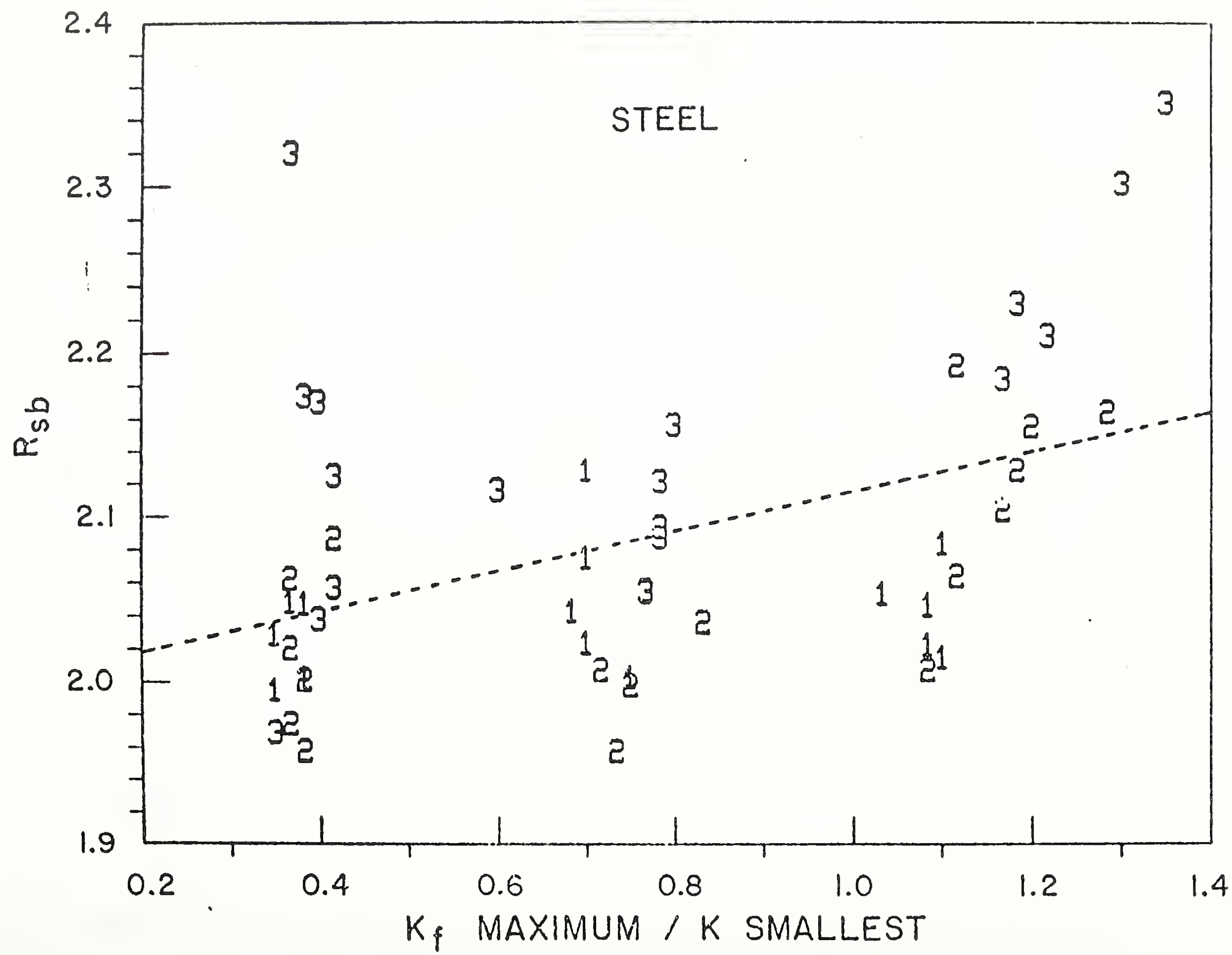
PLOT CHARACTERS REPRESENT CODED CRACK LENGTH

Fig. 13



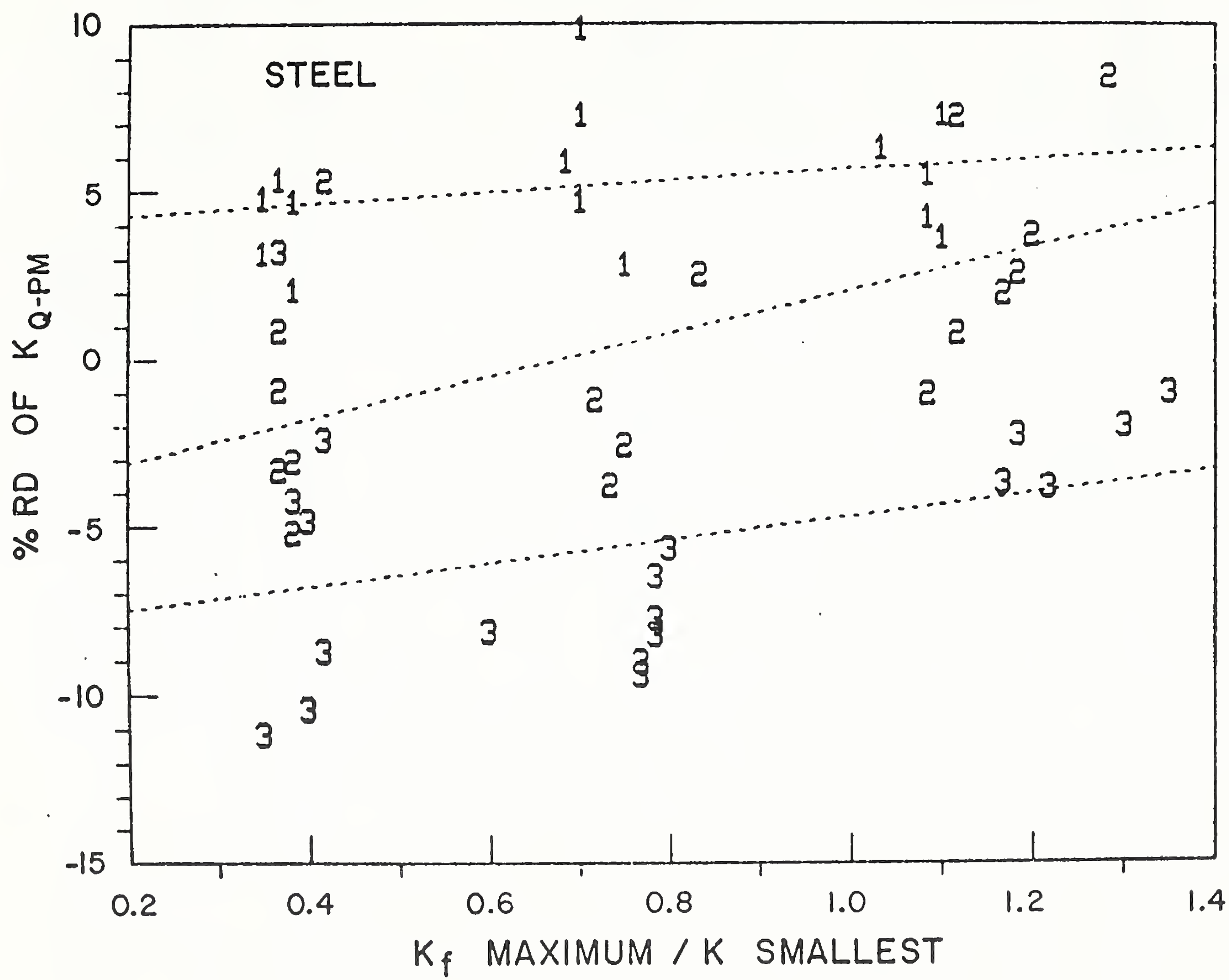
PLOT CHARACTERS REPERSENT CODED CRACK LENGTH DATA FOR
CTS SPECIMENS R T AND L ONLY

Fig. 14



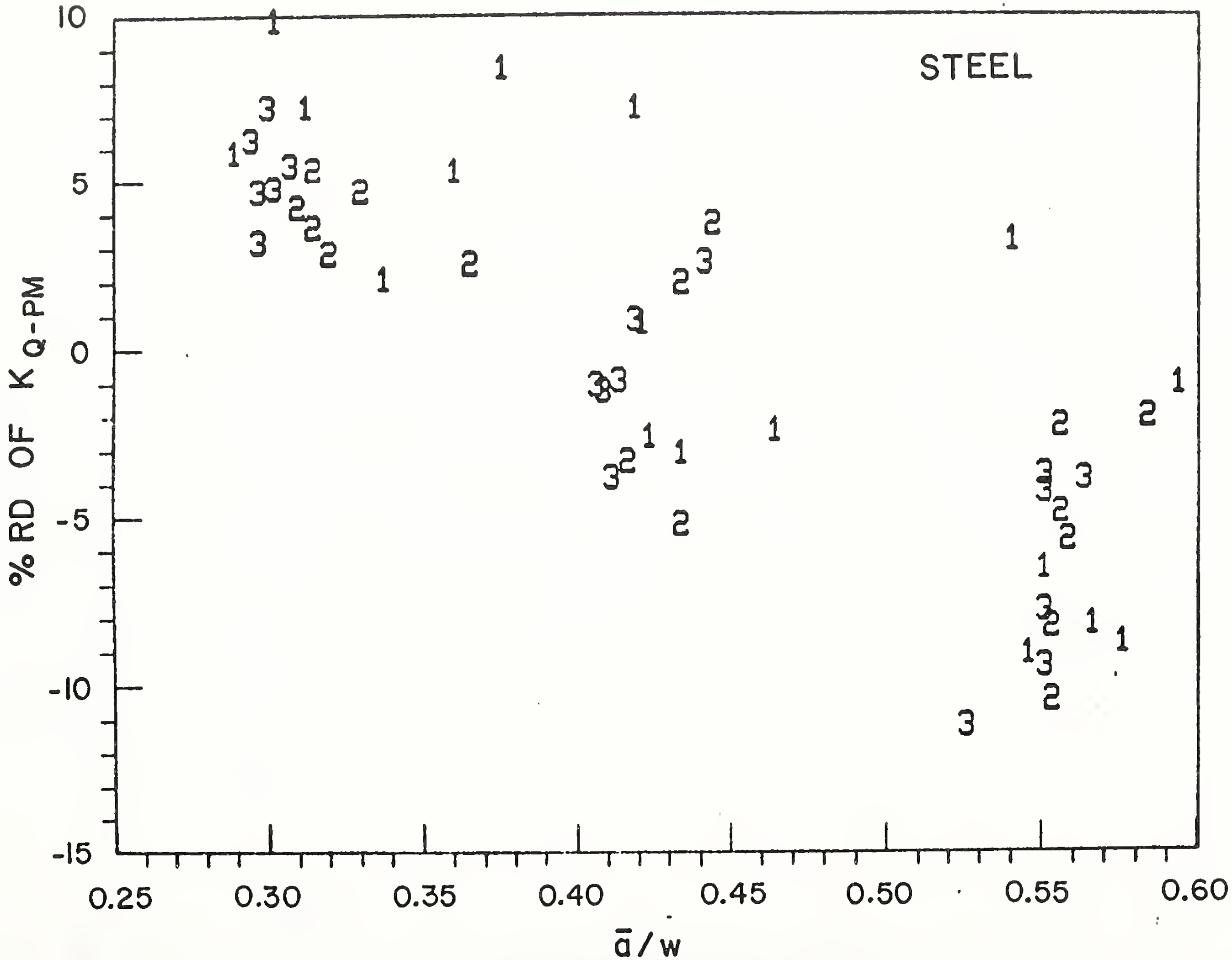
PLOT CHARACTERS REPRESENT CODED CRACK LENGTH

Fig. 15



PLOT CHARACTERS REPRESENT CODED CRACK LENGTH

Fig. 16



PLOT CHARACTERS REPRESENT CODED NOTCH PREPARATION

Fig. 17

Appendix Table I - Raw Data Used to Compute Responses of Precracked Charpy Tests

Table IA - Aluminum.

Specimen	P_Q	P_M	K_F	NP	Coded a	Coded K_F	E_M	$E_{T/A}$	$\bar{a}$	a_{25}	a_{50}	a_{75}	D_1/P_1
E9	1237	1300	13	3	1	2	11.301	242	111	123	111	99	10.242
E10	1125	1234	13	3	1	2	9.647	231	121	118	121	123	9.055
E8	645	730	13	3	3	2	6.965	232	185	204	188	164	16.428
E11	765	819	13	3	2	2	6.440	228	172	163	175	179	14.397
E12	502	570	13	3	3	2	4.650	214	218	227	226	202	18.471
E20	425	427	13	3	3	2	3.071	191	242	248	248	230	26.861
E13	1140	1168	20	3	1	3	9.073	262	135	132	136	138	10.663
E18	1020	1114	20	3	1	3	7.528	235	138	138	138	138	8.865
E14	775	787	20	3	3	3	5.250	215	189	186	192	187	13.187
E16	855	882	20	3	2	3	6.671	218	169	164	174	169	11.914
E15	472	499	20	3	3	3	4.062	230	223	217	226	225	23.748
E17	562	577	20	3	3	3	4.322	203	216	221	217	211	19.048
A3	540	562	7	2	3	1	4.240	209	215	201	219	225	21.461
A4	1200	1274	7	2	1	1	10.854	255	114	113	108	121	10.141
B1	1400	1546	7	1	1	1	14.400	266	98	125	85	85	8.394
B2	940	1048	7	1	2	1	8.712	240	153	85	167	207	10.553
E2	1190	1488	7	3	1	1	13.548	269	97	114	89	89	8.156
E3	880	1074	7	3	2	1	8.585	232	143	190	153	87	9.537
E4	740	886	7	3	2	1	8.310	215	179	211	190	135	12.080
A12	1020	1138	13	2	1	2	9.547	238	132	131	134	131	9.250
A20	960	1110	13	2	1	2	8.651	219	135	132	130	137	9.023
A7	805	824	13	2	2	2	5.814	227	175	181	175	170	13.795
A8	870	929	13	2	2	2	7.311	239	160	160	161	159	11.799
A10	495	495	13	2	3	2	3.454	191	222	225	220	221	23.483
A11	547	621	13	2	3	2	4.238	211	210	208	213	209	14.941
A13	1178	1267	20	2	1	3	9.421	232	112	113	113	111	8.783
A17	1117	1198	20	2	1	3	9.819	245	126	127	127	125	9.080
A14	820	864	20	2	2	3	5.599	233	172	172	173	172	11.872
A18	800	825	20	2	2	3	6.640	216	173	173	175	171	13.877
A16	517	525	20	2	2	3	4.502	213	219	220	222	215	24.595
B8	1080	1143	13	1	1	2	9.095	248	128	120	127	139	10.525
B12	1252	1326	13	1	1	2	11.459	239	109	103	105	120	10.137
B7	675	816	13	1	2	2	5.877	231	177	169	179	183	11.460
B9	840	918	13	1	2	2	7.712	229	160	139	168	173	11.116
B10	525	585	13	1	3	2	4.457	203	210	193	212	225	17.933
B11	465	492	13	1	3	2	3.680	206	229	218	232	237	23.561
B15	1275	1407	20	1	1	3	11.740	249	102	99	101	106	8.436
B17	1125	1270	20	1	1	3	10.530	249	117	110	117	123	8.423
B13	810	888	20	1	2	3	6.646	224	170	158	172	179	11.338
B18	850	867	20	1	2	3	6.506	209	164	152	166	175	13.708
B16	550	567	20	1	3	3	4.988	205	209	193	212	222	23.291
B19	475	499	20	1	3	3	4.172	238	232	210	236	249	24.370

Table IB - Titanium.

Specimen	P_Q	P_M	K_F	NP	Coded a	Coded K_F	E_M	$E_{T/A}$	$\bar{a}$	a_{25}	a_{50}	a_{75}	D_1/D_2
41-2	2210	2305	7	2	2	1	21.206	629	148	161	142	140	6.541
41-3	2310	2320	7	2	1	1	21.150	598	138	130	138	145	5.732
41-4	2710	3145	7	2	1	1	34.982	790	110	130	114	85	5.126
41-5	1450	1765	7	2	3	1	16.055	597	185	170	191	175	7.551
40-7	1850	2015	7	1	2	1	21.162	709	169	194	180	134	7.986
4012	2400	2820	7	1	2	1	33.547	954	147	115	155	172	6.011
4016	1200	1420	7	1	3	1	15.833	760	209	209	213	205	9.820
4013	1550	1715	7	3	2	1	14.620	606	178	172	182	179	7.735
4014	1900	2150	7	3	2	1	22.970	700	162	159	169	157	6.689
4018	3050	3550	7	3	1	1	42.298	939	107	96	120	106	4.734
40-1	2725	2860	13	2	1	2	25.910	671	127	123	124	124	5.167
40-6	2430	2536	13	2	1	2	22.968	707	135	139	139	127	5.561
40-2	2200	2224	13	2	2	2	21.427	777	160	162	168	150	7.337
40-4	1970	2012	13	2	2	2	17.670	644	170	172	174	165	7.422
40-5	1360	1376	13	2	3	2	12.628	642	210	211	210	208	10.949
432A	1140	1354	13	2	3	2	13.744	658	220	226	218	215	9.727
41-8	2480	2564	13	1	1	2	26.910	749	136	133	138	136	5.637
4111	2160	2224	13	1	2	2	20.046	622	148	148	147	149	6.036
41-7	1880	1972	13	1	2	2	19.620	610	171	177	171	166	7.218
4112	2470	2588	13	1	1	2	25.695	806	139	151	147	118	5.972
4115	1590	1704	13	1	3	2	14.849	689	191	198	191	184	8.676
4116	1460	1508	13	1	3	2	13.141	661	196	202	205	182	9.561
4110	2880	3032	13	3	1	2	31.479	735	113	114	117	107	5.263
4113	2460	2608	13	3	1	2	22.583	598	132	131	133	133	5.635
41-9	2540	2564	13	3	1	2	21.817	663	133	127	130	143	5.684
4117	1960	2020	13	3	2	2	16.052	661	161	163	160	160	6.812
4114	1245	1304	13	3	3	2	13.439	605	214	217	214	212	11.660
4118	1190	1243	13	3	3	2	12.210	731	221	229	220	213	11.404

Table IC - Steel.

Specimen	P_Q	P_M	K_F	NP	Coded $\bar{a}$	Coded K_F	E_M	$E_{T/A}$	$\bar{a}$	a_{25}	a_{50}	a_{75}	D_1/P_1
S1	3938	4425	25	1	2	1	56.800	1205	142	146	146	135	4.187
S2	3188	3325	23	1	2	1	39.300	1353	171	165	173	175	5.376
S3	4219	4556	23	1	1	1	57.400	1161	133	127	137	136	4.091
S4	2760	3060	25	1	3	1	37.500	1297	183	179	185	184	5.429
S5	1755	2067	36	1	3	2	25.100	1041	223	218	226	226	8.000
S6	1785	1980	25	1	3	1	25.100	1375	227	225	228	228	8.389
S7	4594	5350	41	1	1	2	84.200	1380	114	114	114	114	3.863
S8	4875	5375	42	1	1	2	84.200	1324	119	121	118	117	3.909
S10	3240	3440	45	1	2	2	47.400	1208	167	167	168	166	5.000
S11	1995	2220	47	1	3	2	26.200	1184	217	216	219	216	6.333
S12	1920	2199	46	1	3	2	24.500	1168	215	213	215	216	7.238
S13	4469	5113	66	1	1	3	70.700	1150	123	125	122	122	3.863
S14	4031	4375	77	1	2	3	58.900	1384	148	147	148	148	4.453
S15	3360	3584	67	1	2	3	43.600	1302	166	165	167	167	4.875
S16	3380	3840	67	1	2	3	52.200	1522	165	165	166	165	4.656
S17	1725	2010	81	1	2	3	23.900	1435	234	233	234	234	8.611
S19	2160	2358	22	1	2	1	29.800	1293	213	212	213	215	7.286
R1	2860	3252	23	2	2	1	37.100	1356	171	169	173	172	5.107
R2	4438	4988	22	2	1	1	74.200	1395	124	125	122	124	3.840
R3	4075	4765	23	2	1	1	68.500	1448	130	129	130	130	4.075
R4	3120	3488	22	2	2	1	41.500	1208	164	163	164	165	4.781
R5	1905	2109	24	2	3	1	23.300	1320	218	218	219	218	7.555
R6	1920	2220	24	2	3	1	28.800	1351	219	219	219	218	7.833
R7	3700	4250	50	2	2	2	57.200	1751	144	144	144	144	4.343
R8	4094	4806	45	2	1	2	65.200	1387	126	126	126	126	3.840
R11	2070	2160	47	2	3	2	26.000	1169	218	219	219	217	7.762
R12	2025	2181	48	2	3	2	26.700	1315	220	217	221	222	7.762
R13	4600	5000	65	2	1	3	66.900	1131	122	122	122	121	3.978
R14	4750	4906	66	2	1	3	60.400	1075	124	124	124	124	3.931
R15	3340	3496	70	2	2	3	44.400	1519	171	170	172	170	5.094
R16	3000	3452	72	2	2	3	46.100	1534	175	176	176	174	5.000
R18	2160	2280	71	2	3	3	29.200	1502	219	217	221	218	7.810
R20	1935	2067	78	2	3	3	23.300	1300	230	236	235	220	8.278
T1	4750	5113	21	3	1	1	66.700	1075	117	118	118	116	3.840
T2	4656	5125	21	3	1	1	67.500	1278	119	119	119	119	3.840
T3	3440	3600	22	3	2	1	44.800	1395	163	162	165	163	5.219
T4	3380	3612	22	3	2	1	44.800	1370	165	164	167	165	5.125
T5	2080	2300	21	3	3	1	26.200	1130	207	207	208	207	7.150
T6	2055	2274	23	3	3	1	28.900	1453	217	217	218	216	7.619
T7	4625	5188	42	3	1	2	79.000	1363	117	117	117	116	3.954
T8	4750	5281	42	3	1	2	82.600	1391	118	119	119	116	4.000
T9	3060	3520	44	3	2	2	42.600	1386	162	163	164	160	4.750
T10	3360	3640	43	3	2	2	43.000	1400	161	161	161	161	4.906
T11	2055	2190	47	3	2	2	26.400	1403	217	217	217	217	7.667
T12	2070	2151	46	3	3	2	25.200	1342	217	217	217	217	7.619
T13	4969	5300	62	3	1	3	82.500	1227	116	116	116	116	3.860
T14	4531	5094	65	3	1	3	71.700	1190	121	121	121	121	3.840
T15	3480	3672	65	3	2	3	44.000	1458	160	160	161	160	4.906
T16	3180	3440	71	3	2	3	47.100	1490	174	174	174	173	5.125
T17	1935	2286	70	3	3	3	27.200	1286	217	218	218	215	7.048
T18	1905	2184	73	3	3	3	26.400	1442	222	222	222	221	7.778

Appendix Table II - Reference Toughness and Computed Precracked Charpy Responses.

Table IIA - Aluminum.

Specimen	K_{IC}	K'_Q	% RD	R_{sb}	K_{Q-PM}	% RD	K^*_d	% RD	K'_J	% RD	K_J	% RD	K_Q	% RD
E9	38.85	37.73	-2.89	1.87	30.42	-21.69	36.55	-5.91	42.76	10.06	48.87	25.80	28.94	-25.51
E10	38.85	36.89	-5.04	1.90	30.81	-20.68	37.52	-3.42	43.15	11.07	45.97	18.34	28.08	-27.72
E8	38.85	36.95	-4.88	1.92	28.52	-26.60	38.07	-2.02	41.00	5.53	44.65	14.92	25.18	-35.19
E11	38.85	36.62	-5.74	1.91	29.00	-25.36	34.74	-10.59	37.77	-2.77	41.65	7.22	27.09	-30.28
E12	38.85	35.52	-8.58	2.12	29.19	-24.86	36.84	-5.18	38.97	.30	39.75	2.32	25.71	-33.82
E20	38.85	33.58	-13.56	2.12	27.43	-29.39	31.19	-19.72	32.90	-15.31	34.76	-10.52	27.30	-29.72
E13	38.85	39.28	1.11	2.00	31.98	-17.68	36.75	-5.40	41.45	6.69	45.77	17.82	31.20	-19.69
E18	38.85	37.23	-4.16	1.96	31.12	-19.90	36.67	-5.61	41.20	6.05	41.94	7.95	28.48	-26.69
E18	38.85	37.23	-4.16	1.96	31.12	-19.90	36.67	-5.61	41.20	6.05	41.94	7.95	28.48	-26.69
E14	38.85	35.59	-8.39	2.15	31.71	-18.38	36.03	-7.26	38.70	-.39	39.14	.74	31.20	-19.68
E16	38.85	35.83	-7.77	2.00	30.55	-21.36	37.25	-4.12	40.60	4.52	42.11	8.40	29.62	-23.77
E15	38.85	36.81	-5.25	1.96	26.76	-31.13	32.62	-16.03	34.45	-11.32	37.69	-2.98	25.28	-34.92
E17	38.85	34.55	-11.07	2.10	29.06	-25.20	34.52	-11.15	36.54	-5.94	38.11	-1.91	28.28	-27.21
A3	38.85	35.07	-9.72	2.02	28.03	-27.84	32.29	-16.89	34.19	-11.99	37.64	-3.11	26.94	-30.67
A4	38.85	38.77	-.21	1.87	30.39	-21.78	36.61	-5.76	42.60	9.65	48.15	23.94	28.62	-26.33
B1	38.85	39.59	1.92	2.03	33.25	-14.42	41.44	6.65	49.80	28.19	53.94	38.85	30.11	-22.50
B2	38.85	37.58	-3.27	2.07	32.41	-16.58	40.52	4.31	44.81	15.33	46.50	19.69	29.07	-25.18
E2	38.85	39.81	2.47	1.94	31.79	-18.17	40.47	4.17	48.76	25.50	52.23	34.45	25.42	-34.56
E2	38.85	39.81	2.47	1.94	31.79	-18.17	40.47	4.17	48.76	25.50	52.23	34.45	25.42	-34.56
E3	38.85	36.95	-4.90	1.96	31.01	-20.17	39.40	1.41	44.01	13.29	45.23	16.42	25.41	-34.59
E4	38.85	35.57	-8.45	2.20	33.04	-14.94	44.03	13.33	47.63	22.59	48.08	23.76	27.60	-28.96
A12	38.85	37.43	-3.65	1.91	30.53	-21.41	39.60	1.94	44.83	15.40	46.69	20.17	27.37	-29.56
A20	38.85	35.93	-7.52	1.90	30.38	-21.80	38.56	-.75	43.48	11.92	44.70	15.05	26.27	-32.37
A7	38.85	36.59	-5.83	1.98	29.83	-23.22	33.92	-12.69	36.80	-5.28	39.85	2.57	29.14	-24.99
A8	38.85	37.52	-3.43	1.95	30.17	-22.34	37.14	-4.40	40.80	5.01	43.23	11.27	28.25	-27.27
A10	38.85	33.55	-13.65	1.92	26.28	-32.37	29.56	-23.92	31.22	-19.63	34.66	-10.79	26.28	-32.37
A11	38.85	35.23	-9.31	2.11	29.67	-23.63	35.70	-8.10	37.89	-2.47	37.12	-4.46	26.13	-32.73
A13	38.85	36.94	-4.92	1.83	29.83	-23.21	35.52	-8.57	41.47	6.75	44.70	15.06	27.74	-28.61
A17	38.85	37.97	-2.27	1.92	30.91	-20.44	39.03	.47	44.55	14.67	46.81	20.50	28.81	-25.85
A14	38.85	37.03	-4.69	2.02	30.59	-21.26	34.64	-10.83	37.67	-3.03	38.84	-.03	29.03	-25.27
A18	38.85	35.71	-8.09	1.94	29.43	-24.26	36.11	-7.06	39.24	.99	42.39	9.12	28.53	-26.55
A16	38.85	35.41	-8.86	1.97	27.13	-30.17	32.85	-15.44	34.74	-10.58	39.23	.97	26.71	-31.24
A19	38.85	34.35	-11.58	1.93	27.29	-29.77	34.50	-11.20	36.63	-5.72	38.84	-.04	24.16	-37.81
B8	38.85	38.21	-1.65	1.86	29.87	-23.12	35.78	-7.91	40.72	4.82	45.22	16.40	28.22	-27.36
B12	38.85	37.52	-3.43	1.88	30.62	-21.18	36.44	-6.20	42.79	10.14	49.04	26.23	28.91	-25.58
B7	38.85	36.88	-5.08	1.99	29.98	-22.83	37.17	-4.33	40.26	3.64	40.25	3.60	24.80	-36.16
B9	38.85	36.70	-5.54	1.93	29.81	-23.26	39.11	.66	42.96	10.57	44.40	14.28	27.28	-29.78
B10	38.85	34.63	-10.87	1.99	27.95	-28.06	34.41	-11.42	36.52	-5.99	38.06	-2.02	25.08	-35.44
B10	38.85	34.63	-10.87	1.99	27.95	-28.06	34.41	-11.42	36.52	-5.99	38.06	-2.02	25.08	-35.44
B11	38.85	34.85	-10.28	2.08	27.85	-28.30	32.40	-16.61	34.17	-12.05	36.52	-5.99	26.33	-32.24
B15	38.85	38.30	-1.41	1.90	31.05	-20.07	38.15	-1.81	45.44	16.95	49.04	26.23	28.14	-27.57
B17	38.85	38.29	-1.45	1.90	30.90	-20.46	39.49	1.65	45.71	17.65	47.68	22.74	27.36	-29.57
B13	38.85	36.35	-6.43	2.03	30.99	-20.24	38.05	-2.05	41.45	6.69	42.13	8.43	28.26	-27.25
B18	38.85	35.07	-9.74	1.88	28.97	-25.43	33.64	-13.40	36.83	-5.21	41.13	5.88	28.40	-26.89
B16	38.85	34.74	-10.59	1.90	26.86	-30.86	32.87	-15.40	34.90	-10.17	40.16	3.37	26.05	-32.94
B19	38.85	37.42	-3.67	2.19	29.09	-25.12	35.01	-9.88	36.92	-4.97	39.25	1.02	27.67	-28.79

Table IIB - Titanium

Specimen	K_{Ic}	K'_Q	% RD	R_{sb}	K_{Q-PM}	% RD	K^*_d	% RD	K'_J	% RD	K_J	% RD	K_Q	% RD
41-2	77.90	74.82	-3.95	1.97	68.86	-11.60	76.96	-1.21	84.10	7.96	88.26	13.30	66.03	-15.24
41-3	77.90	72.93	-6.38	1.83	64.78	-16.84	76.56	-1.72	84.56	8.55	86.41	10.92	64.50	-17.20
41-4	77.90	83.86	7.65	2.01	73.10	-6.16	87.61	12.46	100.79	29.38	105.50	35.43	62.99	-19.14
41-5	77.90	72.93	-6.38	2.09	68.90	-11.55	79.94	2.62	84.81	8.87	83.32	6.95	56.60	-27.34
40-7	85.50	79.43	-7.10	2.06	69.80	-18.36	81.18	-5.05	87.11	1.88	92.19	7.83	64.08	-25.05
4012	85.50	92.15	7.78	2.39	83.68	-2.13	99.78	16.70	109.15	27.66	110.79	29.57	71.21	-16.71
4016	85.50	82.23	-3.83	2.14	67.27	-21.32	84.74	-.88	88.72	3.77	87.94	2.86	56.85	-33.51
4013	85.50	73.46	-14.09	1.90	63.49	-25.75	72.23	-15.52	77.00	-9.94	78.21	-8.53	57.38	-32.89
4014	85.50	78.96	-7.65	2.06	70.82	-17.17	86.73	1.44	93.58	9.45	94.59	10.63	62.59	-26.80
4018	85.50	91.43	6.94	2.23	80.93	-5.35	97.46	13.99	112.76	31.89	115.40	34.98	69.53	-18.68
4018	85.50	91.43	6.94	2.23	80.93	-5.35	97.46	13.99	112.76	31.89	115.40	34.98	69.53	-18.68
40-1	85.50	77.29	-9.60	2.07	74.25	-13.16	82.58	-3.42	92.47	8.16	93.64	9.53	70.74	-17.26
40-6	85.50	79.32	-7.22	1.95	69.41	-18.82	79.20	-7.37	87.78	2.67	89.52	4.70	66.51	-22.22
40-2	85.50	83.16	-2.74	2.10	72.23	-15.52	79.35	-7.20	85.76	.31	90.97	6.39	71.45	-16.44
40-4	85.50	75.73	-11.43	2.07	70.20	-17.89	76.48	-10.55	82.00	-4.09	84.43	-1.25	68.74	-19.60
40-5	85.50	75.57	-11.61	2.10	65.74	-23.11	73.14	-14.45	76.54	-10.48	78.75	-7.89	64.98	-24.00
432A	80.20	76.55	-4.55	2.31	70.59	-11.98	85.51	6.62	89.17	11.18	84.49	5.34	59.43	-25.89
41-8	77.90	81.65	4.82	1.99	70.64	-9.32	86.00	10.40	95.21	22.22	97.08	24.63	68.33	-12.29
4111	77.90	74.41	-4.48	1.90	66.44	-14.70	77.40	-.64	84.59	8.58	85.81	10.16	64.53	-17.16
41-7	77.90	73.69	-5.40	2.05	69.31	-11.02	82.27	5.60	88.14	13.14	89.17	14.46	66.08	-15.17
4112	77.90	84.70	8.73	2.06	72.75	-6.61	83.43	7.09	92.04	18.15	95.42	22.50	69.43	-10.87
4115	77.90	78.30	.52	2.14	69.69	-10.54	75.84	-2.64	80.16	2.90	81.30	4.37	65.03	-16.52
4116	77.90	76.73	-1.50	1.99	64.17	-17.62	71.08	-8.76	74.91	-3.84	77.44	-.59	62.13	-20.24
4110	77.90	80.88	3.83	1.98	71.85	-7.76	83.48	7.16	95.53	22.63	100.61	29.16	68.25	-12.39
4113	77.90	72.98	-6.31	1.96	69.97	-10.18	76.56	-1.72	85.17	9.34	88.26	13.29	66.00	-15.28
41-9	77.90	76.80	-1.42	1.94	69.25	-11.11	75.41	-3.20	83.79	7.55	86.91	11.57	68.60	-11.94
4117	77.90	76.71	-1.53	1.92	66.07	-15.19	71.25	-8.54	76.94	-1.23	78.90	1.29	64.11	-17.71
4114	77.90	73.39	-5.79	2.08	64.48	-17.22	76.13	-2.28	79.54	2.10	82.14	5.44	61.56	-20.97
4118	77.90	80.65	3.53	2.14	65.39	-16.06	77.01	-1.14	80.28	3.05	79.86	2.52	62.60	-19.64

Table IIC - Steel.

Specimen	K_{Ic}	K'_Q	% RD	R_{sb}	K_{Q-PM}	% RD	K^*_d	% RD	K'_J	% RD	K_J	% RD	K_Q	% RD
S1	120.50	142.42	18.19	2.09	126.92	5.33	157.17	30.43	175.78	45.88	196.26	62.87	112.95	-6.26
S2	120.50	150.91	25.24	2.00	116.87	-3.01	140.83	16.87	153.27	27.19	173.54	44.02	112.05	-7.01
S3	120.50	139.80	16.01	2.00	123.05	2.11	151.11	25.40	170.84	41.78	193.87	60.88	113.94	-5.44
S4	120.50	147.76	22.62	2.06	117.64	-2.38	149.10	23.73	160.81	33.45	174.28	44.63	106.10	-11.95
S5	120.50	132.38	9.86	2.12	110.72	-8.12	139.62	15.87	147.46	22.38	158.38	31.44	94.01	-21.99
S6	120.50	152.14	26.25	2.13	110.02	-8.69	141.85	17.72	149.67	24.21	160.27	33.00	99.19	-17.69
S7	120.50	152.41	26.48	2.04	127.61	5.90	171.39	42.23	199.40	65.48	226.69	88.13	109.58	-9.06
S8	120.50	149.29	23.89	2.13	132.43	9.90	174.78	45.04	201.64	67.33	228.75	89.83	120.11	-.32
S10	120.50	142.60	18.34	2.00	117.45	-2.53	158.18	31.27	172.71	43.33	188.90	56.77	110.62	-8.20
S11	120.50	141.18	17.16	2.12	112.70	-6.47	147.95	22.78	156.56	29.93	159.05	31.99	101.28	-15.95
S12	120.50	140.22	16.36	2.06	109.69	-8.97	134.31	11.46	142.23	18.04	152.94	26.92	95.77	-20.52
S13	120.50	139.13	15.46	2.09	129.30	7.31	162.69	35.02	186.52	54.79	211.15	75.23	113.02	-6.21
S14	120.50	152.63	26.67	2.17	130.71	8.47	162.03	34.47	180.05	49.42	202.28	67.87	120.43	-.06
S15	120.50	148.04	22.86	2.06	121.48	.82	149.83	24.34	163.73	35.88	180.78	50.02	113.89	-5.48
S16	120.50	160.06	32.83	2.19	129.23	7.24	166.81	38.43	182.44	51.40	197.37	63.79	113.75	-5.60
S17	120.50	155.42	28.98	2.35	119.33	-.97	143.34	18.95	151.12	25.41	159.77	32.59	102.41	-15.01
S19	120.50	147.53	22.43	2.16	115.59	-.04	144.43	19.86	153.08	27.04	167.74	39.20	105.89	-12.12
R1	120.50	151.08	25.38	1.96	114.30	-5.14	139.91	16.10	152.26	26.36	168.62	39.93	100.53	-16.58
R1	120.50	151.08	25.38	1.96	114.30	-5.14	139.91	16.10	152.26	26.36	168.62	39.93	100.53	-16.58
R2	120.50	153.24	27.17	2.05	126.97	5.37	170.12	41.18	194.74	61.61	216.71	79.84	112.97	-6.25
R3	120.50	156.12	29.56	2.05	126.16	4.70	164.73	36.71	186.98	55.17	210.58	74.75	107.89	-10.46
R4	120.50	142.60	18.34	1.97	116.55	-3.28	145.82	21.01	159.62	32.46	175.60	45.73	104.25	-13.49
R5	120.50	149.06	23.70	2.04	108.01	-10.36	131.75	9.33	139.36	15.65	150.41	24.82	97.57	-19.03
R6	120.50	150.80	25.15	2.17	114.71	-4.80	146.68	21.72	155.10	28.71	167.70	39.17	99.21	-17.67
R7	120.50	171.68	42.47	2.04	123.56	2.54	158.59	31.61	176.98	46.87	197.74	64.10	107.57	-10.73
R8	120.50	152.80	26.80	2.00	123.95	2.86	160.06	32.83	182.69	51.61	203.90	69.21	105.58	-12.38
R11	120.50	140.28	16.41	2.09	110.63	-8.19	138.35	14.82	146.35	21.45	158.89	31.86	106.02	-12.02
R12	120.50	148.78	23.47	2.16	113.71	-5.64	142.24	18.04	150.36	24.78	161.94	34.39	105.57	-12.39
R13	120.50	137.98	14.51	2.02	125.62	4.25	154.98	28.62	177.95	47.68	205.02	70.14	115.57	-4.09
R14	120.50	134.52	11.63	2.02	124.88	3.64	148.23	23.01	169.68	40.82	195.52	62.26	120.91	.34
R15	120.50	159.90	32.70	2.11	122.88	1.98	153.81	27.65	167.40	38.92	184.46	53.08	117.40	-2.58
R16	120.50	160.69	33.35	2.16	124.96	3.70	162.48	34.84	176.27	46.29	189.67	57.40	108.60	-9.88
R18	120.50	159.01	31.96	2.23	117.81	-2.23	147.36	22.29	155.83	29.32	168.86	40.14	111.61	-7.38
R20	120.50	147.93	22.76	2.30	118.13	-1.97	138.85	15.23	146.44	21.53	155.82	29.31	110.58	-8.23
T1	120.50	134.52	11.63	2.00	124.35	3.20	152.04	26.18	175.98	46.04	202.86	68.35	115.52	-4.13
T2	120.50	146.67	21.72	2.03	126.27	4.79	154.82	28.48	178.61	48.23	204.81	69.97	114.72	-4.80
T3	120.50	153.24	27.17	2.02	119.43	-.89	144.96	20.30	158.81	31.79	182.05	51.08	114.12	-5.29
T4	120.50	151.86	26.02	2.06	121.56	.88	147.80	22.66	161.65	34.15	182.85	51.74	113.75	-5.60
T4	120.50	151.86	26.02	2.06	121.56	.88	147.80	22.66	161.65	34.15	182.85	51.74	113.75	-5.60
T5	120.50	137.92	14.45	1.97	107.13	-11.10	131.92	9.47	140.20	16.35	154.74	28.41	96.88	-19.60
T6	120.50	156.39	29.79	2.17	115.44	-4.20	146.00	21.17	154.50	28.21	167.04	38.62	104.32	-13.43
T7	120.50	151.47	25.70	2.03	126.18	4.71	166.88	38.49	193.16	60.30	220.77	83.21	112.48	-6.65
T8	120.50	153.02	26.99	2.08	129.27	7.28	170.90	41.83	197.48	63.89	226.15	87.68	116.28	-3.51
T9	120.50	152.74	26.76	1.96	115.95	-3.78	146.62	21.68	160.77	33.42	177.14	47.01	100.80	-16.35
T10	120.50	153.51	27.40	2.01	119.05	-1.20	143.35	18.97	157.33	30.56	177.59	47.38	109.90	-8.80
T11	120.50	153.68	27.53	2.09	111.18	-7.74	139.01	15.36	147.10	22.07	159.65	32.49	104.32	-13.43
T12	120.50	150.30	24.73	2.06	109.20	-9.38	136.04	12.89	143.95	19.46	155.98	29.45	105.08	-12.79
T13	120.50	143.72	19.27	2.05	128.07	6.28	171.44	42.27	198.77	64.95	225.20	86.89	120.07	-.36
T14	120.50	141.53	17.45	2.05	127.15	5.52	163.03	35.30	187.49	55.59	211.86	75.81	113.10	-6.14
T15	120.50	156.66	30.01	2.01	119.25	-1.03	144.29	19.74	158.49	31.53	179.26	48.76	113.02	-6.21
T16	120.50	158.37	31.43	2.13	123.61	2.58	162.19	34.60	176.10	46.14	191.28	58.74	114.27	-5.17
T17	120.50	147.13	22.10	2.19	116.05	-3.69	145.26	20.55	153.71	27.56	162.05	34.49	98.23	-18.48
T18	120.50	155.80	29.29	2.21	115.93	-3.79	143.15	18.80	151.23	25.51	161.96	34.40	101.12	-16.08

Appendix Table III

Results of Kruskal-Wallis Test of Significance, Cumulative Probability Values, for Factor Crack-Size , $\bar{a}$.

Aluminum	N	R_{sb}	K'_Q	K_{Q-PM}	K_Q	K'_J	K_J	K^*_d
Accuracy (based upon y_i)	43	>99.9[4]	100.0	>99.9	99.4	100.0	100.0	>99.9
(based upon Y)	24	99.4	>99.9	99.9	95.7	>99.9	>99.9	99.9
Reproducibility (based on s)	17	96.8	76.9	69.7	57.8	94.6	69.0	96.8
Titanium (R, T, & L data)								
Accuracy (y_i)	28	96.9	69.3	94.9	98.5	96.8	99.7	69.4
(Y)	16	95.1	76.0	94.1	92.7	96.2	97.8	83.8
Reproducibility (s)	11	37.2	2.6	8.7	79.2	6.9	34.6	36.0
Steel								
Accuracy (y_i)	51	99.9	98.0	100.0	100.0	100.0	100.0	100.0
(Y)	27	99.6	88.7	>99.9	99.9	>99.9	>99.9	>99.9
Reproducibility (s)	21	75.5[2] N = 20	86.9	78.2	42.0	60.3	8.2	59.5
Combined[1]								
Accuracy (y_i)	122	100.0	98.6	100.0	100.0	100.0	100.0	100.0
(Y)	67	99.9	94.9	100.0	>99.9	100.0	100.0	100.0
Reproducibility (s)	49	99.547[3] N = 48	95.4	90.0	0.0	94. 6	42.1	96.3

[1] Includes specimens listed above for all three materials

[2] N = 20 for R_{sb} calculation

[3] N = 48 for R_{sb} calculation

[4] > 99.9995

Appendix Table IV

Results of Kruskal-Wallis Test of Significance,
Cumulative Probability Values, for the Factor K_f maximum.

Aluminum	N	R_{sb}	K'_Q	K_{Q-PM}	K_Q	K'_J	K_J	K^*_d
Accuracy (based upon y_i)	43	56.9	79.5	98.2	83.9	96.0	94.8	95.5
(based upon Y)	24	52.8	78.0	94.7	63.7	88.3	88.2	84.9
Reproducibility (based on s)	17	70.7	38.1	72.4	43.6	60.4	87.5	53.7
Titanium (R, T, & L data)								
Accuracy (y_i)	28	49.8	22.6	3.8	96.1	76.9	80.5	83.6
(Y)	16	20.9	36.6	44.0	91.9	84.7	73.4	89.9
Reproducibility (s)	11	89.8	89.8	95.9	84.7	95.9	98.6	95.9
Steel								
Accuracy (y_i)	51	98.5	52.0	95.4	96.8	52.9	37.6	68.8
(Y)	27	96.0	49.5	70.4	69.6	32.0	13.0	51.4
Reproducibility (s)	21	25.5[2] N = 20	43.4	81.2	40.7	85.1	90.8	74.5
Combined[1]								
Accuracy (y_i)	122	99.3	84.1	98.0	99.9	56.8	50.9	62.3
(Y)	67	92.7	39.6	66.7	98.1	16.1	11.9	31.8
Reproducibility (s)	49	3.5[3] M = 48	31.8	1.1	59.5	20.4	10.7	40.5

[1] Includes specimens listed above for all three materials.
[2] N = 20 for R_{sb} only.
[3] N = 48 for R_{sb} only.

Appendix Table V

Results of Kruskal-Wallis Test of Significance,
Cumulative Probability Values, for the Factor Notch Preparation, NP.

Aluminum	N	R_{sb}	K'_Q	K_{Q-PM}	K_Q	K'_J	K_J	K^*_d
Accuracy (based upon y_i)	43	68.9	36.3	68.4	0.0	41.0	50.8	62.5
(based upon Y)	24	61.2	36.7	67.8	4.6	56.9	60.0	66.1
Reproducibility (based on s)	17	51.3	86.1	67.2	83.6	8.2	56.2	18.4
Titanium (R, T, & L data)								
Accuracy (y_i)	28	57.5	91.6	37.8	49.2	28.8	25.5	57.5
(Y)	16	25.0	80.1	16.7	2.5	23.9	17.6	50.7
Reproducibility (s)	11	40.9	47.7	52.8	6.9	16.0	38.2	2.6
Steel								
Accuracy (y_i)	51	63.5	79.8	15.3	22.6	7.7	7.6	21.7
(Y)	27	35.3	72.1	13.0	23.4	8.3	0.7	26.0
Reproducibility (s)	21	77.8[2] N = 20	36.9	94.1	58.2	58.2	74.4	77.6
Combined[1]								
Accuracy (y_i)	122	61.3	33.3	61.4	26.8	50.6	47.5	72.1
(Y)	67	59.1	22.6	43.3	21.9	52.7	40.7	73.9
Reproducibility (s)	49	53.5[3] N = 48	40.2	48.0	38.2	43.6	26.1	57.6

[1] Includes specimens listed above for all three materials.
[2] N = 20 for R_{sb} only.
[3] N = 48 for R_{sb} only.

Appendix Table VI

Residual-Standard-Deviation from Multiple Linear Regression Analyses for Seven Responses and Three Materials.

			$\bar{a}$ (Eq. 14)		$\bar{a} + K_f$ (Eq. 16)		$\bar{a}$ + Kf + NP (Eq. 17)	
Material	Response[1]	N	res. S.D.	ν	res. S.D.	ν	res. S.D.	ν
4	R_{sb}	43	0.077	41	0.076	40	0.073	39
5	R_{sb}	28	0.118	26	0.119	25	0.105	24
6	R_{sb}	51	0.072	49	0.060**	48	0.059	47
4	K'_Q	43	2.39	41	2.41	40	2.44	39
5	K'_Q	28	5.94	26	6.06	25	6.03	24
6	K'_Q	51	6.56	49	6.49	48	6.46	47
6	K'_Q[2]	36	6.14	34	5.65*	33	5.42	32
4	K_{Q-PM}	43	3.03	41	3.02	40	2.97	39
5	K_{Q-PM}	28	4.70	26	4.77	25	3.18	24
6	K_{Q-PM}	51	3.07	49	2.52**	48	2.38	47
4	K_Q	43	3.95	41	3.83	40	3.87	39
5	K_Q	28	4.95	26	3.70**	25	3.67	24
6	K_Q	51	4.09	49	3.72**	48	3.76	47
4	K'_J	43	6.23	41	5.94*	40	6.00	39
5	K'_J	28	8.67	26	8.64	25	8.64	24
6	K'_J	51	7.08	49	6.72*	48	6.62	47
4	K_J	43	5.28	41	4.92**	40	4.98	39
5	K_J	28	8.15	26	8.14	25	8.13	24
6	K_J	51	6.91	49	6.65*	48	6.65	47
4	K^*_d	43	5.82	41	5.64	40	5.70	39
5	K^*_d	28	7.60	26	7.57	25	7.49	24
6	K^*_d	51	6.10	49	5.77*	48	5.65	47

[1] For the R_{sb} responses, for which reference values of the response are not available, the residual standard deviation is computed from the response R_{sb}. For each of the K responses the computation is made using the % RD of K and the magnitude of the residual S.D. will reflect this.

[2] Includes results for only specimens with $\bar{a}$ > 140 mils.

* Significant at the 10 percent level

**Significant at the 5 percent level

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

The significance of four variables in the technique used to precrack Charpy specimens of metallic materials is determined by analyses of seven responses computed from results of slow-bend Charpy V-notch tests. The variables include crack size, stress-intensity factor at the start of precracking (K_f max), notch preparation prior to precracking, and material. Values for the crack-size factor range from a/W = 0.25 to 0.6. Three levels of K_f max were used and they range from 0.2 to 1.2 times the value recommended in ASTM Method E399. The notch preparation factor included three levels of root radius: (1) a standard 0.25 mm root-radius V-notch modified by sharpening the root with a razor blade; (2) a machined, non-standard V-notch of 0.125 mm root radius; and (3) a standard V-notch modified by sharpening to about 0.05 mm by electric discharge machining. The materials included an aluminum alloy, a maraging steel, and a titanium alloy. Three analytical methods are used to determine the significance of each of the test variables. These analyses are conducted for each of seven response parameters (each represent alternative methods for evaluations of fracture toughness) that were evaluated for each test. The results indicate that: (1) All seven computed responses are linearly related to crack length and the sensitivity to crack length is a function of both response parameter and material. (2) Precracking at either very high or very low levels of stress-intensity factor, K_f, are to be avoided. (3) The method of notch preparation prior to precracking does not signficantly affect the test response.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

Aluminum; Charpy; crack size; fatigue precracking; fracture toughness; K_f maximum; Kruskal-Wallis test; linear regression; notch preparation; precracking; statistical tests; steel; stress-intensity factor; titanium; slow-bend testing.

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