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A SEMIEMPIRICAL FRACTURE ANALYSIS FOR SMALL SURFACE CRACKS

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ABSTRACT

A semiempirical modification of Irwin's fracture analysis for a semielliptical surface crack in a plate is proposed. When it is applied to surface crack test data from the literature, a single toughness parameter is obtained which relates fracture stress to crack size with reasonable accuracy. The method appears usable when crack size and material thickness are too small to allow a valid analysis using conventional fracture mechanics principles. It is even effective when fracture stresses are above yield. A similiar analysis for through-the-thickness cracks is discussed but not evaluated. Application to low-cycle fatigue crack propagation studies is proposed.

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SUMMARY

This report presents a semiempirical modification of Irwin's fracture analysis for a semielliptical surface crack in a plate. The plastic zone correction factor is replaced by a term chosen so that the modified Irwin equation predicts fracture at ultimate tensile strength for zero crack depth. The effects of normal experimental error and material property variations are considered, and a statistical procedure for averaging the results of a series of tests is presented. A similar analysis for through-the-thickness cracks is discussed but not evaluated.

Surface-crack test data from the literature (for aluminum, magnesium, titanium, and steel alloys and aluminum weldments) are analyzed. The method yields a toughness parameter for each material which relates fracture stress to crack size, generally within about ±5 percent. The method appears to be usable when crack size and material thickness are too small to allow a valid fracture mechanics analysis. It is even effective when fracture stresses are above yield.

At present the analysis is limited to crack depths less than about half the material thickness. The available data are not sufficient to determine whether the modified toughness parameter is independent of material thickness.

INTRODUCTION

The most well known fracture analysis for surface cracks is that of Irwin (ref. 1). This analysis relates the fracture stress for a specimen or structure containing a semielliptical surface crack to the crack dimensions, the material's yield strength, and a material constant called the plane strain fracture toughness and designated K_{IC}.

The application of this analysis to practical problems is not always straightforward. As explained in reference 1, the analysis is considered valid only when the crack depth is less than half the material thickness and when the gross stress at fracture is less than the material's yield strength. The specimen necessary to determine K_{IC} (ref. 2) may be many times thicker than in the intended application, and the applicability of thick-section laboratory data to thin-section hardware is questionable.

When the Irwin analysis is used to predict fracture stress and the crack depth approaches zero, the predicted fracture stress is more than twice the material's yield strength. It may be meaningless to speak of zero crack depth in relation to engineering materials that contain microscopic defects and inhomogeneities. But for engineering use, the fracture stress for a vanishingly small crack should be the material's ultimate tensile strength.

In the present report, Irwin's plastic zone correction factor is replaced by a term chosen so that the modified equation predicts fracture at ultimate tensile strength when the crack depth is reduced to zero. McClintock and Irwin (ref. 3) state that until suitable elastic-plastic analyses are available, empirical adjustments of the plastic zone correction factor can be justified. Application of the same principle to Irwin's fracture equation for through-the-thickness cracks is discussed, but the available data are either unsuitable or insufficient for a critical evaluation.

SYMBOLS

a	crack depth
c	one-half crack length
i	index in summation
K_{IC}	opening-mode (plane strain) fracture toughness
K_{IU}	modified K_{IC}
K_c	mixed-mode (plane stress) fracture toughness
K_u	modified K_c
t	specimen thickness
W	specimen width
Δ	expected error; read, "expected error in . . ."
σ	gross stress at fracture
σ_u	material ultimate strength
σ_{ys}	material tensile yield strength (0.2 percent offset)
θ	variable of integration
Φ	complete elliptic integral of the second kind

ANALYSIS FOR SURFACE CRACKS

Irwin Analysis

In its fundamental form, Irwin's fracture equation for a semielliptical surface crack is (from ref. 1)

$$K_{IC}^2 = \frac{1.2\,\pi\sigma^2}{\Phi^2}\left[a + \frac{1}{4\sqrt{2}\,\pi}\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2\right] \tag{1a}$$

where

$$\Phi = \int_0^{\pi/2}\sqrt{1 - \left(1 - \frac{a^2}{c^2}\right)\sin^2\theta}\;d\theta$$

Here, the second term in the brackets represents the plastic zone correction term. It was assumed by Irwin that the effects of localized yielding at the crack tip may be accounted for by adding a portion of the plastic zone to the actual crack depth. For convenience, equation (1a) is usually written as

$$K_{IC}^2 = \frac{1.2\,\pi a\sigma^2}{\Phi^2 - 0.212\left(\frac{\sigma}{\sigma_{ys}}\right)^2} \tag{1b}$$

or in terms of fracture stress as

$$\sigma = K_{IC} \div \sqrt{\frac{1.2\,\pi a}{\Phi^2} + \frac{0.212}{\Phi^2}\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2}$$

The preceeding equation may be written in terms of the normalized crack depth a/Φ^2 by assuming that $\Phi^2 = \sqrt{2}$ in the second term under the radical, giving

$$\sigma \approx K_{IC} \div \sqrt{1.2\,\pi\frac{a}{\Phi^2} + 0.15\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2} \tag{1c}$$

This assumption is equivalent to assuming that $a/2c \approx 0.23$. Since only the plastic zone correction is affected, any error in σ should be small.

Because it is based on linear elastic theory, the analysis is not valid if the fracture stress is greater than yield. Brown and Srawley (ref. 2) indicate that it is valid (i.e., measured K_{IC} is constant) only when the crack depth is greater than about $2\frac{1}{2}$ times the square of the ratio of K_{IC} to yield strength. Because of geometrical considerations, it is restricted to crack depths less than half the material thickness. Thus application of Irwin's analysis to material thicknesses less than about $5\left(K_{IC}/\sigma_{ys}\right)^2$ is uncertain.

Modified Irwin Analysis

By altering only the plastic zone correction term, Irwin's equation can be made to predict fracture at ultimate strength for zero crack depth. This is done by replacing fracture stress with ultimate strength and crack depth with zero in equation (1a), then solving for the new "plastic zone correction factor." The equation then becomes

$$K_{IU}^2 = \frac{1.2\,\pi\sigma^2}{\Phi^2}\left[a + \frac{\Phi^2}{1.2\,\pi}\left(\frac{K_{IU}}{\sigma_u}\right)^2\right] \tag{2a}$$

which can be written as

$$K_{IU}^2 = \frac{1.2\,\pi a\sigma^2}{\Phi^2\left[1 - \left(\frac{\sigma}{\sigma_u}\right)^2\right]} \tag{2b}$$

or

$$\sigma = K_{IU} \div \sqrt{1.2\,\pi\,\frac{a}{\Phi^2} + \left(\frac{K_{IU}}{\sigma_u}\right)^2} \tag{2c}$$

The modified fracture toughness parameter is designated K_{IU} to distinguish it from the Irwin parameter K_{IC}. For a given crack size and fracture stress, K_{IU} is almost always greater than K_{IC}. However, when fracture stress is very much less than yield or ultimate (as for a large crack in a brittle material),

$$K_{IU} = K_{IC} \approx \sigma\sqrt{1.2\,\pi\,\frac{a}{\Phi^2}}$$

Since only the plastic zone corrections differ, this analysis and Irwin's must be subject to the same geometrical restrictions. Irwin estimated that his analysis will be reasonably accurate as long as the crack depth is less than half the material thickness. If the crack depth is large with respect to the thickness, the effect of the free back surface is to increase the actual stress intensity at the crack tip. Equation (1a) then underestimates the actual stress intensity, and the apparent stress intensity decreases with increasing a/t. Thus, unless there is firm evidence to the contrary, the modified Irwin analysis should also be restricted to cases where the crack depth is less than half the material thickness.

Other researchers, notably Kobayashi (ref. 4) and Smith (ref. 5), have developed correction factors for deep flaws. It should be possible to combine the elastic portion of such a deep-flaw analysis with the plastic zone correction of the present analysis. However, this was not attempted here.

Equation (2b) breaks down if the fracture stress is not less than the tensile ultimate strength. This phenomenon sometimes occurs and is usually called "notch strengthening." In such a case, a correlation based on an artificially elevated ultimate strength value might be possible but is beyond the scope of this report.

Expected Error

In an experimental determination of K_{IU}, the error ΔK_{IU} to be expected due to the normal variation of material properties and due to imprecision of physical measurements is

$$\Delta K_{IU} = \left|\frac{\partial K_{IU}}{\partial \frac{a}{\Phi^2}}\right| \Delta \frac{a}{\Phi^2} + \left|\frac{\partial K_{IU}}{\partial \sigma}\right| \Delta\sigma + \left|\frac{\partial K_{IU}}{\partial \sigma_u}\right| \Delta\sigma_u$$

Differentiating equation (2b) yields

$$\Delta K_{IU} = K_{IU}\left[\frac{\Phi^2}{2a}\,\Delta\frac{a}{\Phi^2} + \frac{1}{1-\left(\frac{\sigma}{\sigma_u}\right)^2}\,\frac{\Delta\sigma}{\sigma} + \frac{\left(\frac{\sigma}{\sigma_u}\right)^2}{1-\left(\frac{\sigma}{\sigma_u}\right)^2}\,\frac{\Delta\sigma_u}{\sigma_u}\right]$$

In this report it is assumed that $\Delta(a/\Phi^2) = 0.0006$ inch (0.015 mm), $\Delta\sigma/\sigma = 0.03$, and $\Delta\sigma_u/\sigma_u = 0.03$. The expected error in a/Φ^2 corresponds to a 0.001 inch (0.025 mm) error in crack depth measurement for a crack with a shape factor $a/2c \approx 0.31$. The expected errors in fracture stress and ultimate strength are considered to be normal, representative precision levels for careful tests involving parent metal (for weldment tests, however, somewhat larger values might be more appropriate). Using these values, the previous equation then becomes

$$\Delta K_{IU} = \overline{K_{IU}} \left[\frac{0.0003}{\frac{a}{\Phi^2}} + 0.03 \frac{1 + \left(\frac{\sigma}{\sigma_u}\right)^2}{1 - \left(\frac{\sigma}{\sigma_u}\right)^2} \right] \tag{3}$$

or, when written in terms of a/Φ^2 or σ/σ_u only

$$\Delta K_{IU} = \overline{K_{IU}} \left\{ 0.03 + \frac{1}{\frac{a}{\Phi^2}} \left[0.0003 + \frac{0.05}{\pi} \left(\frac{\overline{K_{IU}}}{\sigma_u} \right)^2 \right] \right\} \tag{4a}$$

$$\Delta K_{IU} = \overline{K_{IU}} \left\{ 0.03 + \frac{\left(\frac{\sigma}{\sigma_u}\right)^2}{1 - \left(\frac{\sigma}{\sigma_u}\right)^2} \left[\frac{0.00036\,\pi}{\left(\frac{\overline{K_{IU}}}{\sigma_u}\right)^2} + 0.06 \right] \right\} \tag{4b}$$

where $\overline{K_{IU}}$ is the "true" value (or the weighted average value; see next section).

From equation (4b) the maximum stress ratio σ/σ_u for a given allowable error $\Delta K_{IU}/\overline{K_{IU}}$ can be determined. This is shown for range of $\overline{K_{IU}}/\sigma_u$ observed for the data examined in this report as follows:

	ΔK_{IU} $\overline{K_{IU}}$								
	0.20			0.10			0.05		
$\overline{K_{IU}}/\sigma_u$	0.2	0.5	1.0	0.2	0.5	1.0	0.2	0.5	1.0
$(\sigma/\sigma_u)_{max}$	.81	.85	.86	.67	.72	.73	.43	.49	.50

The $(\sigma/\sigma_u)_{max}$ values are valid only for $\Delta(a/\Phi^2) = 0.006$ inch, $\Delta\sigma/\sigma = 0.03$, and $\Delta\sigma_u/\sigma_u = 0.03$.

In the same manner as for equation (3), the expected error in K_{IC} can be determined as

$$\Delta K_{IC} \approx \overline{K_{IC}}\left(\frac{0.0003}{\frac{a}{\Phi^2}} + 0.05\,\frac{\Phi^2}{Q} - 0.02\right) \tag{5}$$

where $Q = \left[\Phi^2 - 0.212(\sigma/\sigma_{ys})^2\right]$ and $\Delta\sigma_{ys}/\sigma_{ys}$ is assumed to be 0.02. As before, this error is considered to be representative of a careful test.

Weighted Average

As flaw size decreases, the expected error in K_{IU} (eq. (3)) increases. But as flaw size decreases, fracture stress tends to increase, and the error in K_{IU} is compounded. Thus for small flaws, K_{IU} measurements are very sensitive to small experimental errors and material property variations. It is desirable, then, to average the results of as many tests as possible.

If the tests cover a range of flaw size and/or fracture stress, they will not all have the same precision. According to Wilson (ref. 6) the observations should be weighted inversely proportional to the square of their expected error. The weighted average value of K_{IU} is then

$$\overline{K_{IU}} = \frac{\sum \frac{(K_{IU})_i}{(\Delta K_{IU})_i^2}}{\sum \frac{1}{(\Delta K_{IU})_i^2}} \tag{6}$$

where ΔK_{IU} is given by equation (3).

The inverse-square weighting procedure and the nature of the error function combine to weight the large-flaw, low-stress tests very heavily. For example, if $\overline{K_{IU}}/\sigma_u = 0.5$, a test at $\sigma = 0.5\ \sigma_u$ is weighted 35 times as much as a test where $\sigma = 0.9\ \sigma_u$. It is desirable to place more weight on the test expected to be the most precise, but the weighting function given by equation (6) and (3) appears to be unusually severe. Perhaps, it would suffice to weight inversely proportional to the expected error rather than to its square. However, the use of the second power is customary statistical procedure. Also, as will be shown later, the use of equation (6) results in a fairly accurate correlation of fracture stress with crack size for several materials.

It should be noted that this weighted averaging procedure is not the same as a conventional curve fit. There, one might mathematically determine the value of K_{IU} which minimizes the sum of the squares of the fracture stress deviations (differences between stress observed and stress predicted by eq. (2c)). The weighted average, however, is based on a prior assumption of the magnitudes of the errors that might be expected and on the knowledge of the effect such errors will have on the calculated value of K_{IU}.

It is difficult to determine whether the variations in apparent K_{IU} for some sets of data represent a real trend or merely confirm the error expectation. Error analysis cannot prove that K_{IU} is a material constant. It can only show that, if K_{IU} is a constant, the variations are within the bounds of expected error. However, it will be assumed in this report that K_{IU} is a constant and that the weighted average (eq. (6)) is a suitable operating definition.

A similar weighted averaging procedure should be used for a set of K_{IC} values, but only for the domain where K_{IC} is reasonably constant. The rationale of linear elastic fracture mechanics does not allow the consideration of apparent K_{IC} values obtained outside that domain.

ANALYSIS FOR THROUGH CRACKS

The conventional fracture equation for a centrally cracked sheet is (from ref. 7)

$$K_c^2 = \sigma^2 W \tan\left[\frac{\pi c}{W} + \frac{1}{2W}\left(\frac{K_c}{\sigma_{ys}}\right)^2\right] \tag{7}$$

As was done for the surface crack, equation (7) may be modified to predict fracture at ultimate strength for zero crack length. The modified equation is

$$K_u^2 = \sigma^2 W \tan\left[\frac{\pi c}{W} + \arctan \frac{1}{W}\left(\frac{K_u}{\sigma_u}\right)^2\right] \tag{8}$$

The modified fracture toughness parameter is called K_u to distinguish it from the conventional parameter K_c.

The lack of suitable data and the uncertainties associated with mixed-mode fracture testing do not allow a critical evaluation of equation (8). However, it is presented here for possible future evaluation.

APPLICATION TO DATA FROM THE LITERATURE

To test the present analysis, sets of surface-crack test data were selected from the literature. These data cannot be analyzed by conventional fracture mechanics procedures. The tests do not meet the criteria (discussed previously) for a valid test and, indeed, the apparent K_{IC} values obtained were not constant. Published data that covered only a limited flaw size range or which exhibited unusually severe scatter were not considered.

These test data from the literature, along with the pertinent parameters (calculated at NASA Lewis), are tabulated in tables I to V at the end of this report. Where important material properties were not reported, they are estimated on the basis of the best available information.

Battelle Memorial Institute Data for Titanium Alloy

These data (from ref. 8) are examined first as they represent the largest sample size and show some interesting trends. The material is a titanium alloy (6Al-4V) solution-treated and aged, and the specimens were 0.020, 0.040, and 0.060 inch (0.5, 1.0, and 1.5 mm) thick.

Figure 1(a) shows apparent K_{IC} (eq. (1b)) to be a unique function of the normalized crack depth a/Φ^2 and independent of material thickness for these tests. The target flaw depths were 25, 50, and 75 percent of each thickness. About half the flaws were actually deeper than half thickness. As discussed earlier, apparent K_{IC} values are usually depressed for crack depths greater than half the thickness. Thus, one would expect a lower K_{IC} value for a very deep flaw in a thin specimen than for the same size flaw in much thicker material. However, no such deep-flaw effect can be seen here.

On first examination of figure 1(a), one might conclude that apparent K_{IC} is reasonably constant for $a/\Phi^2 > 0.025$ inch (0.63 mm) and is about 50 ksi $\sqrt{\text{in.}}$ (55 $\text{MNm}^{-3/2}$). If so, the minimum crack depth for a valid test (ref. 2) would be $2\frac{1}{2}\left(K_{IC}/\sigma_{ys}\right)^2 = 2\frac{1}{2}(50/160)^2 = 0.24$ inch (6.2 mm). This is about five times as large as the deepest crack actually tested. Therefore, the preliminary conclusion is unfounded, and the data should not be analyzed using conventional fracture mechanics procedures.

For each specimen the modified fracture toughness parameter K_{IU} was computed using equation (2b). The weighted average K_{IU} (eq. (6)) was calculated and then used to determine the expected error (eqs. (4a) and (b)). The four specimens having $a/\Phi^2 \sim$ 0.04 inch (1 mm) were excluded from the weighted average because, for them, the apparent absence of depth-to-thickness effect is unconfirmed; that is, there are no tests with the same flaw size in a thicker material (such that $a/t < \frac{1}{2}$) giving the same apparent K_{IC} value. For the remaining specimens, however, the absence of depth-to-thickness effect is evident. Thus, for these specimens only, the limitation recommended by Irwin ($a/t < \frac{1}{2}$) was ignored.

In figures 1(b) and (c) the computed K_{IU} values and expected error bands are plotted. The observed K_{IU} values are, in general, evenly distributed within the bounds of expected error. These same figures also illustrate the large variation in K_{IU} to be expected for tests with small cracks and resulting high fracture stresses.

In figure 1(d), fracture stress is predicted using equation (2c) and the weighted average K_{IU}. Note that the fracture stress for zero crack size is the material's ultimate strength. Except for the largest cracks, equation (2c) correctly predicts the shape of the fracture stress - flaw size curve and the data are within about ±5 percent of the predicted value. This degree of accuracy is probably sufficient for most engineering purposes.

Even though a good correlation was obtained, the problem of partial-thickness cracks in the thin sheet can still be subject to further scrutiny. For the data shown in figure 1 an equally good correlation can be made by treating the surface crack as a through-crack of the same length. Using equation (8), an average nominal value (based on original crack length) of K_u was determined for the four largest cracks. This value was then used in equation (8) to predict fracture stress as a function of crack length only. As can be seen in figure 2, the data agree with predicted stresses within about ±6 percent.

For this material and thickness range, then, we can predict fracture based on either crack length or (normalized) crack depth. From an inspection standpoint, the correlation based on surface crack length would be preferred. But, if we wish to step outside the narrow boundaries of these tests, we must know which of these correlations might be accidental and which (if, indeed, either) is applicable to other cases. For the thicker materials to be examined later, correlations based on crack length are not adequate.

Lockheed Missiles & Space Co. Data for Magnesium Alloy

Reference 9 presents surface-crack test data for the magnesium alloy HM21A-T8 in 0.143-inch (3.6-mm) thickness. For all these tests the fracture stresses were greater than the material's yield strength. These tests are clearly outside the domain of linear elastic fracture mechanics. As expected, the apparent K_{IC} values (fig. 3(a)) are not constant. The calculated K_{IU} values (figs. 3(b) and (c)) are generally within the boundaries of expected error but appear to cluster along the upper bound. Whether this is due to a nonrandom error or to a systematic variable is not clear.

In analyzing these data the crack depth limitation suggested by Irwin ($a/t < \frac{1}{2}$) was observed, there being no evidence to justify ignoring it. Specifically, specimens having cracks deeper than half the thickness were excluded from all further consideration. The computed fracture stress (fig. 3(d)) fits the data reasonably well. Again, it should be noted that an analysis of these data could not have been made at all using conventional elastic fracture mechanics.

Similar results for this same material in the transverse grain direction are shown in figure 4. Since they differ only quantitatively from the longitudinal direction they will not be discussed further.

Note the four longitudinal specimens (fig. 3) and the five transverse specimens (fig. 4) having crack size factors greater than 0.06 inch (1.5 mm). Lower values of σ and K_{IC} were obtained from the narrower specimens, which suggests that they were not wide enough to simulate an infinite plate containing a flaw of this size. A discussion of finite-width effects in surface-cracked specimens is beyond the scope of this report. However, the point is called to the reader's attention.

Douglas Aircraft Co. Data for Several Alloys and Weldments

Reference 10 reports surface-crack test data for 3/8-inch (9.5-mm) thick 2014-T651 aluminum alloy at -423° F (20 K). Figure 5 shows the variation of K_{IC} and fracture stress with crack size. The predicted fracture stress (based on K_{IU}) fits the data very well.

Additional tests reported in reference 10 for 4340 alloy steel 1/4 inch (6.3 mm) thick are shown in figure 6. Good agreement between calculated and observed fracture stress is obtained here also.

Reference 11 contains surface crack data for 0.10- and 0.25-inch (2.5- and 6.3-mm) thick 2014-T6 aluminum alloy tested at room temperature and -423° F (20 K). The variations of K_{IC} and fracture stress with crack size are shown in figures 7 and 8. The fracture stress prediction is good at room temperature and very good at -423° F (20 K). The room-temperature ultimate strength values represent but a single test for each thickness and must be judged accordingly. If they were but 5 percent higher (which would not be atypical) the correlations would be even better. Note also that most fracture stresses are above yield.

Reference 12 presents some interesting and very informative data on the behavior of surface cracks in 2014-T6 aluminum alloy parent metal and weldments 0.25 inch (6.3 mm) thick at room temperature and -423° F (20 K). The problem of surface cracks in welds is especially important to the design of spacecraft propellant tanks, as welds are often the most likely places for cracks to form and propagate. But because the yield strength is low, the minimum specimen needed for a valid K_{IC} test is often unrealistically large. Figures 9 to 11 show the variation of K_{IC} and fracture stress with crack size for parent metal, welds with 4043 filler wire, and welds with 716 filler wire, respectively. Correlation for all three cases is very good, especially since scatter for weldment tests is often severe.

Effect of Material Thickness

Figures 5 and 7 to 9 illustrate the range of $\overline{K_{IU}}$ values observed for what is nominally a single material, 2014-T6 aluminum alloy. Unfortunately, there are too many extraneous variables (composition, temperature, grain direction, and strength level). A series of tests where thickness is the only significant variable is required to determine whether K_{IU} is a materials constant and independent of specimen geometry.

Application to Fatigue Crack Propagation Studies

Because it is effective when stresses are high and cracks are too small for conventional linear elastic fracture analysis, this method might be useful for low-cycle fatigue crack propagation studies. However, further discussion of this application is beyond the scope of the present report.

CONCLUSIONS

1. The modified Irwin analysis can be used to predict fracture with reasonable accuracy when crack size and/or material thickness are too small for valid analysis by conventional linear elastic fracture mechanics. The method is usable even when fracture stresses are greater than yield.
2. The weighted-averaging procedure that was used gives a suitable, unambiguous value of the modified toughness parameter K_{IU}.
3. Systematic tests are required to determine whether the parameter K_{IU} is indeed a material constant and independent of material thickness. But, even if it proves not to be, the method would still be useful for specific design problems.

4. Irwin's fracture equation for through-the-thickness cracks can also be modified to predict fracture at ultimate strength for zero crack length. However, there are not sufficient data for a critical evaluation.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 1, 1969,
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12. Eyring, C. L.: Fracture Strength of 2014-T6 Aluminum Alloy Weldments. Rep. SM-45961, Douglas Aircraft Co., Sept. 1, 1964.

TABLE I. - SURFACE TEST DATA FROM REFERENCE 8

[Titanium-6Al-4V alloy; solution treated and aged; tested at 70°; ultimate strength (average of three thicknesses and 12 tests), 170.7 ksi; yield strength (average of three thicknesses and 11 tests), 161.9 ksi; weighted average K_{IU} (eq. (6)), 76.5 ksi $\sqrt{in.}$]

Specimen	Specimen width, W, in.	Specimen thickness, t, in.	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi $\sqrt{in.}$	
							K_{IC} (a)	K_{IU} (b)
2023N	2.987	0.020	0.0131	0.0346	158.2	0.00681	26.80	67.49
2045N	2.991	.020	.0123	.0279	164.7	.00562	25.28	91.23
2025N	2.994	.020	.0169	.0540	155.3	.01009	32.23	72.98
2044N	2.990	.020	.0162	.0390	161.5	.00780	29.22	85.52
2028E	2.990	.021	.0051	.0111	158.5	.00224	15.28	39.26
2003E	2.987	.021	.0106	.0428	161.9	.00726	28.98	84.53
2029E	2.988	.020	.0102	.0394	157.5	.00683	27.16	65.53
2043E	2.988	.021	.0151	.1134	153.0	.01295	36.93	76.23
2008E	2.992	.021	.0190	.1753	148.5	.01699	40.99	76.21
2015N	2.991	.022	.0077	.0138	162.6	.00347	19.55	61.07
2037N	2.997	.021	.0120	.0307	162.6	.00608	26.08	80.89
2004N	2.990	.021	.0169	.0451	160.9	.00886	31.17	88.06
2035E	2.988	.021	.0045	.0114	159.3	.00226	15.54	40.94
4003N	2.990	.044	.0115	.0300	166.8	.00592	26.51	117.26
4108N	2.993	.044	.0124	.0288	164.8	.00579	25.70	93.40
4032N	2.991	.042	.0229	.0525	161.2	.01056	33.85	97.80
4088N	2.992	.044	.0236	.0605	157.6	.01198	35.35	87.18
4096N	2.990	.042	.0304	.0820	153.7	.01607	39.90	86.97
4104N	2.992	.045	.0355	.0917	154.1	.01813	42.43	93.67
4073E	2.992	.041	.0088	.0348	167.1	.00596	27.23	122.65
4081E	2.990	.042	.0106	.0346	167.6	.00642	28.08	137.44
4037E	2.992	.043	.0207	.1086	154.0	.01593	40.88	87.48
4077E	2.990	.044	.0240	.1096	153.9	.01744	42.54	91.23
4103E	2.992	.045	.0345	.2377	137.4	.02895	48.62	76.50
4005N	2.994	.045	.0103	.0294	165.1	.00568	25.79	95.14
4068N	2.990	.044	.0205	.0597	157.2	.01148	34.71	83.91
4051N	2.993	.045	.0343	.0889	152.9	.01757	41.41	88.51
4063E	2.990	.042	.0085	.0365	164.4	.00600	26.90	91.90
4120E	2.992	.044	.0234	.1225	153.2	.01799	43.18	90.46
4075E	2.990	.040	.0307	.1976	144.3	.02528	48.00	83.39
4094E	2.992	.042	.0273	.2190	139.5	.02376	44.94	72.44
6002N	2.991	.064	.0131	.0321	153.9	.00641	25.12	55.28
6004N	2.990	.064	.0134	.0343	155.0	.00679	26.13	59.22
6001N	2.991	.062	.0269	.0648	148.9	.01296	34.44	67.31
6010N	2.993	.064	.0298	.0690	150.0	.01387	35.85	71.86
6005N	2.993	.064	.0431	.1021	145.1	.02047	42.04	76.52
6025N	2.994	.063	.0435	.1001	146.3	.02014	42.03	78.24
6035E	2.994	.063	.0165	.0509	153.1	.00962	30.92	65.94
6037E	2.993	.063	.0187	.0548	151.8	.01052	31.95	66.10
6038E	2.992	.064	.0312	.1253	148.8	.02132	45.03	86.08
6045E	2.991	.063	.0309	.1335	146.6	.02189	44.98	82.21
6033E	2.993	.064	.0460	.3470	121.1	.03948	49.30	[c]66.29
6034E	2.994	.063	.0477	.3544	118.6	.04080	48.96	[c]64.67
6011N	2.992	.064	.0138	.0317	154.3	.00638	25.07	55.94
6016N	2.991	.064	.0131	.0365	156.4	.00710	27.08	63.87
6017N	2.994	.065	.0304	.0694	150.0	.01397	35.96	72.12
6018N	2.994	.066	.0317	.0713	149.0	.01437	36.19	71.08
6003N	2.994	.065	.0460	.1062	146.4	.02136	43.32	80.78
6013N	2.987	.065	.0453	.1042	143.2	.02096	41.90	73.96
6039E	2.994	.063	.0200	.0573	153.0	.01107	33.03	70.48
6036E	2.994	.062	.0198	.0561	150.3	.01087	32.07	64.17
6030E	2.994	.062	.0315	.1216	147.1	.02108	44.13	81.73
6043E	2.994	.064	.0305	.1226	145.6	.02085	43.45	78.20
6022E	2.994	.063	.0486	.3429	121.4	.04104	50.35	[c]67.92
6041E	2.994	.062	.0470	.3470	119.9	.04014	49.14	[c]65.52

[a]Eq. (1b)
[b]Eq. (2b)
[c]Excluded from weighted average; see text.

TABLE II. - SURFACE CRACK TEST DATA FROM REFERENCE 9

(a) Magnesium alloy HM21A-T8; longitudinal grain; tested at 70° F. Ultimate strength (average of 12 tests), 34.0 ksi; yield strength (average of 12 tests), 23.8 ksi; weighted average K_{IU} (eq. (6)), 23.7 ksi$\sqrt{in.}$

Specimen	Specimen width, W, in.	Specimen thickness, t, in.	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi$\sqrt{in.}$	
							K_{IC} (a)	K_{IU} (b)
CL1	2.000	0.1428	0.042	0.433	30.742	0.03824	14.18	27.32
CL3	1.999	.1439	.026	.404	31.978	.02477	12.26	28.77
CL5	2.000	.1445	.040	.422	31.280	.03654	14.23	29.62
CL7	1.999	.1448	.060	.420	29.706	.05056	15.27	26.66
CL9	2.000	.1450	.060	.420	29.724	.05056	15.28	26.73
CL11	1.999	.1450	.062	.473	29.251	.05335	15.42	25.74
CL2	2.001	.1430	.026	.282	31.667	.02384	11.73	26.08
CL4	2.001	.1442	.028	.273	32.166	.02527	12.31	30.64
CL6	2.001	.1448	.032	.284	32.171	.02841	13.00	32.54
CL8	2.001	.1452	.024	.237	32.771	.02170	11.75	35.18
CL10	2.001	.1455	.028	.273	32.360	.02527	12.43	32.55
CL12	2.001	.1454	.042	.332	31.488	.03643	14.17	30.93
CL13	1.999	.1455	.034	.610	31.145	.03273	13.57	27.27
CL14	2.000	.1451	.600	.600	33.425	.00599	6.58	27.42
CL15	2.000	.1455	.034	.680	30.722	.03294	13.35	25.27
CL16	2.000	.1450	.025	.615	31.862	.02445	12.20	27.71
CL17	1.999	.1455	.028	.580	31.351	.02717	12.52	25.93
CL18	2.000	.1456	.052	.640	28.091	.04845	14.10	21.31
CL19	1.999	.1453	.050	.626	28.916	.04668	14.42	23.06
CL20	1.999	.1455	.048	.565	29.495	.04449	14.46	24.28
HL2	3.951	.1450	.048	.625	28.975	.04500	14.21	22.81
HL3	3.951	.1448	.070	.820	26.744	.06484	15.25	21.41
HL4	3.951	.1448	.068	.980	27.530	.06438	15.86	23.11
HL5	3.951	.1439	.076	1.000	24.978	.07133	14.66	[c]19.09
HL6	3.951	.1432	.084	.970	24.214	.07767	14.68	[c]18.66
HL7	3.934	.1447	.032	1.520	31.096	.03177	13.45	26.61
HL8	3.933	.1447	.074	1.510	25.040	.07176	14.82	[c]19.25
HL9	3.934	.1448	.092	1.500	20.277	.08799	12.65	[c]14.55
HL10	3.934	.1443	.086	1.500	21.138	.08264	12.88	[c]15.06
HL11	3.934	.1442	.083	1.500	20.800	.07994	12.43	[c]14.43
HL12	3.934	.1420	.088	1.520	20.587	.08450	12.62	[c]14.60
FL13	1.998	.1447	.036	.590	31.062	.03444	13.84	27.53
FL14	1.995	.1444	.034	.580	31.378	.03262	13.69	28.58
FL15	1.973	.1442	.072	.618	26.995	.06353	15.16	21.73
FL17	1.973	.1449	.064	.600	27.842	.05739	15.06	22.56
FL21	1.999	.1430	.068	.740	25.883	.06239	14.31	19.36
FL7	1.973	.1450	.023	.424	32.517	.02218	11.96	32.19
FL8	1.997	.1453	.026	.400	32.047	.02475	12.30	29.31
FL9	1.973	.1449	.066	.530	28.541	.05745	15.50	24.44
FL10	1.972	.1448	.038	.410	31.243	.03482	13.88	28.70
FL11	1.912	.1449	.040	.840	29.458	.03885	13.63	22.58
FL12	1.974	.1447	.063	.488	28.641	.05440	15.13	24.07
FL4	1.973	.1454	.023	.230	33.182	.02084	11.75	42.66
FL5	1.912	.1453	.024	.236	33.261	.02169	12.03	45.87
FL6	1.976	.1453	.026	.235	33.022	.02316	12.23	40.98

[a]Eq. (1b).
[b]Eq. (2b).
[c]Excluded from weighted average; a/t ≥ 1/2.

TABLE II. - Concluded. SURFACE CRACK TEST DATA FROM REFERENCE 9

(b) Magnesium alloy HM21A-T8, transverse grain; tested at 70° F. Ultimate strength (average of 12 tests), 38.0 ksi; yield strength (average of 12 tests), 25.5 ksi; weighted average K_{IU} (eq. (6)), 23.9 ksi$\sqrt{in.}$

Specimen	Specimen width, W, in.	Specimen thickness, t, in.	Crack depth, a, in.	Crack length, 2c,	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi$\sqrt{in.}$	
							K_{IC} (a)	K_{IU} (b)
DT1	2.000	0.1457	0.054	0.435	32.121	0.04703	16.09	25.31
DT3	2.000	.1457	.052	.428	32.258	.04550	15.93	25.28
DT5	2.010	.1457	.048	.425	32.670	.04260	15.75	25.63
DT7	2.000	.1453	.062	.460	31.796	.05301	16.77	25.96
DT9	2.000	.1455	.062	.451	31.478	.05275	16.49	25.06
DT11	2.000	.1455	.064	.471	31.134	.05461	16.53	24.64
DT2	2.000	.1455	.033	.235	34.639	.02793	13.75	27.34
DT4	2.000	.1453	.038	.272	33.930	.03220	14.32	26.26
DT6	2.000	.1450	.040	.278	33.862	.03364	14.57	26.58
DT8	2.000	.1455	.038	.262	33.402	.03190	13.90	24.29
DT10	2.000	.1452	.032	.256	34.642	.02783	13.82	27.30
DT13	2.001	.1456	.026	.500	34.758	.02513	13.60	26.47
DT14	2.000	.1451	.028	.600	34.390	.02722	13.94	25.90
DT15	2.001	.1455	.090	.596	28.787	.07472	17.35	[a]23.41
DT16	2.000	.1450	.074	.562	30.138	.06362	17.10	[a]24.23
DT17	2.001	.1456	.072	.605	27.797	.06326	15.38	19.91
DT18	2.000	.1450	.044	.660	32.345	.04180	15.62	24.46
DT20	2.000	.1451	.064	.940	29.152	.06070	16.24	21.74
GT2	3.953	.1442	.075	1.120	28.105	.07123	16.76	[a]21.64
GT3	3.950	.1442	.068	.840	30.074	.06339	17.27	24.05
GT4	3.964	.1444	.084	.900	27.690	.07690	16.98	[a]21.77
GT5	3.964	.1443	.088	1.000	27.400	.08120	17.23	[a]21.88
GT6	3.963	.1444	.084	1.080	26.542	.07865	16.31	[a]20.20
GT7	3.963	.1450	.027	1.500	34.372	.02685	13.93	25.65
GT8	3.966	.1450	.096	1.500	24.587	.09151	16.03	[a]18.94
GT9	3.964	.1452	.092	1.480	25.017	.08790	16.05	[a]19.13
GT11	3.964	.1452	.086	1.520	24.687	.08271	15.33	[a]18.13
GT12	3.963	.1453	.0902	1.590	22.803	.08673	14.25	[a]16.30
FT13	1.999	.1440	.010	.608	36.425	.00995	9.35	24.77
FT14	1.9997	.1442	.010	.600	37.226	.00995	9.72	35.91
FT15	2.000	.1439	.060	.545	32.097	.05350	17.23	26.93
FT16	1.912	.1437	.070	.580	29.985	.06133	16.73	23.47
FT17	1.997	.1441	.069	.820	27.415	.06403	15.32	19.45
FT18	1.997	.1444	.074	.600	30.166	.06454	17.29	[a]24.47
FT7	1.972	.1449	.016	.378	35.562	.01562	11.17	24.49
FT8	1.972	.1448	.030	.394	35.447	.02815	14.72	32.05
FT9	1.998	.1450	.046	.385	33.414	.04038	15.81	27.38
FT10	1.999	.1450	.038	.517	33.460	.03578	15.17	25.93
FT11	1.912	.1448	.055	.402	32.575	.04685	16.30	26.59
FT12	1.974	.1449	.052	.400	33.217	.04483	16.44	28.12
FT4	1.999	.1452	.028	.200	35.687	.02372	13.26	31.06
FT5	1.999	.1450	.028	.232	35.461	.02453	13.47	30.01
FT6	1.998	.1450	.034	.254	35.197	.02912	14.42	30.94

[a]Eq. (1b).
[b]Eq. (2b).
[c]Excluded from weighted average; $a/t \geq 1/2$.

TABLE III. - SURFACE CRACK TEST DATA FROM REFERENCE 10

[Specimen width, 1.0 in.]

(a) Aluminum alloy 2014-T651; tested at -423° F. Ultimate strength (average of two tests), 94.5 ksi; yield strength (estimated, no test reported), 81.9 ksi; weighted average K_{IU} (eq. (6)), 52.5 ksi$\sqrt{in.}$; specimen thickness, 0.375 inch

Specimen	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi$\sqrt{in.}$	
					K_{IC} (a)	K_{IU} (b)
11	0.008	0.012	93.7	0.00419	12.74	93.65
12	.019	.037	87.1	.00791	15.85	38.88
3	.030	.065	85.0	.01314	19.94	43.39
13	.031	.061	84.4	.01277	19.44	41.25
4	.052	.123	81.3	.02466	26.12	48.71
5	.074	.185	79.5	.03680	31.20	54.84
15	.081	.147	79.8	.03605	30.83	54.99
6	.084	.239	77.7	.04625	34.30	57.07
16	.090	.189	78.0	.03827	30.92	52.54
17	.092	.190	75.3	.03849	29.82	47.52
20	.096	.203	78.0	.04109	32.05	54.44
7	.104	.311	74.0	.05936	36.88	56.33
8	.117	.365	71.7	.06877	38.39	56.08
9	.129	.423	67.7	.07836	38.53	52.77
10	.139	.482	64.5	.08744	38.67	50.69

(b) 4340 alloy steel; tempered at 475° F for 2 hours; tested at 70° F. Ultimate strength (average of two tests), 278.4 ksi; yield strength (number of tests not reported), 230.6 ksi; weighted average K_{IU} (eq. (6)), 70.2 ksi$\sqrt{in.}$; specimen thickness, 0.25 inch

3	0.020	0.041	245.5	0.00831	45.79	92.12
8	.035	.092	205.9	.01813	56.36	79.98
9	.037	.088	201.1	.01763	53.97	74.98
12	.039	.124	183.8	.02322	56.70	72.40
11	.040	.129	173.9	.02404	54.36	67.03
15	.049	.156	174.3	.02920	60.03	74.16
14	.051	.170	158.7	.03131	56.28	66.36
18	.052	.198	158.0	.03453	58.99	69.24
16	.053	.161	164.1	.03059	57.54	68.98
19	.056	.208	154.7	.03668	59.41	69.19
13	.058	.127	174.8	.02566	55.89	69.85
20	.077	.211	148.4	.04121	59.92	69.13

[a]Eq. (1b).
[b]Eq. (2b).

TABLE IV. - SURFACE CRACK TEST DATA FROM REFERENCE 11

[Specimen width, 1.0 in. (2.54 cm).]

(a) Aluminum alloy 2014-T6; tested at 70° F. Ultimate strength (one test), 72.1 ksi; yield strength (one test), 67.0 ksi; weighted average K_{IU} (eq. (6)), 40.3 ksi $\sqrt{in.}$; specimen thickness, 0.10 inch

Specimen	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi $\sqrt{in.}$	
					K_{IC} (a)	K_{IU} (b)
A15	0.019	0.043	69.870	0.00866	13.35	51.28
A14	.024	.049	68.870	.00993	13.99	45.08
A17	.025	.046	69.240	.01098	14.85	50.61
A16	.034	.065	66.880	.01440	16.33	41.76
A19	.039	.094	64.450	.01880	18.03	38.30
A18	.046	.108	63.895	.02168	19.16	39.44
A20	.047	.198	61.150	.03290	23.00	40.66
A21	.049	.150	61.930	.02843	21.43	39.61
A22	.050	.189	59.345	.03307	22.21	[c]36.91

(b) Aluminum alloy 2014-T6; tested at -423° F. Ultimate strength (two tests), 99.7 ksi; yield strength (estimated, no test reported), 78.5 ksi; weighted average K_{IU} (eq. (6)), 36.4 ksi $\sqrt{in.}$; specimen thickness, 0.10 inch

A1	0.005	0.010	98.300	0.00203	9.24	51.36
A2	.009	.018	95.935	.00365	12.05	41.30
A3	.015	.030	91.360	.00608	14.71	34.54
A4	.019	.040	88.715	.00810	16.48	33.96
A5	.021	.045	87.490	.00910	17.22	33.79
A6	.025	.058	85.340	.01166	19.04	34.60
A7	.030	.069	83.985	.01388	20.39	35.65
A8	.033	.080	82.105	.01599	21.40	35.53
A9	.034	.080	82.445	.01605	21.50	36.06
A10	.038	.078	82.670	.01580	21.24	36.09
A11	.042	.120	78.245	.02320	24.62	37.33
A12	.048	.145	76.265	.02759	26.15	38.19

[a]Eq. (1b).
[b]Eq. (2b).
[c]Excluded from weighted average; $a/t \geq 1/2$.

TABLE IV. - Concluded. SURFACE CRACK TEST

DATA FROM REFERENCE 11

(c) Aluminum alloy 2014-T6; tested at 70° F. Ultimate strength (one test), 70.3 ksi; yield strength (one test), 62.7 ksi; weighted average K_{IU} (eq. (6)), 43.2 ksi $\sqrt{in.}$; specimen thickness, 0.25 inch

Specimen	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi $\sqrt{in.}$	
					K_{IC} (a)	K_{IU} (b)
AT16	0.012	0.025	71.380	0.00506	10.49	(d)
AT17	.025	.050	68.680	.01013	14.18	63.85
AT18	.035	.080	66.840	.01610	17.47	53.51
AT19	.052	.120	65.160	.02413	20.79	52.59
AT20	.079	.200	60.770	.03970	24.78	46.86
AT21	.097	.310	54.550	.05794	26.82	40.46
AT22	.125	.650	41.850	.09587	26.13	[c]31.32

(d) Aluminum alloy 2014-T6; tested at -423° F. Ultimate strength (one test), 91.5 ksi; yield strength (estimated, no test reported), 72.0 ksi; weighted average K_{IU} (eq. (6)), 52.2 ksi $\sqrt{in.}$; specimen thickness, 0.25 inch

AT1	0.005	0.010	90.500	0.00203	8.51	53.65
AT3	.020	.043	87.880	.00870	17.13	57.14
AT4	.023	.047	86.710	.00952	17.59	51.45
AT2	.025	.061	86.510	.01218	20.10	56.91
AT5	.026	.054	86.305	.01094	18.77	52.76
AT6	.028	.060	85.980	.01214	19.73	53.76
AT7	.030	.063	85.225	.01276	19.99	51.35
AT8	.039	.086	84.055	.01737	23.04	54.43
AT10	.047	.099	82.040	.02004	24.00	50.92
AT9	.049	.103	81.950	.02085	24.45	51.66
AT11	.054	.131	79.815	.02618	26.83	51.28
AT12	.056	.145	79.035	.02866	27.87	51.56
AT13	.072	.202	76.020	.03923	31.32	52.53

[a]Eq. (1b).
[b]Eq. (2b).
[c]Excluded from weighted average; $a/t \geq 1/2$.
[d]Cannot be computed; $\sigma \geq \sigma_u$.

TABLE V. - SURFACE CRACK TEST DATA FROM REFERENCE 12

[Specimen thickness, 0.25 in.]

(a) Aluminum alloy 2014-T6 parent metal; tested at 70° F. Ultimate strength (average of three tests), 72.1 ksi; yield strength (average of three tests), 63.6 ksi; weighted average K_{IU} (eq. (6)), 54.9 ksi $\sqrt{in.}$

Specimen width, W, in.	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi $\sqrt{in.}$	
					K_{IC} (a)	K_{IU} (b)
0.75	0.010	0.021	71.2	0.00425	9.57	58.19
	.020	.043	71.5	.00870	13.77	103.14
	.031	.061	70.9	.01277	16.47	86.68
	.039	.082	68.4	.01660	18.08	54.31
	.044	.100	68.2	.02014	19.93	58.13
	.058	.120	65.8	.02431	20.94	48.82
	.062	.150	65.6	.02999	23.36	53.26
	.063	.173	65.7	.03377	25.00	57.03
	.070	.219	63.8	.04122	26.89	54.07
	.071	.189	64.8	.03715	25.78	55.41
1.00	.023	.040	71.40	.01064	15.27	105.12
	.048	.080	68.9	.02306	21.64	69.25
	.050	.127	67.2	.02519	22.06	57.31
	.065	.173	64.5	.03401	24.53	51.77
	.074	.219	64.3	.04193	27.29	56.60

(b) Aluminum alloy 2014-T6 parent metal; tested at -423° F. Ultimate strength (average of three tests), 98.7 ksi; yield strength (estimated, no test reported), 80.0 ksi; weighted average K_{IU} (eq. (6)), 46.7 ksi $\sqrt{in.}$

0.75	0.010	0.020	96.6	0.00405	12.77	57.80
	.018	.036	92.3	.00730	16.27	43.12
	.021	.044	90.8	.00891	17.70	42.38
	.0260	.058	88.8	.01170	19.85	42.67
	.0390	.079	86.7	.01601	22.48	44.52
	.0440	.100	84.1	.02014	24.53	44.24
	.0520	.124	82.6	.02484	26.76	46.14
	.0620	.152	80.3	.03033	28.69	46.67
	.0660	.168	78.9	.03331	29.54	46.51
	.0720	.201	77.9	.03908	31.68	48.67
	.0720	.208	77.2	.04009	31.81	48.15

[a] Eq. (1b).
[b] Eq. (2b).

TABLE V. - Continued. SURFACE CRACK TEST

DATA FROM REFERENCE 12

[Specimen thickness, 0.25 in.]

(c) Aluminum alloy 2014-T6 weldments (4043 filler); tested at 70° F. Ultimate strength (average of two tests), 42.4 ksi; yield strength (average of two tests), 31.9 ksi; weighted average K_{IU} (eq. (6)), 17.9 ksi$\sqrt{in.}$

Specimen width, W, in.	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi$\sqrt{in.}$	
					K_{IC} (a)	K_{IU} (b)
0.75	0.025	0.042	43.0	0.01193	10.10	(c)
	.053	.150	35.4	.02907	12.66	21.35
	.065	.155	34.0	.03105	12.37	19.51
	.069	.173	32.0	.03439	12.19	17.59
	.074	.327	27.7	.05299	13.16	16.37
	.088	.234	31.4	.04601	13.84	19.49
	.095	.208	30.2	.04202	12.56	17.15

(d) Aluminum alloy 2014-T6 weldments (4043 filler); tested at -423° F. Ultimate strength (average of two tests), 54.0 ksi; yield strength (average of two tests), 49.0 ksi; weighted average K_{IU} (eq. (6)), 26.6 ksi$\sqrt{in.}$

0.75	0.035	0.080	50.1	0.01610	13.03	33.08
	.058	.157	45.2	.03075	16.18	28.13
	.081	.208	42.0	.04118	17.25	26.33
	.100	.250	40.0	.04973	17.96	25.78

[a]Eq. (1b).
[b]Eq. (2b).
[c]Cannot be computed; $\sigma \geq \sigma_u$.

TABLE V. - Concluded. SURFACE CRACK TEST

DATA FROM REFERENCE 12

[Specimen thickness, 0.25 in.]

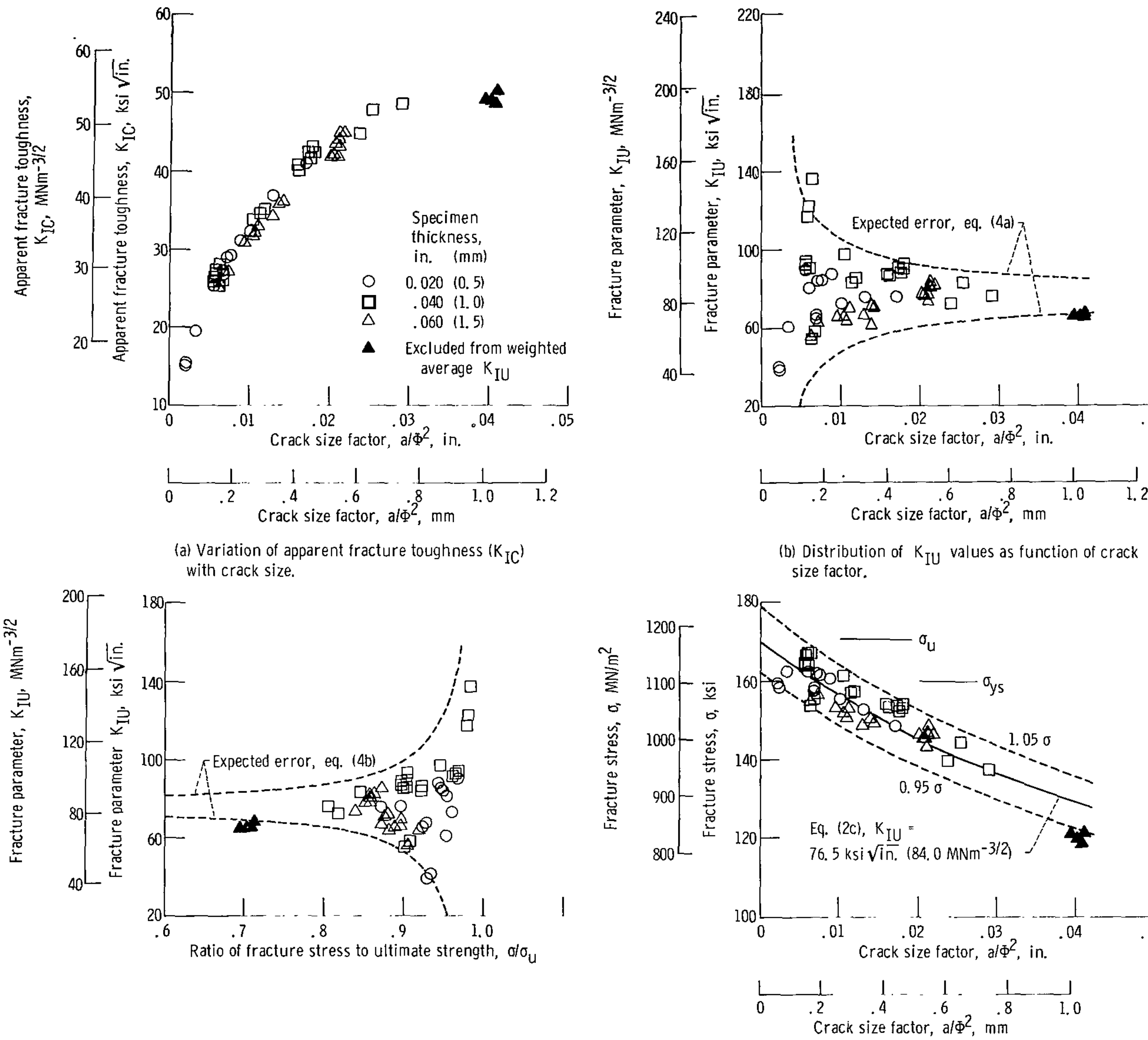
(e) Aluminum alloy 2014-T6 weldments (716 filler); tested at 70° F. Ultimate strength (average of four tests), 46.2 ksi; yield strength (average of four tests), 36.7 ksi; weighted average K_{IU} (eq. (6)), 15.6 ksi $\sqrt{in.}$

Specimen width, W, in.	Crack depth, a, in.	Crack length, 2c, in.	Fracture stress, σ, ksi	Crack size factor, a/Φ^2, in.	Fracture toughness parameter, ksi $\sqrt{in.}$	
					K_{IC} (a)	K_{IU} (b)
0.75	0.028	0.060	40.0	0.01214	9.17	17.78
	.030	.064	37.6	.01295	8.74	14.28
	.046	.101	36.5	.02040	10.63	16.49
	.054	.185	31.1	.03372	11.66	14.99
	.057	.127	32.4	.02562	10.47	14.12
	.062	.169	31.9	.03305	11.77	15.56
	.074	.192	31.2	.03794	12.29	15.99
	.074	.199	30.5	.03903	12.18	15.57
	.082	.263	29.4	.04910	13.20	16.39

(f) Aluminum alloy 2014-T6 weldments (716 filler); tested at -423° F. Ultimate strength (average of two tests), 59.5 ksi; yield strength (average of two tests), 55.5 ksi; weighted average K_{IU} (eq. (6)), 17.0 ksi $\sqrt{in.}$

0.75	0.014	0.029	53.9	0.00587	8.38	18.94
	.018	.036	54.1	.00730	9.36	21.55
	.027	.054	47.4	.01094	9.94	15.93
	.030	.070	49.9	.01406	11.98	21.09
	.044	.090	45.6	.01823	12.33	18.61
	.047	.118	39.9	.02345	12.20	15.99
	.058	.139	38.3	.02782	12.72	16.21
	.062	.162	38.6	.03197	13.77	17.61
	.074	.185	35.7	.03680	13.60	16.62
	.079	.203	31.9	.04018	12.64	14.71
	.081	.219	32.6	.04290	13.37	15.67

[a]Eq. (1b).
[b]Eq. (2b).



(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

(b) Distribution of K_{IU} values as function of crack size factor.

(c) Distribution of K_{IU} values as function of fracture stress ratio.

(d) Fracture stress as function of crack size factor.

Figure 1. - Fracture parameters for titanium -6Al-4V alloy, solution-treated and aged (data from ref. 8).

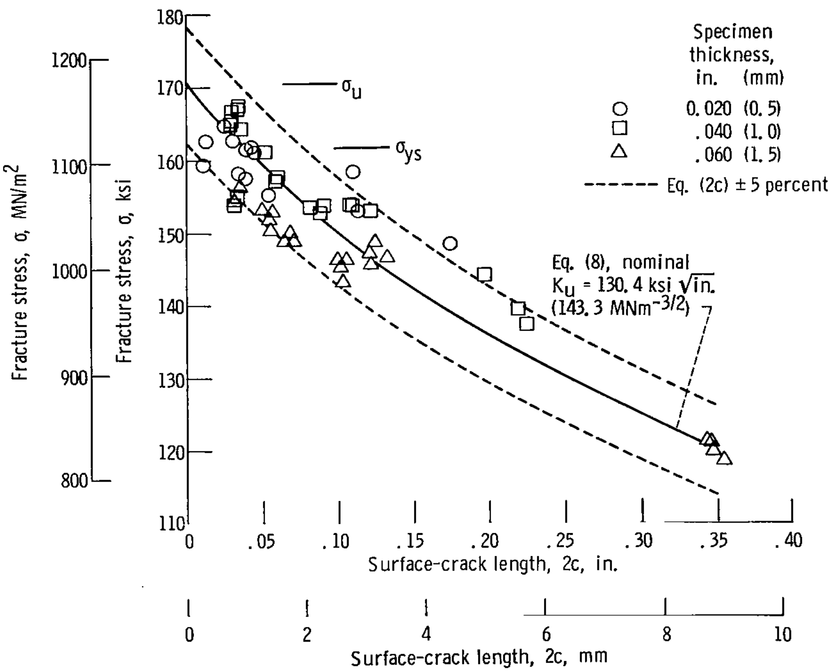
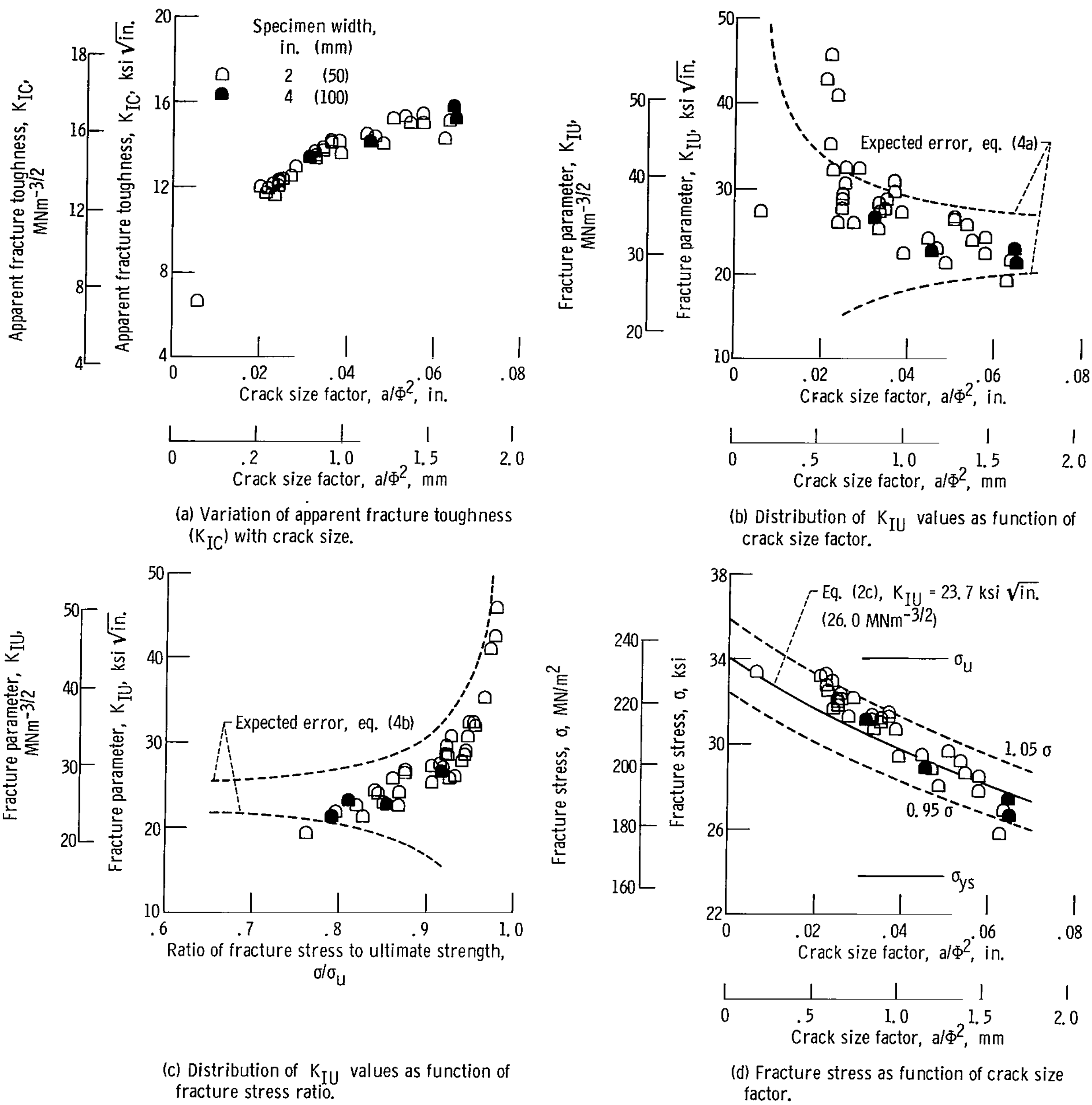


Figure 2. - Correlation between fracture stress and surface-crack length for titanium-6Al-4V alloy, solution treated and aged (data from ref. 8).



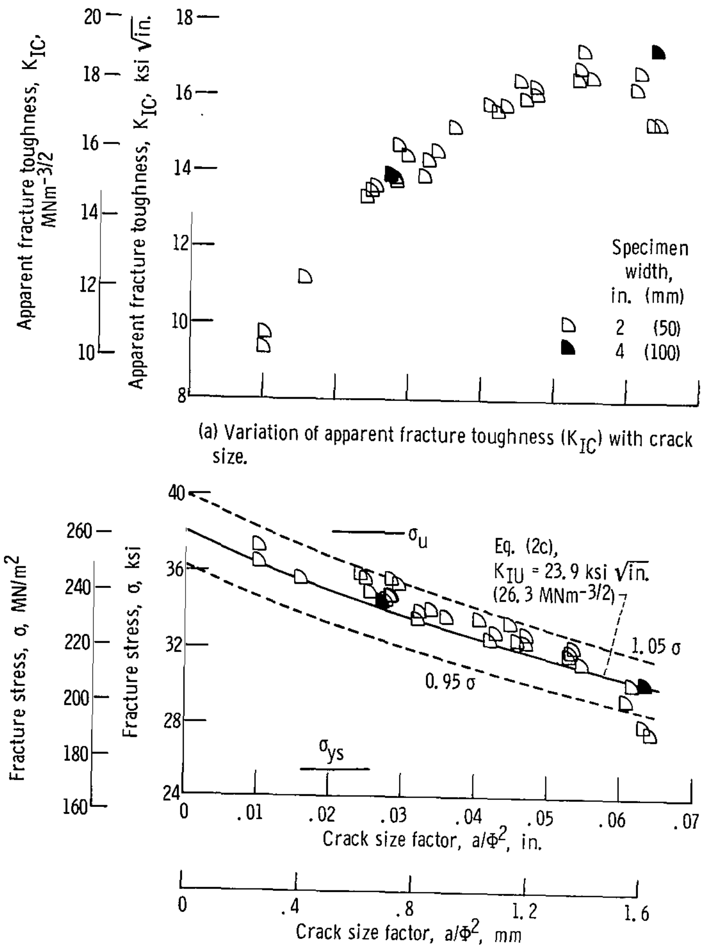
(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

(b) Distribution of K_{IU} values as function of crack size factor.

(c) Distribution of K_{IU} values as function of fracture stress ratio.

(d) Fracture stress as function of crack size factor.

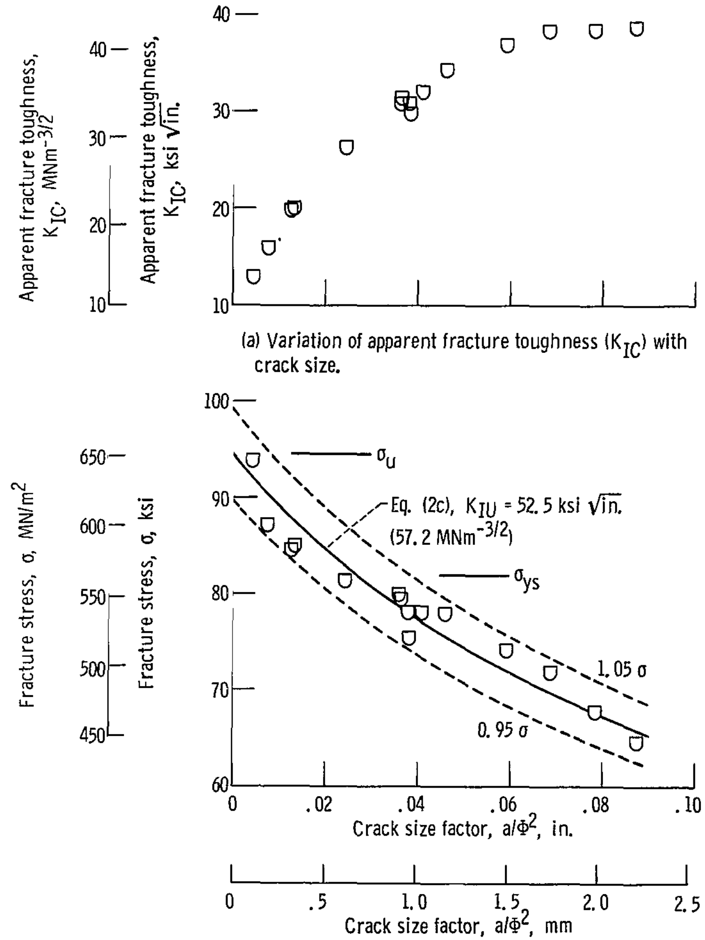
Figure 3. - Fracture parameters for magnesium alloy HM21A-T8, 0.143 inch (3.6 mm) thick, longitudinal grain (data from ref. 9).



(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

(b) Fracture stress as function of crack size factor.

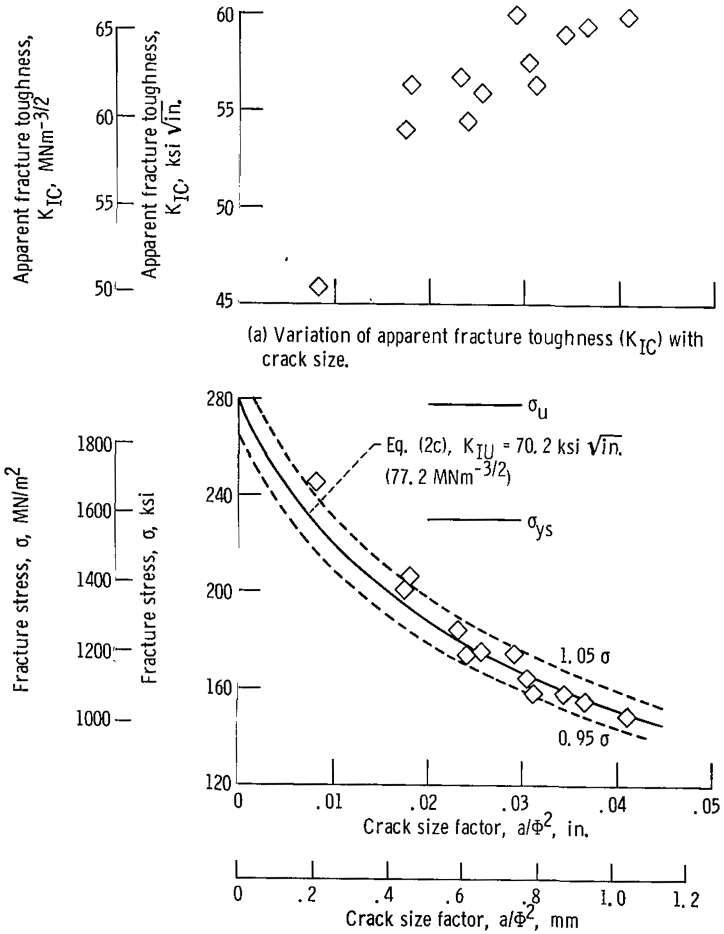
Figure 4. - Fracture parameters for magnesium alloy HM21A-T8, 0.143 inch (3.6 mm) thick, transverse grain. (Data from ref. 9.)



(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

(b) Fracture stress as function of crack size factor.

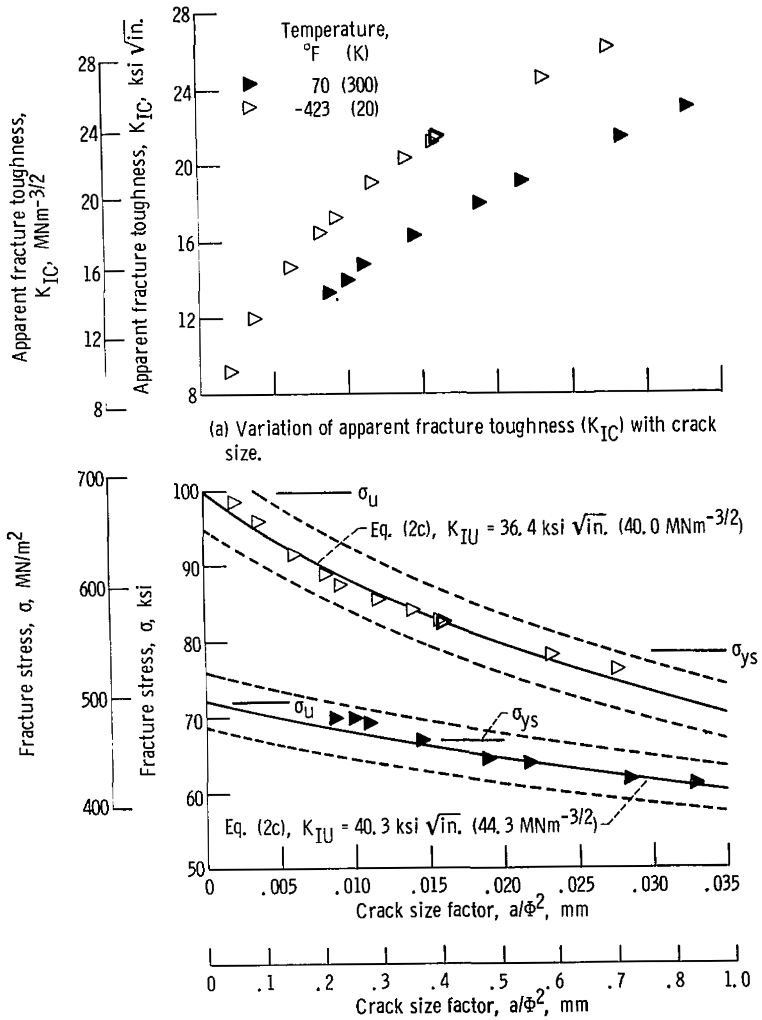
Figure 5. - Fracture parameters for aluminum alloy 2014-T651, 3/8 inch (9.5 mm) thick, tested at -423° F (20 K). (Data from ref. 10.)



(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

(b) Fracture stress as function of crack size factor.

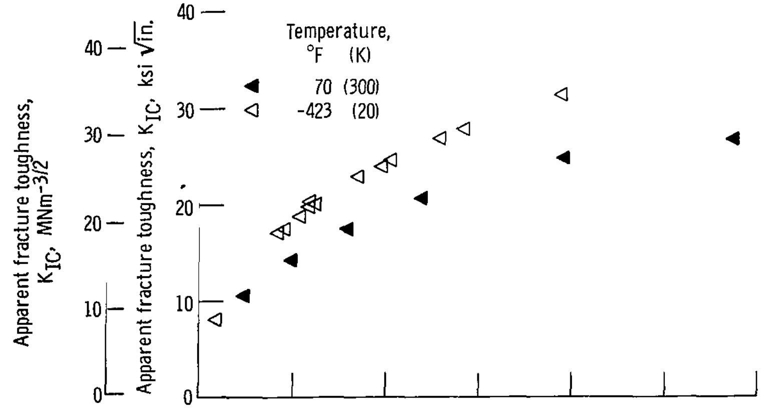
Figure 6. - Fracture parameters for heat-treated AISI 4340 steel, 1/4 inch (6.3 mm) thick. (Data from ref. 10.)



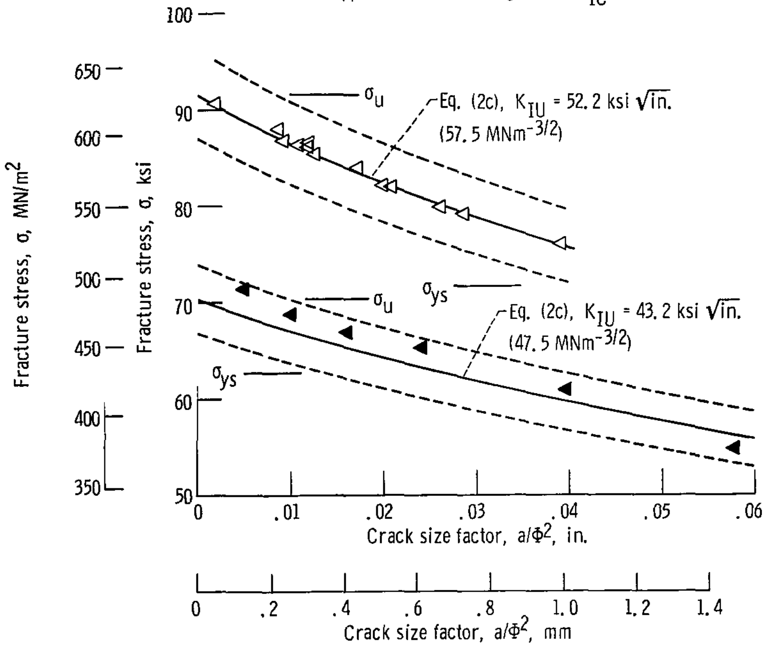
(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

(b) Fracture stress as function of crack size factor. (Dashed curves indicate eq. (2c) ± 5 percent.)

Figure 7. - Fracture parameters for 2014-T6 aluminum alloy, 0.1 inch (2.5 mm) thick. (Data from ref. 11.)

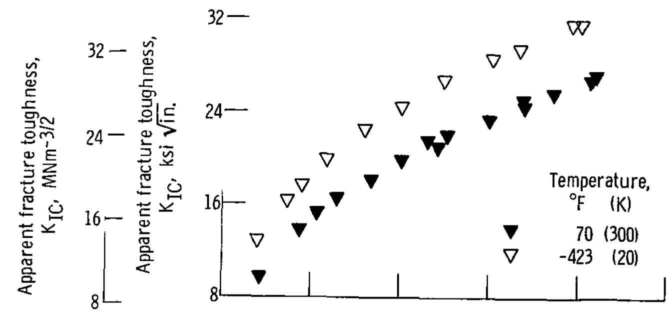


(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

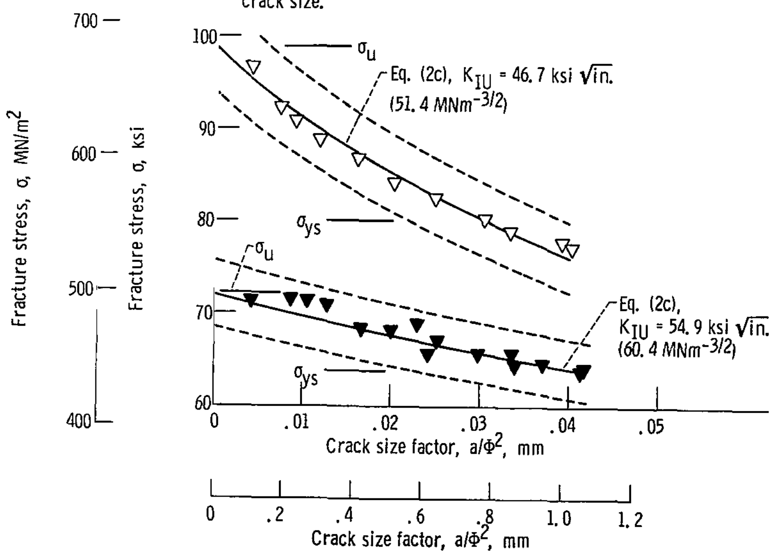


(b) Fracture stress as function of crack size factor. (Dashed curves indicate eq. (2c) ± 5 percent.)

Figure 8. - Fracture parameters for 2014-T6 aluminum alloy, 0.25 inch (6.3 mm) thick. (Data from ref. 11.)

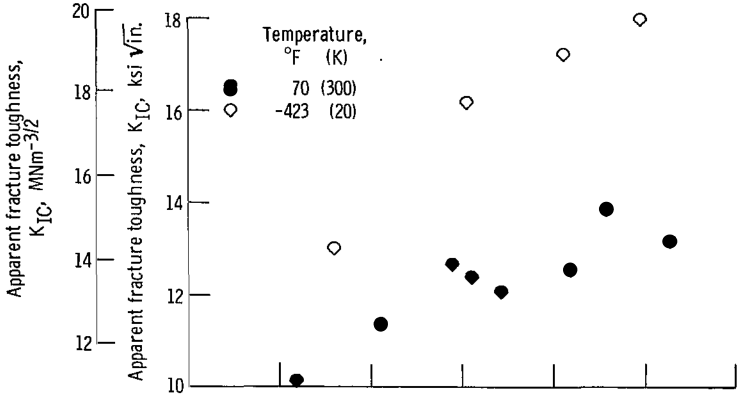


(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

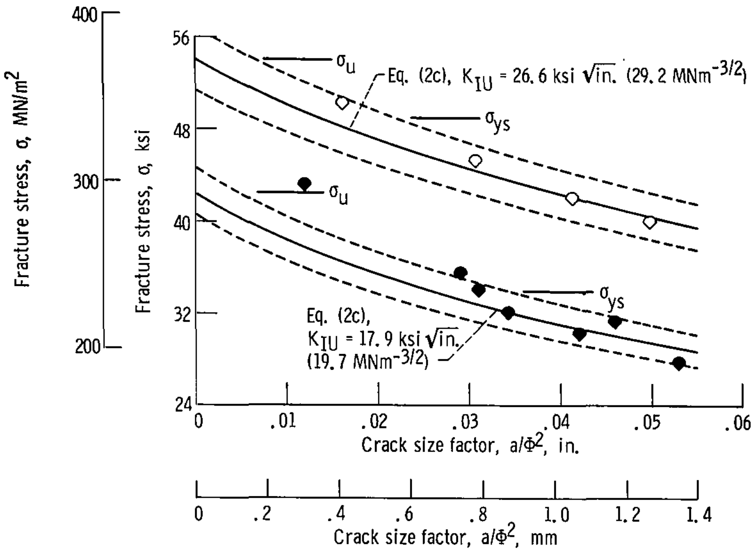


(b) Fracture stress as function of crack size factor. (Dashed curves indicate eq. (2c) ± 5 percent.)

Figure 9. - Fracture parameters for 2014-T6 aluminum alloy parent metal, 0.25 inch (6.3 mm) thick. (Data from ref. 12.)

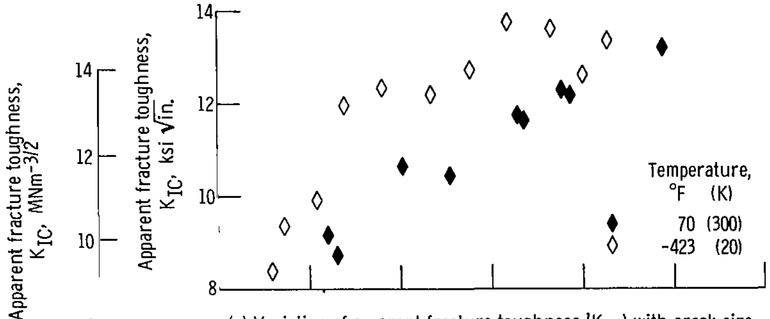


(a) Variation of apparent fracture toughness (K_{IC}) with crack size.

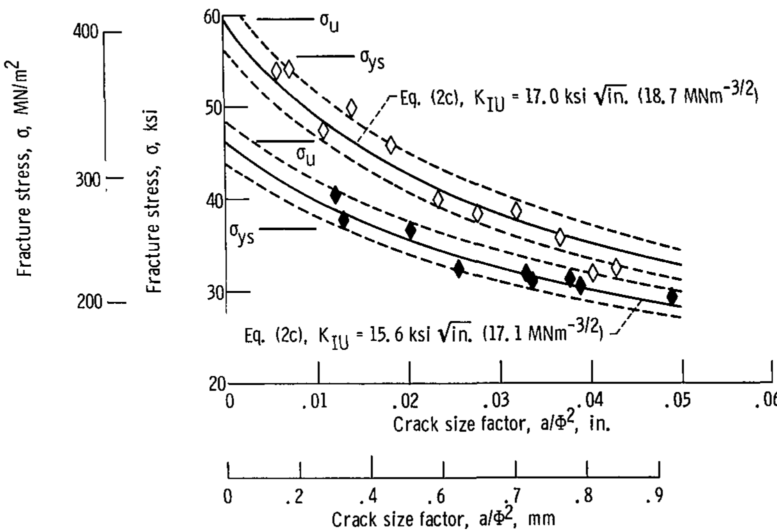


(b) Fracture stress as function of crack size factor. (Dashed curves indicate eq. (2c) ± 5 percent.)

Figure 10. - Fracture parameters for 2014-T6 aluminum alloy 0.25 inch (6.3 mm) thick, welded with 4043 filler wire. (Data from ref. 12.)



(a) Variation of apparent fracture toughness (K_{IC}) with crack size.



(b) Fracture stress as function of crack size factor. (Dashed curves indicate eq. (2c) ± 5 percent.)

Figure 11. - Fracture parameters for 2014-T6 aluminum alloy 0.25 inch (6.3 mm) thick, welded with 716 filler wire. (Data from ref. 12.)

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