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EFFECT OF SHEET THICKNESS ON THE FRACTURE RESISTANCE K_c PARAMETER FOR TITANIUM ALLOYS

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13. ABSTRACT

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The effect of thickness on K_c varied with each alloy. The more frangible alloys evidenced peak K_c values in thinner specimens than those alloys manifesting higher fracture resistance. Slit tips with 1-mil radii indicated lower K_c values than tips of 3 to 5 mils. No influence of initial crack length was noted over the range studied. The data were applied to a model which postulates the K_c dependency on thickness.

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PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

NRL Problem M01-24
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GLOSSARY

a, a_c	half-length of crack; subscript c refers to critical value
B	specimen thickness
B_{SL}	shear-lip thickness when $B = B_{SL}$
B_{SL_O}	one-half shear-lip thickness when shear lip has formed its characteristic size and $B > B_{SL}$
CCT	center-crack tension specimen
COD	crack-opening displacement
E	Young's modulus
$\mathcal{G}_c$	strain energy release rate per unit area; crack extension force
k_{ff}, k_{SL}	material constants. Subscript ff refers to flat fracture; SL to shear lip
K_c	stress-intensity factor; subscript c refers to critical value (plane stress)
P	load
R	resistance to crack growth
σ_G	gross or nominal stress, P/A
σ_{ys}	yield stress
W	specimen width

EFFECT OF SHEET THICKNESS ON THE FRACTURE RESISTANCE K_c PARAMETER FOR TITANIUM ALLOYS

INTRODUCTION

All structures contain flaws or cracks as a result of material and fabricating imperfections or metal fatigue during service. Whether these cracks will affect the life expectancy of the structure depends to a great extent on the material property known as fracture resistance. Since metal strength is inversely related to fracture resistance, small cracks embedded in high-strength alloys are of concern to structural designers. Once these cracks begin to propagate under the influence of an applied stress, the low fracture toughness of the metal may not provide sufficient resistance to arrest the crack and structural failure can result.

Because of the importance fracture resistance plays in any assessment of service life of aerospace vehicles, a reliable parameter is needed by which this property can be evaluated. For high-strength sheet metals, fracture mechanics analysis provides a design parameter known as the plane stress fracture toughness value K_c. For infinitely wide sheet,

$$K_c = \sigma\sqrt{\pi a_c}, \tag{1}$$

where σ is operating stress and a_c is one-half the crack length. The K_c parameter can be experimentally determined in the laboratory and may be used to delineate

a. The crack length at failure for a known operating stress, or

b. The failure stress at a known crack length.

The manner in which a crack is developed in the specimen is immaterial. If a crack is introduced into a sheet specimen which is subsequently subjected to a tensile load, the specimen will fail when the conditions of Eq. (1) are satisfied. If, instead, the panel is loaded to a predetermined stress and a notch or hole produced in the loaded specimen, it will fail when the flaw is of sufficient length to meet the condition of Eq. (1).

EXPERIMENTAL PROCEDURES

Materials

The fracture resistance of four structural titanium sheet alloys has been investigated. Mechanical property data, fracture resistance values, and heat treatments are presented in Table 1. All test specimens were so oriented that the path of the fracture was parallel to the rolling direction of the sheet; if anisotropy is present, this will be the direction least resistant to fracture. It is evident that the level of fracture resistance in the weaker direction should categorize materials since the direction of operating loads cannot be assured.

Table 1
Mechanical and Fracture Resistance Properties of Four Titanium Sheet Alloys

Titanium Alloy	Sheet Thickness (in.)	YS 0.2% Offset (ksi)	TS (ksi)	Elong. (%)	Re. in Area (%)	K_c Blunt (ksi$\sqrt{in}$)	K_c Sharp (ksi$\sqrt{in}$)	Heat Treatment
6Al-4V	0.032	—	135.9	—	—	51.5	53.5	Solution Anneal:
	0.063	151.1	156.3	1.0	2.0	74.4	64.2	1780°F, 20 min.
	0.090	158.5	168.9	3.0	—	97.6	77.5	Water Spray Quench
	0.125	146.0	158.2	4.2	7.5	90.4	—	Age: 975°F, 8 hr, Aircool
4Al-3Mo-1V	0.042	161.5	167.0	0.5	0.3	—	50.2	Solution Anneal:
	0.058	153.4	174.5	0.75	1.8	—	54.8	1650°F, 15 min.
	0.087	152.9	172.0	0.5	1.1	64.0	62.5	Water Spray Quench
	0.124	159.8	172.1	1.0	1.0	64.5	35.0	Age: 925°F, 14 hr, Aircool
16V-2.5Al	0.041	181.6	190.5	1.5	3.9	56.6	52.4	Solution Anneal:
	0.059	176.5	187.6	4.7	9.5	65.2	46.3	1380°F, 15 min.
	0.118	181.7	192.0	4.0	9.5	51.2	44.4	Water Spray Quench
								Age: 960°F, 4 hr, Aircool
13V-11Cr-3Al	0.040	198.1	199.4	0	2.9	55.8	34.1	Age: 900°F, 72 hr, Aircool
	0.063	207.3	220.9	2.7	6.3	41.5	38.9	
	0.090	200.6	203.5	0	—	52.6	29.8	
	0.125	216.5	227.0	2.2	2.1	35.7	23.2	

Test Procedure

The K_c values for sheet are measured with a center-cracked tension (CCT) specimen. This panel design was chosen as it is a structural prototype precursor and the stress analysis is well documented (1). The configuration of the CCT specimen is shown in Fig. 1. The central slit is produced by electric discharge (Elox) to give a 1/16-in.-wide slit with slit tip radii typically 0.003 to 0.006 in. (designated "blunt"). To assess the effect of tip radius size on the K_c value, companion specimens had slits sharpened by a second Elox operation which extended the slit and developed a tip radius of 0.001 in.

When the specimen is loaded in tension, load and crack-opening displacement (COD) are simultaneously plotted by an X-Y recorder. Crack opening is measured by a displacement probe instrumented with strain gages which is positioned in a circular hole in the center of the initial slit. A previous calibration between COD and crack length permits calculation of the crack length at any point during the test (2). At the onset of instability the load (proportional to gross stress σ_G) and crack length 2a are employed to calculate K_c fracture resistance from the equation

$$K_c = \sigma_c \sqrt{\pi a_c}\, f\ 2a/W. \qquad (2)$$

It has been established that for a range of crack length/width (2a/W) values between 0 and 0.6, the following expression is accurate to within 1 percent:

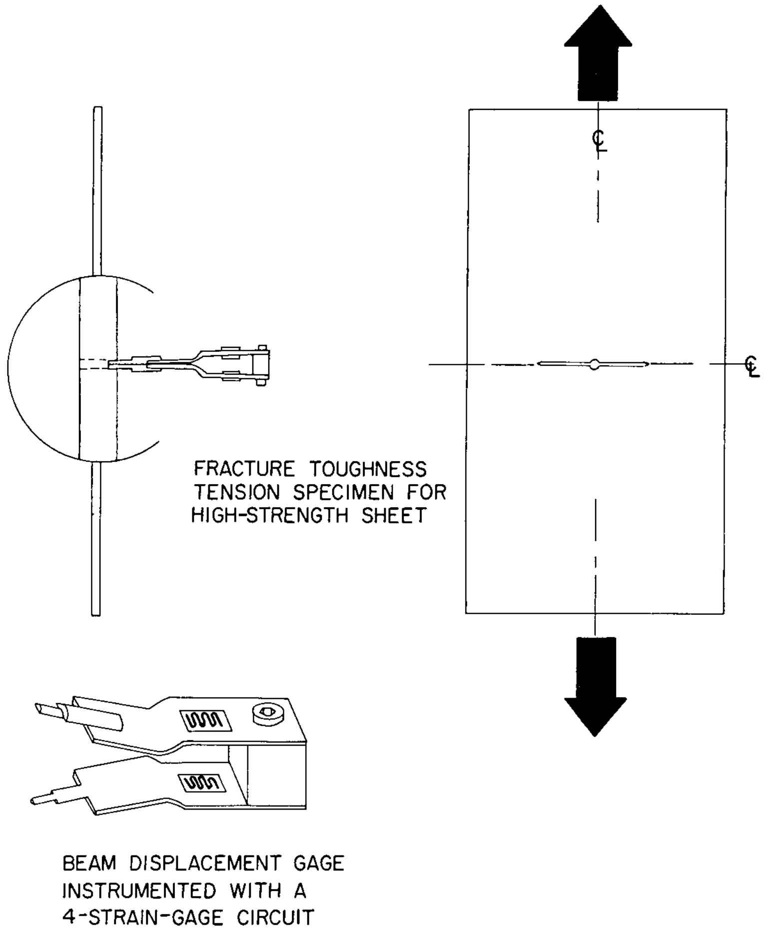

Fig. 1 — Center-cracked sheet tension (CCT) specimen and beam displacement gage used to measure crack-opening displacement

$$f\ 2a/W = 1.77\ [1 - 0.1\ (2a/W) + (2a/W)^2]. \qquad (3)$$

In this technique, determination of crack length from COD measurement delineates the "effective" crack length (actual crack plus plastic zone) so the plastic zone correction factor is not used in the calculation of K_c.

Dependence of Specimen Dimensions on K_c

The K_c value is independent of specimen width and crack length if a judicious selection is made of specimen dimensions (3-6). The objective is to design the panel so that the crack-tip stress field is isolated from the borders of the specimen. Otherwise, the value of K_c is influenced by the panel dimensions and would not relate to the actual fracture resistance of the alloy.

Effect of Width — Because general elastic conditions must prevail in order to use the analytics of fracture mechanics, the specimen width must be sufficient to allow unstable fracture to commence at stress levels less than the yield stress σ_{ys}. Previous work (2) on high-strength aluminum alloys indicates that for K_c to be unaffected by further increases in width, the minimum width W_{min} must meet the following requirements:

$$W_{min} = 27/2\pi\ (K/\sigma_{ys}). \tag{4}$$

Studies are currently being conducted to determine if a downward adjustment in this requirement is possible. For the titanium alloys described in this report, a specimen width of 12 in. was more than adequate. The relationship between K_c/σ_{ys} and width is presented in Fig. 2.

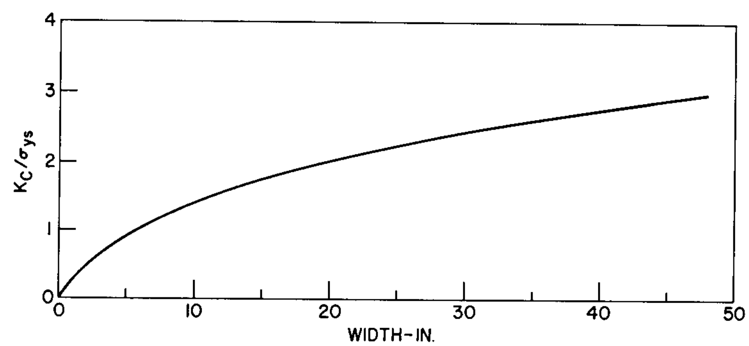

Fig. 2 — Fracture resistance to yield stress ratio K_c/σ_{ys} vs speciemn width W. By estimating the ratio, a specimen width can be ascertained that is sufficient to produce K_c values which are independent of W.

Crack Length-to-Width Ratio — Another specimen variable which can influence K_c is the length of the crack at instability. An extensive investigation of the influence of the crack length-to-width ratio in aluminum alloys established that for $0.15 < 2a/W < 0.50$, constant K_c values were obtained (7,8). Data scatter was excessive for crack lengths outside of this range.

The relationship between 2a/W and K_c is presented in Fig. 3 for two titanium alloys: Ti-6Al-4V and Ti-13V-11Cr-3Al. The graph indicates that the fracture resistance of Ti-6-4 is significantly higher than that of the Ti-13-11-3 alloy. The thicker panels (0.125 in.) of Ti-6-4 evidence a K_c average of 90 ksi-$\sqrt{\text{in.}}$, whereas the 1/16-in.-thick panels average 74 ksi-$\sqrt{\text{in.}}$ The Ti-13-11-3 alloy manifests a slightly lower toughness for the thicker specimens as compared to the thinner panels. There is no evidence that K_c is a function of 2a/W within the crack length/width range investigated.

Sheet Thickness — Unlike specimen width and crack length, the influence of thickness B on K_c cannot be avoided. In Fig. 4a, a schematic diagram showing the postulated dependence of K_c on thickness B is presented. At some sheet thickness specific for each alloy, a maximum value of K_c should be obtained and be accompanied by 100 percent slant fracture. As the thickness increases, lower K_c values are accompanied by increasing

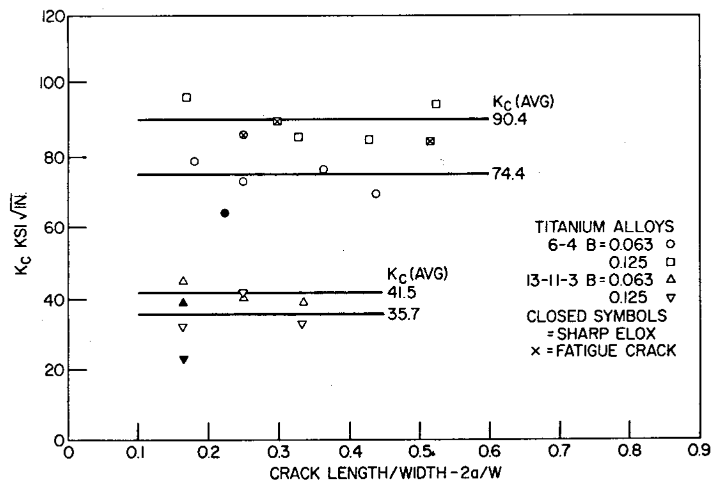

Fig. 3 — Fracture resistance K_c plotted against crack length/width ratio. K_c is independent of 2a/W within the range shown.

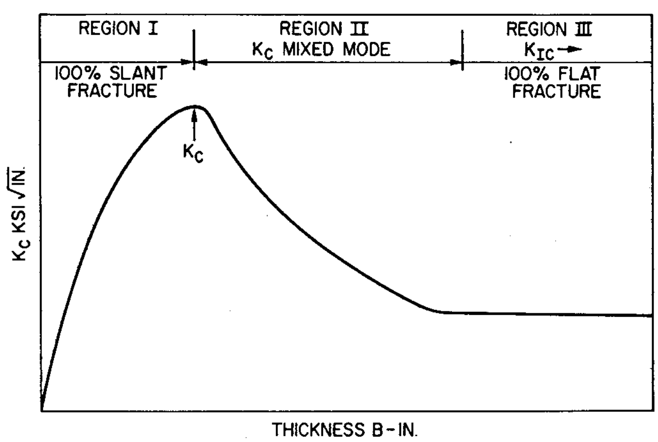

Fig. 4a — Schematic figure showing postulated influence of specimen thickness B upon the fracture resistance K_c

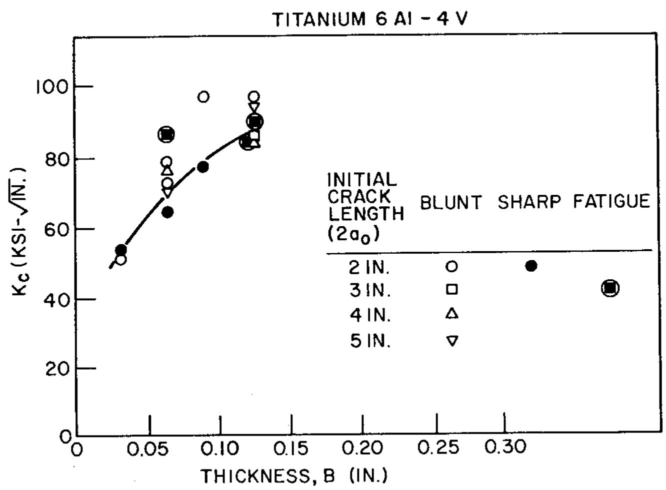

Fig. 4b — Influence of panel thickness B on K_c for Ti-6Al-4V specimens

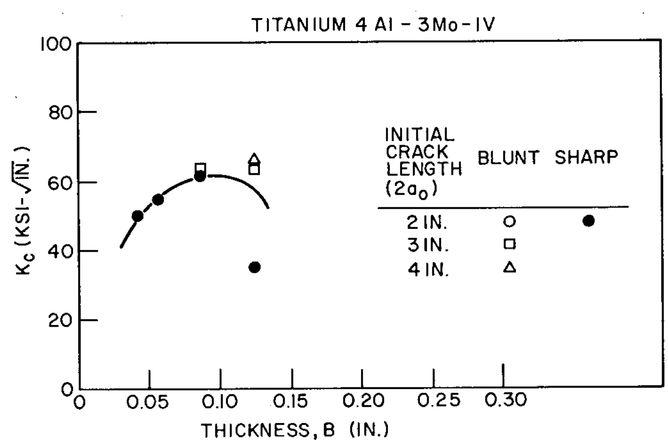

Fig. 4c — Influence of panel thickness B on K_c for Ti-4Al-3Mo-1V specimens

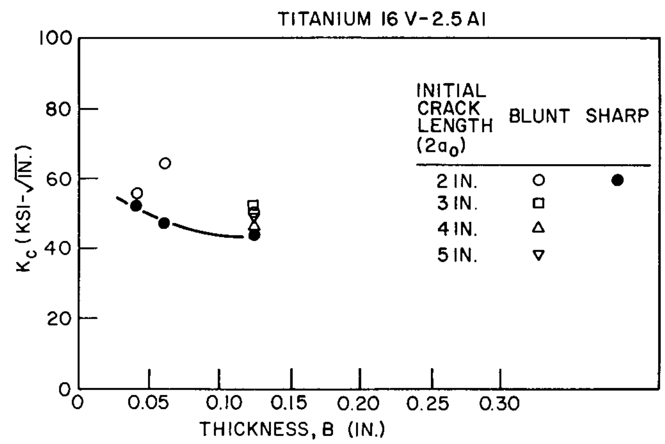

Fig. 4d — Influence of panel thickness B on K_c for Ti-16V-2.5Al specimens

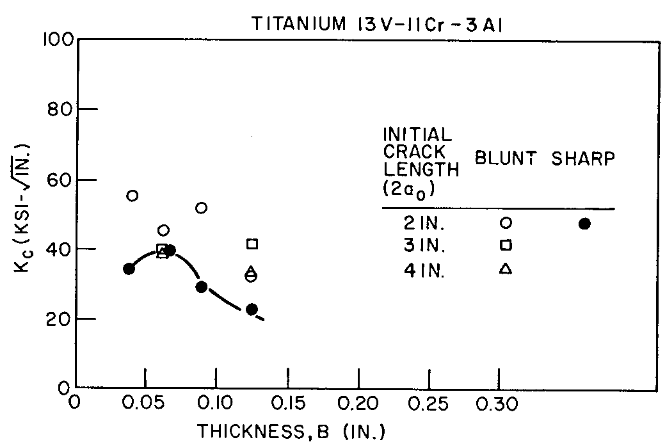

Fig. 4e — Influence of panel thickness B on K_c for Ti-13V-11Cr-3Al specimens amounts of flat fracture to provide the so-called "mixed-mode" appearance. Finally a minimum value K_{Ic} is reached and the fracture surface is entirely flat.

The relationship between K_c and thickness for the four titanium alloys is shown in Figs. 4b through 4e. Panels were tested over a thickness range from 1/32 in. (0.032 in.) to 1/8 in. (0.125 in.); initial slit length and slit tip radius were also varied. While this investigation has not yet been extended to the thicker sheet, some generalizations can be made as to the thickness dependence of K_c.

For Ti-6Al-4V, Fig. 4b, it appears that peak K_c values will occur at $B > 0.125$ in. Figure 4c indicates that for Ti-4-3-1 the maximum K_c occurs when $B \approx 0.1$ in., while for Ti-16-2.5 and Ti-13-11-3 alloys, specimens 1/16-in. thick and less represent the highest K_c fracture resistance.

It is noteworthy that for those alloys in which maximum K_c occurs in the thinnest panels, peak $K_c/\sigma_{ys} = 0.2$ to $0.3\sqrt{\text{in.}}$, whereas for Ti-4-3-1 where maximum K_c is at $B \approx 0.1$ in., K_c/σ_{ys} at this thickness is $0.4\sqrt{\text{in.}}$ In other words, there is an indication that the more frangible alloys achieve maximum K_c (loss of through-thickness elastic constraint) in very thin thickness sections. If it is assumed that maximum K_c occurs at a thickness just sufficient to encompass the crack-tip plastic zone, the inherently small plastic zone size of a brittle alloy would equal panel thickness in very thin panels. The larger plastic enclave of the more fracture resistant alloy would overwhelm a thin panel; therefore, a thicker sheet would be required for the zone size to be equal to panel thickness.

Slit Tip Radius — Specimens containing slits with both sharp (0.001 in.) and blunt (0.003 to 0.006 in.) slit tip radii were investigated as well as fatigue-cracked panels. An extension of the initial slit by a fatigue crack is desirable to assure maximum stress concentration. Previous work has shown that when some crack growth precedes final separation, crack-tip sharpening is unnecessary (9). Tests on aluminum alloys, most of which exhibited some crack growth, indicated that K_c values were independent of slit tip radius, although the amount of crack extension before failure was a function of tip radius (10,11).

In Figs. 4b through 4e, panels containing sharp slit tips produced a lower K_c value at any thickness than did specimens with 3- to 6-mil radius slit tips. This is particularly noteworthy for Ti-6Al-4V, as stable crack extension preceded instability for specimens with both sharp and blunt tips. Since no slow crack growth was observed for Ti-13V-11Cr-3Al and Ti-4Al-3Mo-1V, the lower K_c values for panels with sharp tips are expected. For Ti-16V-2.5Al, stable growth was observed on the sharply tipped specimens of thickness 0.041 and 0.118 in. but not for the bluntly tipped panels; although the corresponding K_c values of the sharp specimens are lower than values from blunt specimens, the difference is only 10 percent. Some of the data scatter manifested by the panels with 3- to 6-mil slit-tip radii can be attributed to variations in melting and processing practice and alloy chemistry. Until the effect of slit tip radius on K_c for titanium alloys is resolved, future specimens will contain either sharp slit tips or fatigue cracks.

MODEL OF K_c DEPENDENCY ON THICKNESS

It would be a considerable convenience if the fracture resistance for all sheet thicknesses of a given alloy could be estimated from a limited number of actual measurements. Two similar models have been developed which purport to explain the effect of material thickness on K_c (12,13). Both consider that flat fracture is a surface phenomenon while shear-lip formation is a volume-sensitive mechanism.

A further postulation of these models is that once the shear lip is fully developed, the total shear-lip thickness no longer increases. This is conceptualized in Fig. 5. For a thin specimen the panel thickness B is equal to shear-lip thickness B_{SL}; i.e., the fracture surface is 100 percent slant fracture. At some increased thickness, the shear lip will form a characteristic size independent of the specimen thickness. The dimension B_{SL_O} is one-half the total shear lip thickness once it has reached its characteristic size.

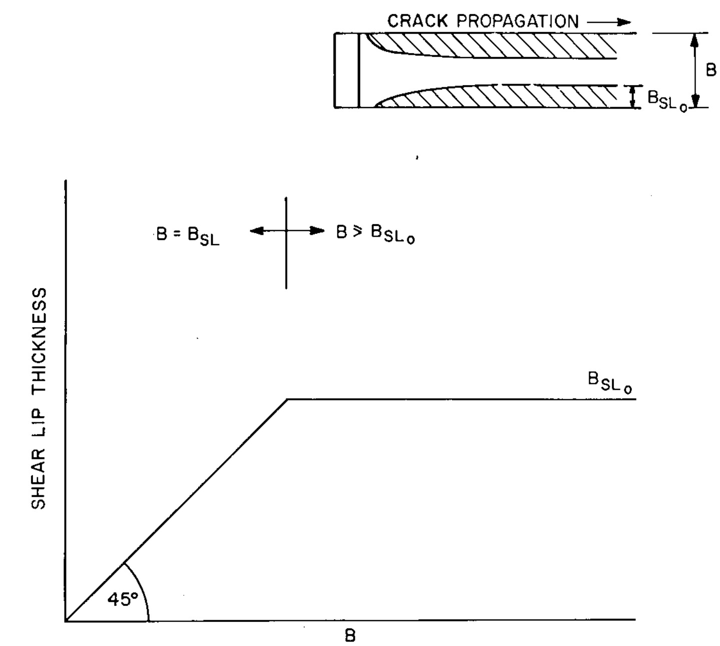

Fig. 5a — Schematic representation of a model describing relationship between panel thickness and slant fracture

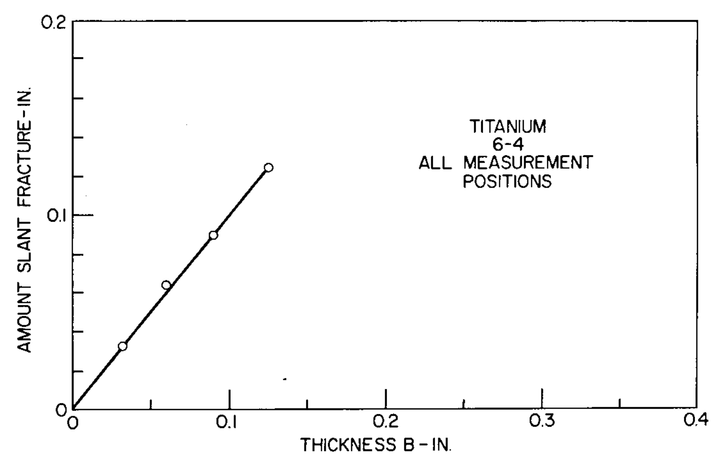

Fig. 5b — Amount of slant fracture (measured in inches) plotted against thickness B for Ti-6Al-4V

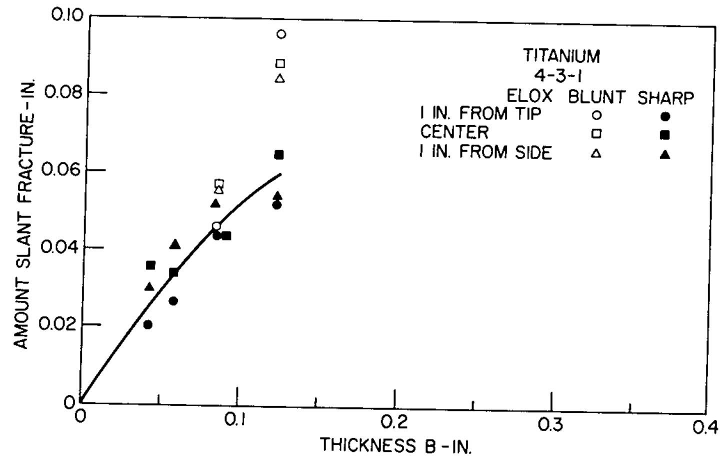

Fig. 5c — Amount of slant fracture (measured in inches) plotted against thickness B for Ti-4Al-3Mo-1V

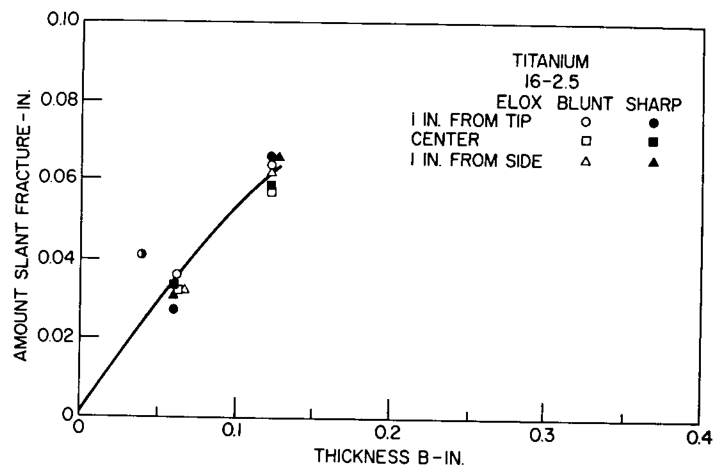

Fig. 5d — Amount of slant fracture (measured in inches) plotted against thickness B for Ti-16V-2.5Al

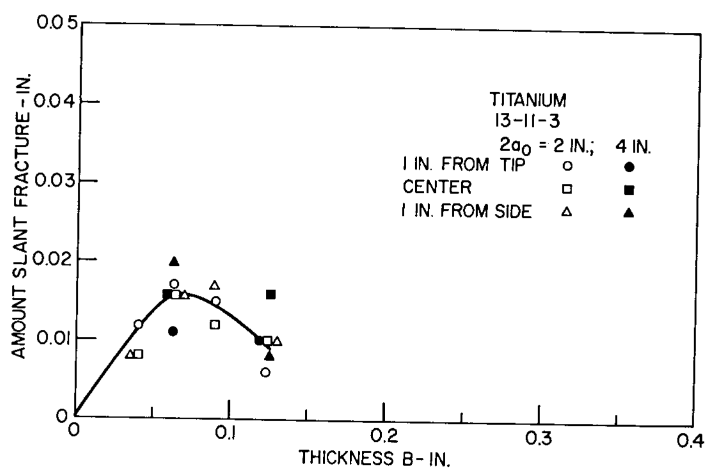

Fig. 5e — Amount of slant fracture (measured in inches) plotted against thickness B for Ti-13V-11Cr-3Al

The relevant equations for the two models are as follows:

Model I

$$\mathcal{G}_c = \frac{1}{2} k_{SL} B_{SL_o} \left(\frac{B}{B_{SL_o}}\right); \quad \left(\frac{B}{B_{SL_o}}\right) \leqslant 1 \tag{5}$$

$$\mathcal{G}_c = \frac{1}{2} k_{SL} B_{SL_o} \left(\frac{B_{SL_o}}{B}\right) + k_{ff} \left(1 - \frac{B_{SL_o}}{B}\right); \quad \frac{B}{B_{SL_o}} \geqslant 1 \tag{6}$$

Model II

$$R = \mathcal{G}_c = \frac{1}{2} k_{SL} B_{SL_o} \left(\frac{B_{SL_o}}{B}\right) + k_{ff}, \tag{7}$$

where

$\mathcal{G}_c = K_c^2/E$

B_{SL_o} = one-half constant shear-lip thickness

B = sheet thickness

$k_{ff} = \mathcal{G}_{Ic}$

k_{SL}, k_{ff} = material constants, where the subscripts SL and ff refer to shear lip and flat fracture, respectively.

Before the titanium data can be compared to the models, the plots of absolute shear lip thickness (B_{SL_o}) in Figs. 5b through 5e must be examined. For the first three alloys, Figs. 5b through 5d, the amount of slant fracture increases with thickness, although there are indications in Figs. 5c and 5d that the constant slant thickness B_{SL_o} is being approached for the thicker specimens. For the Ti-6Al-4V (Fig. 5b) the plot rises at 45 degrees reflecting the condition of 100 percent slant fracture on the fracture surface even for the 1/8-in.-thick panels. The deviation of the data from the proposed behavior necessitated the choice of rather arbitrary values of B_{SL_o} to fit to the model. In Fig. 5e, an average of the data was used to ascertain a B_{SL_o} value.

An examination of the Eqs. (5) through (7) indicates that Models I and II differ only in an evaluation of the contribution of the flat fracture portion of the fracture surface. The application of Model I to the data has been attempted in Figs. 6a through 6d.

For Ti-6Al-4V (Fig. 6a) B_{SL_o} was selected as 0.125 in., and

$$k_{SL} = \frac{2\mathcal{G}_{max}}{B}. \tag{8}$$

Computed values of k fit these data quite well where $B/B_{SL} < 1$.

Application of the model to the data of Ti-4Al-3Mo-1V in Fig. 6b is less satisfactory. Two values of B_{SL_o} were tried, but in no instance could they be fitted through the sharp Elox value for B = 0.125 without developing a negative value for k_{ff} ($\mathcal{G}_{Ic}$), which is untenable.

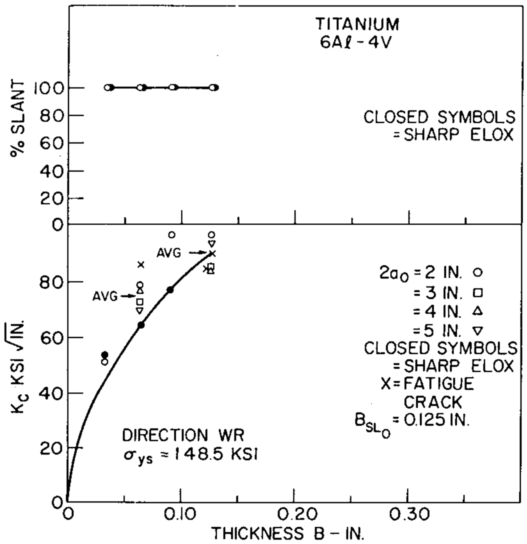

Fig. 6a — Measured K_c values (lower curve) and slant fracture percent (upper) plotted against specimen thickness B. Curves drawn are calculated from the model of Ref. 13. Titanium alloy 6Al-4V.

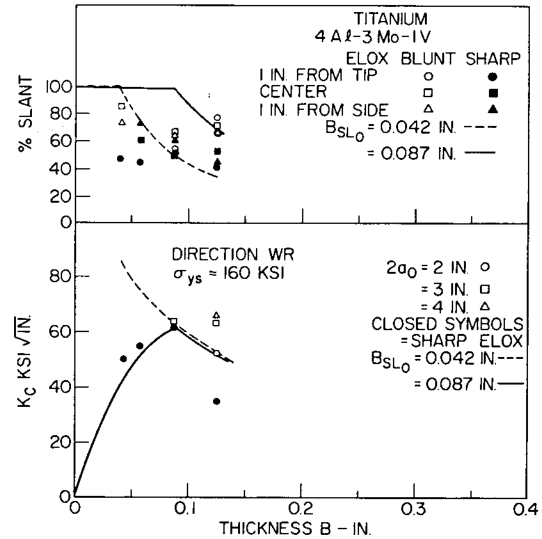

Fig. 6b — Titanium alloy 4Al-3Mo-1V

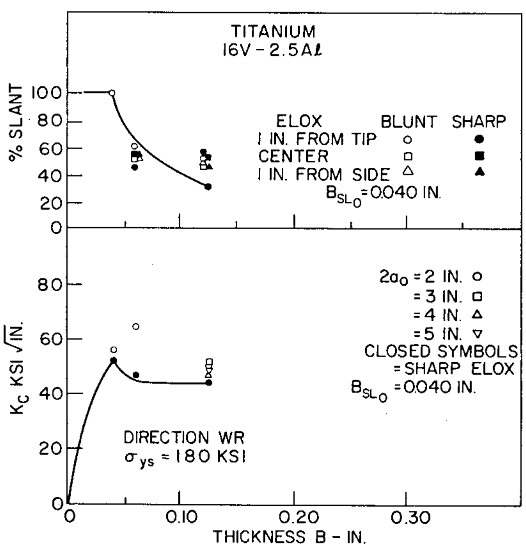

Fig. 6c — Titanium alloy 16V-2.5Al

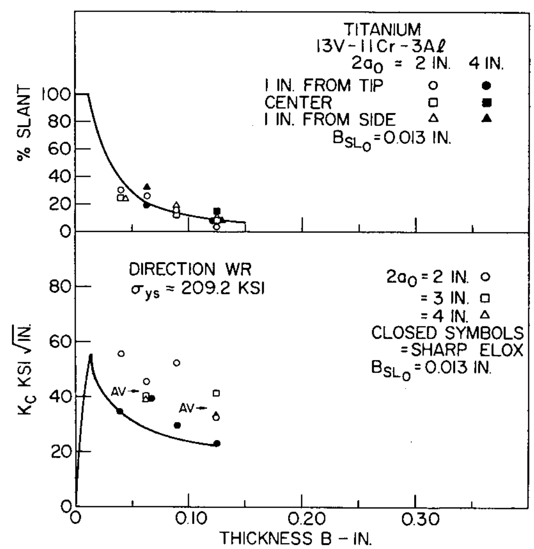

Fig. 6d — Titanium alloy 13V-11Cr-3Al

Data fitted to the values of Ti-16V-2.5Al produce a K_c vs B curve (Fig. 6c), which fits the sharp Elox values but the percent slant vs B curve is less satisfactory. Here B_{SL_O} was taken as 0.040 in., since this thickness developed 100 percent slant fracture.

For Ti-13V-11Cr-3Al (Fig. 6d) it is seen that the amount of slant fracture decreases with increased thickness. An average value of B_{SL_O} = 0.013 in. was selected for the analysis shown in Fig. 6d.

FRACTURE APPEARANCE

The relationship between the amount of fracture surface shear lip and K_c is presented in Fig. 7 for four titanium alloys. Each datum point represents an average of three measurements taken along the fracture path of the specimen. For Ti-13V-11Cr-3Al, Ti-16V-2.5Al, and Ti-4Al-3Mo-1V, the percent slant fracture increases with K_c; the Ti-6Al-4V remains 100 percent slant over a wide K_c range representing specimens from 1/32 to 1/8 in. thick. The Ti-13-11-3 and Ti-16-2.5 alloys indicate an increase in percent slant fracture with decreasing panel thickness.

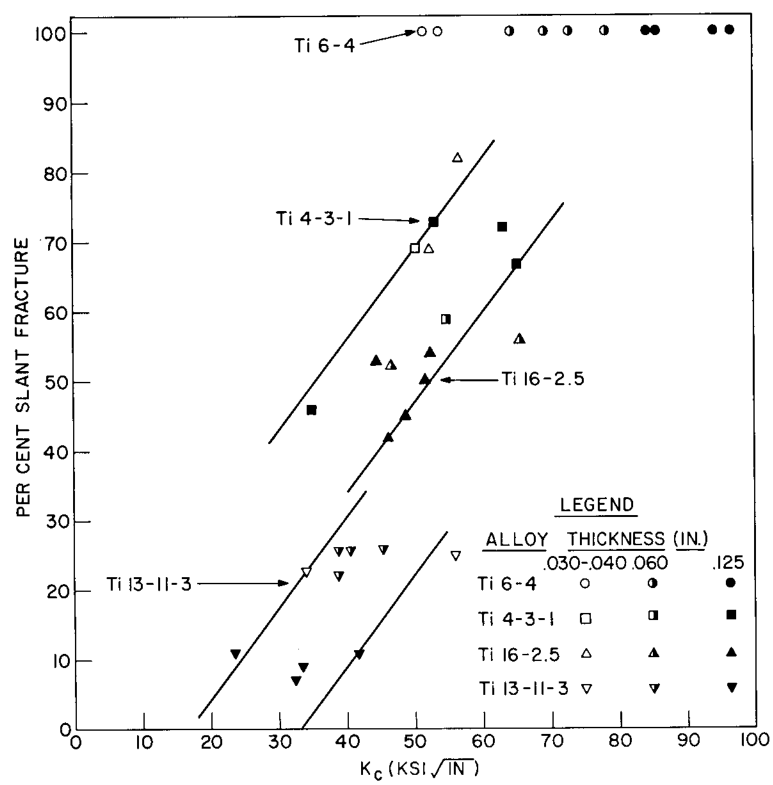

Fig. 7 — Percent slant fracture compared to K_c for four titanium alloys

The reduction in panel thickness along the fracture plane was also measured for each specimen and is shown in Fig. 8. Measurements were made at three positions across the fracture path: 1 in. from the slit tip, at the center point, and 1 in. before the end of the crack run. A positive correlation is indicated between thickness reduction and K_c. No clear trend is discernible between reduction in thickness and specimen thickness.

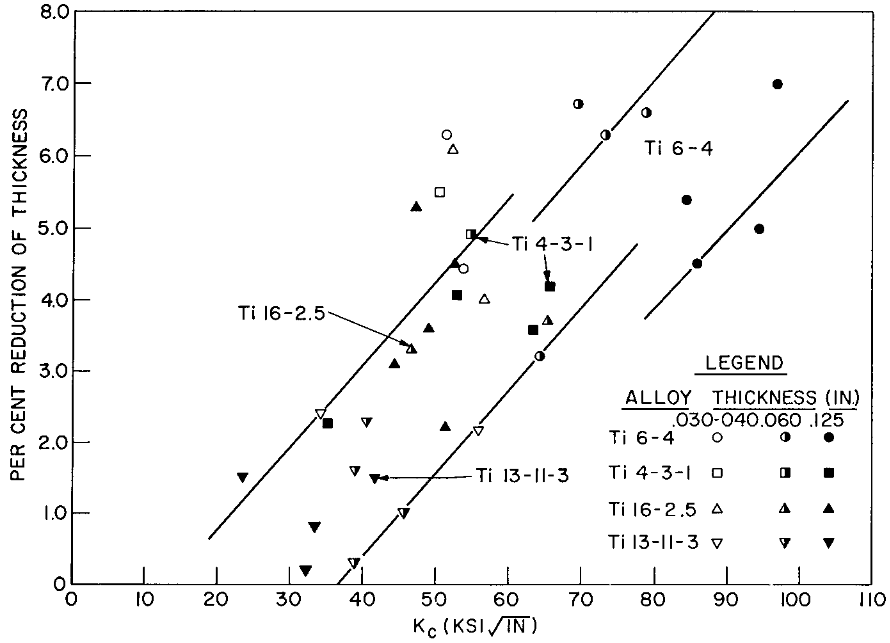

Fig. 8 — Percent reduction in thickness compared to K_c for four titanium alloys

CRITICAL CRACK LENGTH AT VARIOUS LEVELS OF OPERATING STRESS

Loads acting on a structural member cannot be precisely defined since fabricating stresses resulting from misalignment, welding, and rivet coupling can only be estimated. Further, the alloy strength will vary slightly from sheet to sheet and even the thickness of an individual sheet will fluctuate. Therefore, a reasonable estimate of K_c is a useful design parameter. In Fig. 9, the K_c dependence on thickness for the four titanium alloys is compared. Average K_c values can reasonably describe three alloys at least over the thickness range from 0.04 to 0.1 in. However, chemistry, melting practice, and rolling temperatures have a marked influence on the value of K_c and must be carefully controlled in order to optimize the fracture resistance of a particular alloy.

Using the average K_c values, the crack length at failure can be calculated for various levels of operating to yield stress ratios, where crack length

$$2a = \frac{2}{\pi}\left(\frac{K}{\sigma_G}\right)^2 . \qquad (9)$$

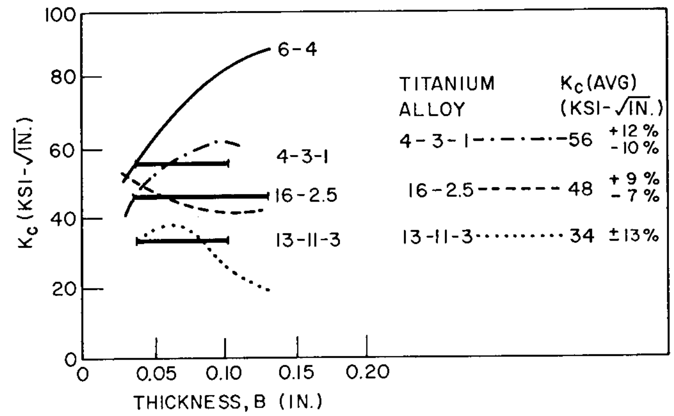

Fig. 9 — Average K_c values over a thickness range of 0.04 to 0.10 in. for three titanium alloys

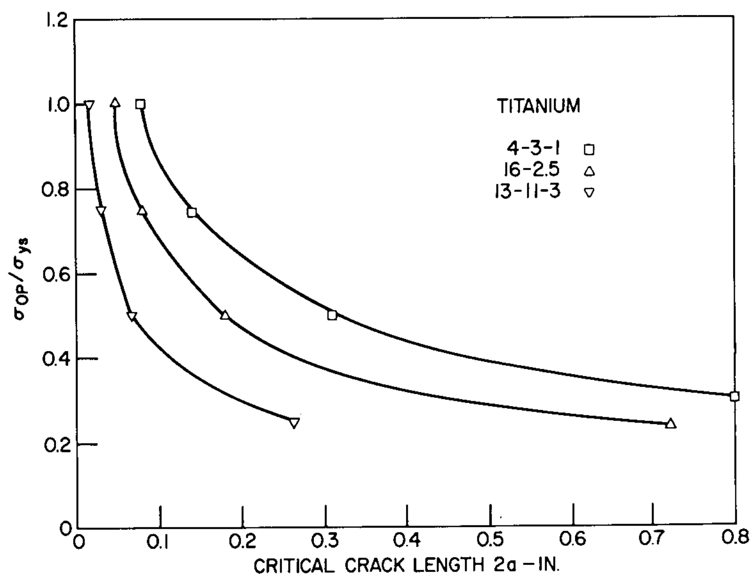

Fig. 10 — Critical crack length 2a at instability plotted against operating stress to yield stress ratio σ_{op}/σ_{ys}

These values are plotted in Fig. 10. The small critical crack sizes required for the onset of instability at moderate operating stresses place a premium on crack inspection techniques when these alloys are employed in a structure.

SUMMARY

This discussion of the thin-sheet fracture resistance problem with particular application to high-strength titanium alloys is intended to emphasize its scope and complexity and to suggest methods of minimizing the geometrical dependencies of K_c. The major attribute of K_c is the relationship it signifies between either the critical crack length at some predetermined operating stress level or the stress level which can be tolerated by a crack of predetermined size.

The usefulness of using a single parameter to define this relationship is evident from a comparison of the fracture resistance values of these high-strength structural sheet alloys of titanium. Inconsistencies observed between the data and the model proposed indicate the need for further experimentation so that a more precise model may be developed.

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