NASA TECHNICAL MEMORANDUM

NASA TM X-71834

(NASA-TM-X-71834) ESTIMATION OF Ksub Ic FROM SLOW BEND PRECRACKED CHARPY SPECIMEN STRENGTH RATIOS (NASA) 22 p HC $3.50 CSCL 20K

N76-14513

Unclas

G3/39 05659

NASA TM X-71834

ESTIMATION OF K_{IC} FROM SLOW BEND PRE-CRACKED CHARPY SPECIMEN STRENGTH RATIOS

by G. Succop and W. F. Brown, Jr.
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at
Developments and Fracture Mechanics Test Method
Standardization Symposium sponsored by the American
Society for Testing and Materials
St. Louis, Missouri, February 10-12, 1976

E8543

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by

George Succop[1] and W. F. Brown, Jr.[2]

INTRODUCTION

The need for rapid and inexpensive fracture tests to estimate plane strain fracture toughness levels is discussed in a recent NMAB report (1). Such "screening tests" would be especially useful in alloy development and quality control where large numbers of tests must be made and where the amount of test material may be limited. Of the various screening tests that have been proposed the simplest are those requiring only a measurement of maximum load and the initial dimensions of the specimen. Three such tests have been in use for several years, namely, the double sharp edge notch and center cracked sheet specimens described in ASTM E 338-68 (2) and the sharply notched cylindrical specimen described in an ASTM Proposed Test Method (3). The fracture toughness index derived from these tests is the ratio of their notch strength to the smooth specimen tensile yield strength, where the notch strength is based on the maximum load divided by the net area of the specimen. Results from tests on sharply notched or cracked

[1]Research Engineer, NASA Lewis Research Center, Cleveland, Ohio 44135

[2]Chief, Fracture Branch, NASA Lewis Research Center, Cleveland, Ohio

sheet specimens were not intended to correlate with K_{Ic} but to serve as an index of mixed mode fracture toughness. The circumferentially notched cylindrical specimen provides high constraint to plastic flow and as might be expected notch strength of these specimens does correlate with the plane strain fracture toughness providing the cylindrical specimen size is sufficient.

An important disadvantage of the notched cylindrical tension specimen is the sensitivity of its notched strength to bending stresses which arise from eccentricity of loading. Unless precision machined fixtures are used the eccentricity will vary from test to test and this variation can result in a substantial contribution to the data scatter (4). Fatigue cracking of notched cylinders is seldom attempted because of the great difficulty in producing cracks which are concentric with the specimen axis. If the material is highly directional in its mechanical properties, circular fatigue cracks cannot be produced. In contrast, the notch bend specimen has none of these disadvantages and should be less expensive to machine.

The ASTM E 399-74 K_{Ic} test method (5) requires that the specimen strength ratios be reported for tests on both bend and compact specimens. These are designated as R_{sb} for the bend specimen and R_{sc} for the compact specimen. These nominal strength ratios are analogous to the strength ratios for notched cylindrical tension specimen and may correlate with K_{Ic}. However, we are not aware that such correlations have been attempted.

In this paper we report strength ratios derived from slow bend tests on 0.25 inch thick precracked Charpy specimens of steels, aluminum alloys and a titanium alloy for which valid K_{Ic} values have been established. The strength ratios are used to develop calibration curves typical of those that could be useful in estimating K_{Ic} for the purposes of alloy development or quality control. It should be noted that $\overline{W}/A$ information for these same specimens is given in another paper.

MATERIALS AND PROCEDURE

The alloys investigated are listed in Table I which gives their K_{Ic} values determined at room temperature in accordance with ASTM E 399-74 using bend specimens. These values represent the average of three determinations for each crack plane orientation indicated. Three precracked Charpy specimens (Fig. A1 of Appendix A) were prepared for each alloy condition with their crack plane orientations corresponding to those of the K_{Ic} specimens. In all but one case, the Charpy blanks were cut from the broken K_{Ic} specimens. The one exception was 2124T851 and in this case, the Charpy blanks were removed from a near surface slice of the three inch plate. Details of fatigue cracking and testing have beeen described previously (6).

The maximum load values were determined from the load indicator of the tensile machine. Load was converted to the nominal strength σ_N by the following relation based on bending of an elastic beam:

$$\sigma_N = \frac{3P_{max}}{2B} \frac{S}{(W-a)^2}$$

where P_{max} is the maximum load, S is the span, B the thickness, W the specimen width, and a the crack length.

RESULTS AND DISCUSSION

The following section describes relations observed between slow bend precracked Charpy strength ratios and a dimensionless plane strain toughness parameter as compared with that expected on the basis of linear elastic behavior. Included is a limited amount of information on the thickness effect. In addition, a previously described (6) statistical analysis was used to illustrate how precracked Charpy strength ratios might be employed to estimate plane strain fracture toughness for the purpose of alloy development or quality control. We wish to emphasize that this statistical analysis is presented only as an example and to provide a relative measure of the performance of the precracked Charpy strength ratio in estimating plane strain toughness for the alloys investigated. Working relationships between Charpy strength ratios and toughness should be established for specific applications and the statistical analysis should be appropriate to the application.

Relations between Strength Ratios and Toughness

Specimen strength ratios can be based on either the ultimate tensile strength or the tensile yield strength. It has been common practice to select the tensile yield strength because of its generally accepted significance in certain fracture mechanics calculations. However, for the present purposes we based the strength ratios on the ultimate tensile strength because in this way the Green and Hundy limit (7) can be used for an upper bound on the data. We found that neither data correlations nor K_{Ic} estimates were improved by using the tensile yield strength as a base. Plots of σ^2_N/σ^2_{ut} versus the average value of the dimensionless toughness parameter $K^2_{Ic}/\sigma^2_{ut}W$ determined from triplicate K_{Ic} tests, are shown in Figures 1 through 5. Also shown in these figures is the theoretical relation between the Charpy strength ratio and the toughness parameter that would be expected for linear elastic behavior. (see Appendix A for derivation of this relation). This elastic line is terminated at the Green and Hundy limit which represents the maximum bending moment for a specimen of a nonstrain-hardening rigid plastic material containing a deep sharp notch (see Appendix B). The scatter of strength ratios among replicate tests of the precracked Charpy specimens is quite small and in most cases completely encompassed by the plotted points. Where the scatter exceeded the extent of the points the range is indicated by a vertical line. The strength ratios follow the trend of the elastic line at low and intermediate values of the toughness parameter but at higher values of toughness the strength ratios should gradually lose sensitivity to changes in toughness. This complete range of behavior is seen only for the 18Ni maraging steel, Fig. 2, but could be expected for the other alloys if sufficiently tough conditions had been tested. For the materials tested the theoretical elastic relation represented the data suprisingly well provided the strength ratios were sufficiently less than the Green and Hundy limit. This behavior might lead to the speculation that the elastic line would be useful as a means for estimating K_{Ic} directly from the strength ratios. However attractive this idea may seem, we wish to emphasize that both the elastic line and the Green and Hundy limit represent idealized material behavior. For real materials the correspondence between their behavior and that established by linear elastic fracture mechanics will depend on the thickness of the Charpy specimen and the material crack growth resistance characteristics. Furthermore, the toughness level above which the strength ratios lose useful sensitivity to changes in toughness will not be usefully set by the Green and Hundy limit but must be determined by conducting a sufficient number of K_{IC} and precracked Charpy tests at very high toughness levels where unfortunately the size requirements are most severe.

Thickness Effect

The difference between the observed precracked Charpy strength ratios and those calculated assuming linear elastic behavior will depend on the combined effects of plastic zone development and cracking. Plastic zone development tends to raise the notch strength while cracking acts to reduce it. If the bend specimens are sufficiently thin, plastic flow will dominate the deformation and the strength ratios will lie above the elastic line at intermediate values of toughness. Increasing the thickness can result in a balance between the strengthening effect of plasticity and the weakening effect of cracking so that the strength ratios lie on the elastic line even though the specimens may be subject to large scale yielding.

These behaviors are illustrated in Fig. 6* which combines the strength ratio data for Charpy specimens of 18 Ni maraging steel (see Fig. 2) with that obtained by Srawley (8) for the same plate of material using standard K_{Ic} specimens of two thicknesses. Precracked Charpy data for 4340 steel (fig. 1) has been added to this figure. The strength ratios for the 0.25 inch thick Charpy specimens lie above the elastic line at intermediate values of the dimensionless toughness parameter but fall well below this line as the Green and Hundy limit is approached. The data for the 1.8 inch thick specimens falls on the elastic line as might be expected since the P_{max}/P_Q ratio for these specimens was very close to unity at all the toughness levels investigated. However, it will be noted that the strength ratios for the 0.5 inch thick specimens fall on the elastic line even though the specimens did not meet the validity requirements of ASTM E 399-74 and exhibited pronounced shear lip development.

Estimation of K_{Ic} from Strength Ratios

Linear regression analysis was used to establish "calibration lines" relating σ_N^2/σ_{ut}^2 to $K_{Ic}^2/\sigma_{ut}^2 W$ for 4340 steel, 18 Ni maraging

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*The a/W values for the precracked Charpy specimens and the K_{Ic} bend specimens are not the same. Therefore, the strength ratios plotted in Fig. 6 have been normalized with respect to the relative crack length of the K_{Ic} specimens (a/W = 0.5) steel and the various aluminium alloys. The 95 percent confidence bands were determined for these lines. This information and the correlation coefficients are shown in Figs. 7 to 9. We judged there was insufficient data to permit a meaningful statistical treatment of the results for 7x75 aluminum and the titanium alloy. For the purpose of the regression analysis it was necessary to make a selection of a cut-off point in terms of the dimensionless toughness parameter in order to confine the analysis to the range of toughness where the strength ratio data are strongly dependent on the changes in toughness. The cut-off was selected at the intersection of the Green and Hundy limit with the line representing linear elastic behavior ($K_{Ic}^2/\sigma_{ut}^2 w$ = 1.2). This resulted in excluding data for the 700 and 725 F aged conditions for the 18Ni maraging steel but included all the data for the 4340 and the various aluminum alloys.

The correlation coefficients are designated by the R values shown in Figs. 7 to 9. These are all quite high as might be expected from the overall distribution of data about the calibration lines. However, it should be noted that for certain alloy conditions, namely the highest strength levels in the 18Ni maraging steel and the two toughest conditions of 7X75 aluminum, substantial changes in the dimensionless toughness parameter were not accompanied by significant changes in the corresponding strength ratios. The lack of correlation in the case of the aluminum alloy may be associated with differences in the testing direction between the two toughest conditions and in the case of the steel associated with a complex aging reaction that occurs in the 18 Ni maraging steels. If the dimensionless toughness parameter is estimated from a single value of the precracked Charpy strength ratio, its true value will lie within the confidence bands 95 out of 100 times. For 4340 steel these bands are quite narrow and define limits of about $\pm$ 10 percent of the value determined by the calibration line. This would represent a $\pm$ 5 percent change in K_{Ic}. For both the 18 Ni maraging steel and the various aluminum alloys, the confidence bands are relatively broad. For example, at their extremes they define limits on the toughness parameter of about 33 percent of the value determined from the calibration line. This would represent a $\pm$ 18 percent change in K_{Ic}. It is interesting to note that the position of the confidence bands with respect to the calibration lines in Figs. 7 to 9 is essentially the same as observed when the calibration lines were based on the $\overline{W}/A$ values rather than strength ratios (6).

GENERAL COMMENTS

When $\overline{W}/A$ values are to be derived from a precracked Charpy slow bend test, the amount of instrumentation and record analysis required is for practical purposes equal to that necessary for an ASTM E-339 K_{Ic} test. The use of strength ratios rather than $\overline{W}/A$ values greatly simplifies the procedure and reduces the cost. However, a price must be paid for these advantages. The range of toughness values over which a useful relation between Charpy strength ratio and K_{Ic} can be established is limited by excessive plasticity in the bend specimen at high toughness levels. The effect of this plasticity is to cause a gradual loss in sensitivity of the Charpy strength ratio to changes in K_{Ic}. If the toughness range is suitably restricted to avoid this effect we found that the strength ratios could be used to estimate K_{Ic} with the same confidence as obtained using $\overline{W}/A$ values derived from the same specimen. However, at the present time this restriction can only be established arbitrarily by inspection of the data over a wide range of toughness values. We did not find a similar limitation on the toughness level when investigating relations between $\overline{W}/A$ values and plane strain fracture toughness for the same materials as reported in this paper. On the otherhand, we did encounter metal conditions where neither the $\overline{W}/A$ values nor the strength ratios correlated with changes in K_{Ic}.

The required confidence for estimation of K_{Ic} from Charpy slow bend tests will depend on the application and it is not now possible for us to make judgements in this respect. However, we do believe that in some circumstances precracked Charpy slow bend strength ratios derived from test methods standardized as to specimen size and test procedure can serve as useful indices of plane strain fracture toughness. These circumstances should be better defined by further research. Based on the information available at this time, it appears that certain factors will tend to reduce the confidence with which K_{Ic} can be estimated. These include situations where the calibration relations are based on a mixture of alloy types from the same alloy class, where variations in crack orientation with respect to the fiber are included in the sample and where complex metallurgical changes are influencing the variations in fracture toughness.

APPENDIX A

LINEAR ELASTIC RELATION BETWEEN THE NOMINAL STRENGTH RATIO FOR A CRACKED BEND SPECIMEN AND THE PLANE STRAIN FRACTURE TOUGHNESS OF THAT SPECIMEN

The relation between the nominal stress σ_n in a cracked three point bend specimen and the crack tip stress intensity factor will depend on the width of the specimen and the relative crack length. An appropriate expression for the stress intensity factor obtained from Srawley and Gross (10) is:

$$\frac{4KB(W-a)^{3/2}}{PS} = Y \quad - - - - [A\cdot 1]$$

where K is the stress intensity factor and Y is a function of a/W. The other terms are defined in Fig A-1.

The net stress in the specimen is given by

$$\sigma_n = \frac{3PS}{2B(W-a)^2} \quad - - - - [A\cdot 2]$$

Solving Eq. (2) for P and substituting in Eq. (1) gives

$$\frac{6K}{\sigma_n (W-a)^{1/2}} = Y \quad - - - - [A\text{-}3]$$

Squaring and rearranging terms

$$\frac{K^2}{W} = \frac{\sigma_n^2 (1 - a/W) Y^2}{36} \quad - - [A\text{-}4]$$

Dividing Eq. (4) by the ultimate tensile strength σ_{ut} squared and substituting the nominal strength σ_N based on maximum load for σ_n and K_{Ic} for K gives the desired relation.

$$\frac{K_{Ic}^2}{\sigma_{ut}^2 W} = \sigma_N^2 \frac{(1-a/W)Y^2}{36\,\sigma_{ut}^2} \quad ---- [A5]$$

For the precracked Charpy specimen we used (1 - a/W) = 0.60 and Y = 3.69 giving:

$$\frac{\sigma_N^2}{\sigma_{ut}^2} = \frac{4.4 K_{Ic}^2}{\sigma_{ut}^2 W} \quad ---- [A6]$$

APPENDIX B

LIMITING NOMINAL STRESS FOR THREE POINT LOADED NOTCH BEND SPECIMENS

Slip line field theory has been used by Green and Hundy (7) to calculate yield point loads from the tensile yield strength for flow bend tests on standard V notch Charpy specimens (ASTM E-23 Type A). The theory assumes a non-strain hardening rigid plastic material, plane strain deformation and a notch sufficiently deep that the deformation cannot reach the surface ($a/W > 0.30$). With the exception of the last condition these assumptions are not completely realized in tests on engineering materials using specimens of commonly encountered proportions. However, Green and Hundy obtained surprisingly good agreement between calculated and experimentally determined yield loads for slow bend tests on V notch Charpy specimens of a mild steel which has a definite yield point. Green (11) found good agreement between the theoretical yield loads and those measured for V notched annealed copper specimens with small width to thickness ratios (W/B = 0.078) subjected to pure bending (four point loading). In a more recent paper MClintock (12) suggested that plastic instability (maximum) loads for notched specimens might be approximated using slip line field theory if the ultimate tensile strength σ_{ut} is used in the calculation rather than the tensile yield strength.

We used the theoretical results of Green and Hundy for three point bending of V notch Charpy bars to determine an upper bound on the notch strength of our precracked Charpy specimens from the ultimate tensile strength, Green and Hundy give the following expression for the load per unit net area of the Charpy bend specimen:

$$P/B(W-a) = 0.484\ k \quad \text{------------------} \quad (\text{B-1})$$

where k is the maximum shearing stress (see Fig. A-1 for other symbols).

Eq. (B-1) may be rewritten in terms of the moment applied to our precracked Charpy specimen as follows:

$$4\ M/1.5B(W-a) = 0.484\ k \quad \text{--------------} \quad (\text{B - 2})$$

The nominal stress in a notch bend specimen is

$$\sigma_n = 6M/B(W-a)^2 \quad \text{--------------------} \quad (\text{B - 3})$$

Combining Eq. (B-2) with Eq. (B-3) and substituting $\sigma_{ut}/2$ for k gives the desired expression for the notch strength

$$\sigma_n = \sigma_{max} = 2.31\ \sigma_{ut} \quad \text{--------------} \quad (\text{B - 4})$$

Eq. (B-4) was used to establish an upper bound on the specimen strength ratios obtained from the precracked Charpy specimens.

We realize that our specimen proportions and material characteristics do not conform at all well to the assumptions made in the slip line ield analysis of the notched bend specimen. However, as can be seen from

Fig. 2 the limit established by Eq. (B-4) appears to be a reasonable upper bound on the data for the maraging steel. Whether or not it woula serve as well for other materials cannot be determined without additional tests.

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TABLE I: ALLOYS INVESTIGATED

Alloy	Plate thickness in.	Heat Treatment	0.2 Percent Yield Strength ksi	Ultimate Tensile Strength ksi	K_{Ic} ksi - in$^{1/2}$	K_{Ic} Data Source
Steels SAE 4340	1	1550 1/2-hr OQ - temper 600 to 925°F, 1 hr.	232 to 183 (L)[a]	See Fig. 1	See Fig. 1	ref. 9
18Ni Marage 250 Grade	2	1550 F, 1 hr AC + Age 700 to 1100°F, 6 hr.	173 to 259 (L)	See Fig. 2	See Fig. 2	ref. 8
Titanium 8Mo-8V-2Fe -3Al	2	1600 F, 1 hr WQ + Age 800 to 1100°F, 8 hr.	156 to 198 (L)	See Fig. 5	See Fig. 5	C
Aluminums						
7075T651	1.4		79(L)	87 (L)	22(TL)[b]	C
	2.5		74(T)	86 (T)	25(LT)	C
	4.0		61(ST)	71 (ST)	19(SL)	C
7075T7351	1.4		63(L)	74 (L)	31(LT)	C
7475T7351	1.8		62(L), 61(T)	73(L), 72(T)	47(LT), 30 (TL)	C
2219T851	1.5		51(L)	67(L)	32(TL)	C
2124T851	3		64(L)	70(L)	31(LT)	C
4.2Cu-0.55Mg -0.8Si-0.75Mn (26SL-93)	3		65(T)	69(T)	23(TS)	C
6061T651	2		45(T)	49(T)	22(TL)	C

a. L-longitudinal, T-transverse, ST-short transverse

b. Crack plane orientation according to ASTM E 399-74

c. Present investigation

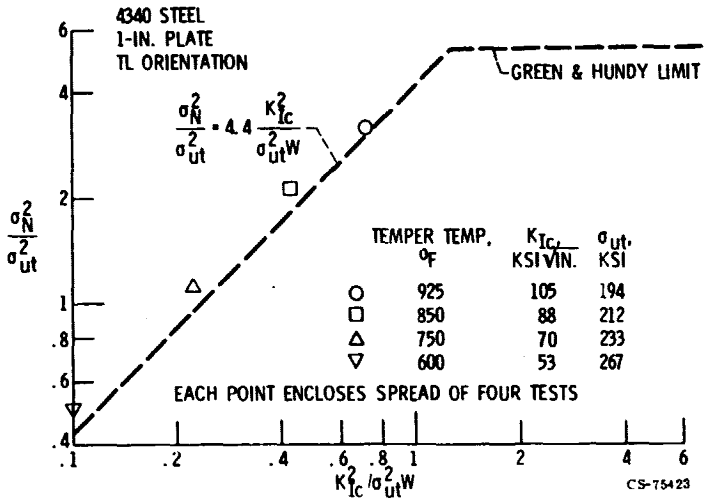

Figure 1. - Strength ratios from 0.25 inch thick precracked Charpy slow bend specimens as a function of a dimensionless plane strain fracture toughness parameter for 4340 steel.

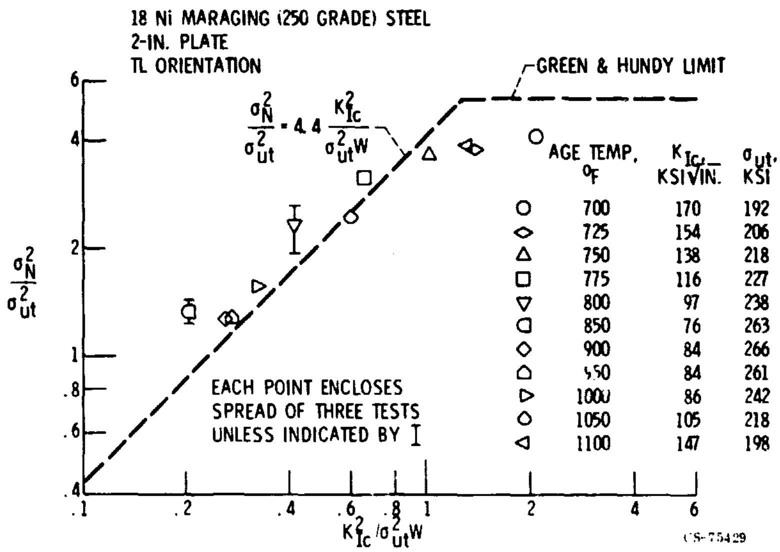

Figure 2. - Strength ratios from 0.25 inch thick precracked Charpy slow bend specimens as a function of a dimensionless plane strain fracture toughness parameter for 18 Ni maraging (250 grade) steel.

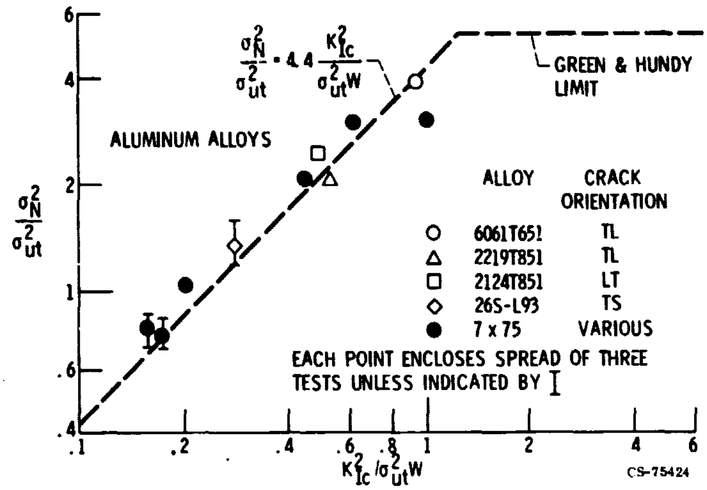

Figure 3. - Strength ratios from 0.25 inch thick precracked Charpy slow bend specimens as a function of a dimensionless plane strain fracture toughness parameter for various aluminum alloys.

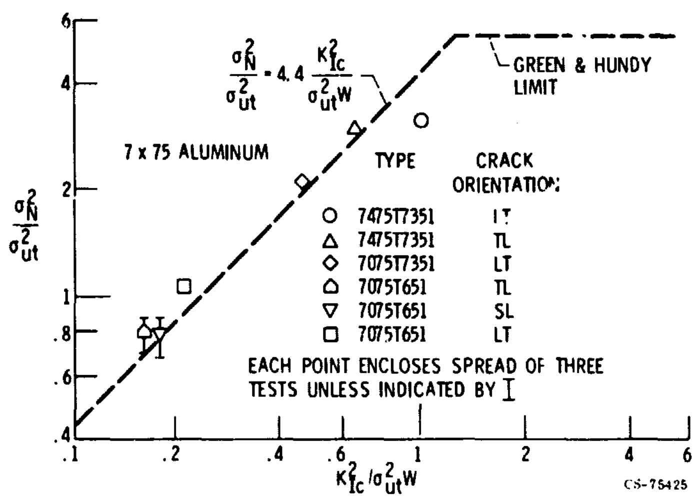

Figure 4. - Strength ratios from 0.25 thick thick precracked Charpy slow bend specimens as a function of a dimensionless plane strain fracture toughness parameter for 7X75 aluminum alloys.

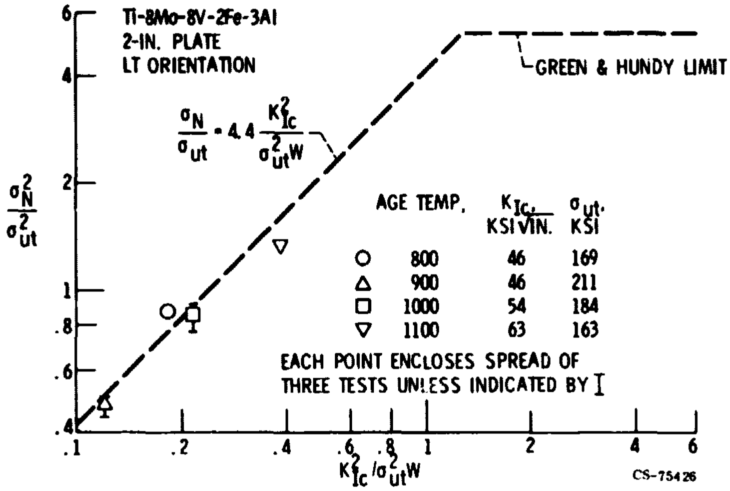

Figure 5. - Strength ratios from 0.25 inch thick precracked Charpy slow bend specimens as a function of a dimensionless plane strain fracture toughness parameter for a beta titanium alloy.

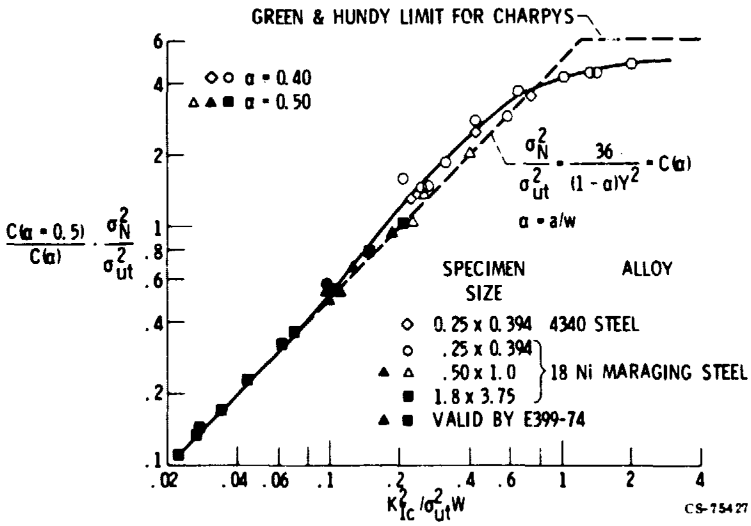

Figure 6. - Strength ratios for several sizes of cracked slow bend specimens as a function of a dimensionless plane strain fracture toughness parameter.

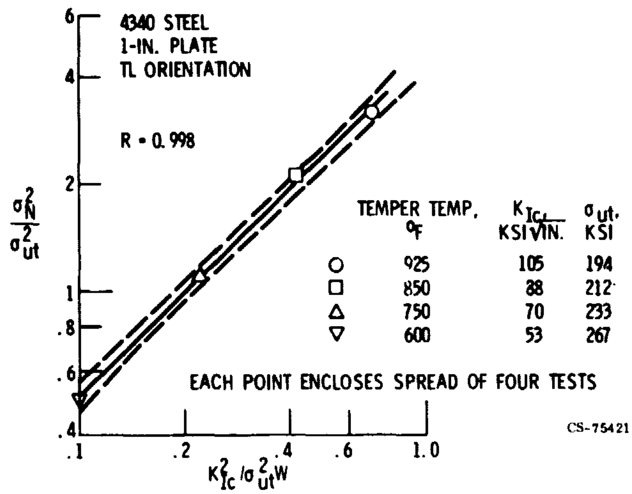

Figure 7. - Correlation coefficient R, calibration line and 95 percent confidence bands for 4340 steel.

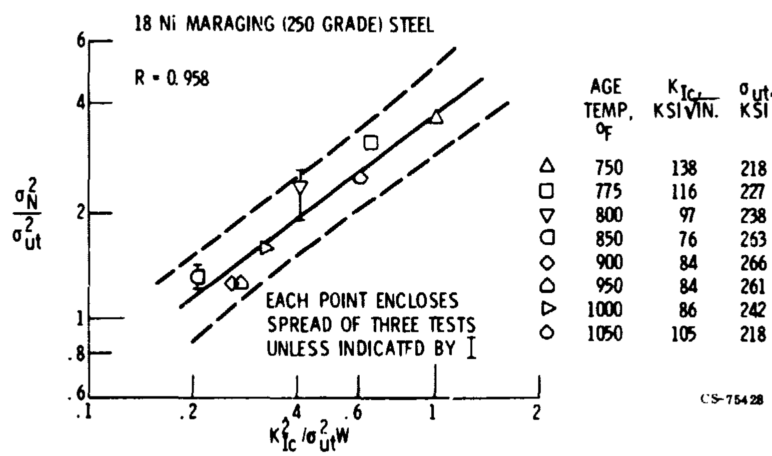

Figure 8. - Correlation coefficient R, calibration line and 95 percent confidence bands for 18 Ni maraging (250 grade) steel.

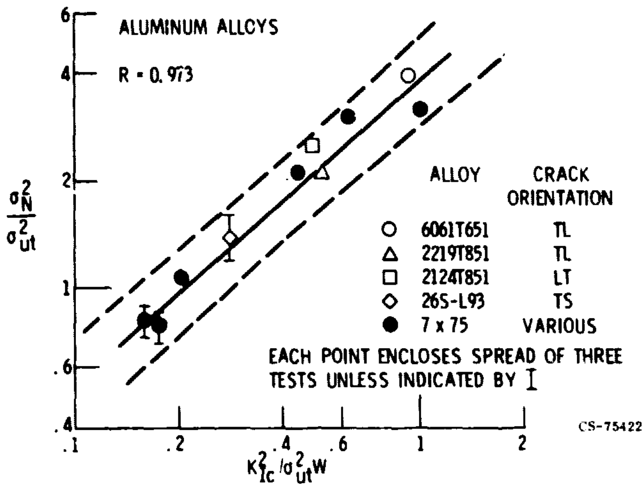

Figure 9. - Correlation coefficient R, calibration line and 95 percent confidence bands for various aluminum alloys.