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A Characterization of the Fracture Resistance of Thick-Section Titanium Alloys

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ABSTRACT

Procedures for design of structures to preclude catastrophic fracture extension must be based on accurate fracture resistance characterizations of the structural material that can only be provided by rational test procedures. For titanium alloys, the two rational fracture resistance test procedures that apply are K_{Ic} tests for brittle materials and Dynamic Tear (DT) tests for the entire range of strength and fracture resistance. The Ratio Analysis Diagram (RAD) is a framework for determining the significance of fracture resistance data in terms of stress level and crack size required for fracture. The RAD is derived from basic linear-elastic fracture concepts involving K_{Ic} and material yield strength; however, either K_{Ic} or DT test data can be indexed to the RAD.

Full-thickness K_{Ic} and 1-in. DT tests were conducted for several 3-in.-thick titanium alloy plates to confirm the relationship between the two parameters and to locate the RAD scales for thick sections. Equal accuracy was obtained when the RAD was indexed to either the DT or K_{Ic} energy scale. Moreover, the DT test accurately predicted that several of the titanium alloys would not satisfy standard ASTM requirements for valid test results. Therefore, the results of the very expensive K_{Ic} test can be predicted by the far less costly DT test for the full range of titanium alloys.

PROBLEM STATUS

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

AUTHORIZATION

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A CHARACTERIZATION OF THE FRACTURE RESISTANCE OF THICK-SECTION TITANIUM ALLOYS

INTRODUCTION

Safe use of high-strength titanium alloys in structures must be based on a complete knowledge of both the inherent resistance of the materials to fracture extension and the particular requirements of the structural application. The Ratio Analysis Diagram (RAD), has been used to interpret fracture resistance properties of structural metals for several years. The RAD was developed for steels (1), aluminum alloys (2), and titanium alloys (3) in section sizes up to 3-in. thick.

The RAD combines metal quality and mechanical constraint aspects of fracture to provide analyses of the conditions for fracture extension in terms of parameters measured by rational test procedures. Rational test methods are required to determine a metal's intrinsic resistance to fracture; such tests impose the condition of maximum crack-tip constraint for the section size. There are a number of test methods for measuring fracture properties; however, at present only two rational test methods can be applied to titanium alloys. Linear-elastic fracture mechanics technology is based on a description of the fracture resistance properties of brittle materials by the critical crack tip stress-intensity factor K_{Ic}. The quantitative aspects of the RAD are derived from linear-elastic calculations of relations between critical defect or flaw sizes and applied stress levels, which are expressed in terms of the ratio of K_{Ic} to material yield strength (σ_{ys}). Linear-elastic methods are not suitable for defining fracture properties of semiductile or ductile metals, i.e., metals that require high elastic or overyield stresses for fracture. Therefore, the Dynamic Tear (DT) test was developed to characterize the fracture resistance properties of metals over the entire range of strength and fracture resistance (plane strain, elastic-plastic, and plastic). In the DT test the energy required to fracture a standard specimen indicates the level of fracture resistance.

For brittle materials, values measured in K_{Ic} tests and in DT tests have a definite relationship because both tests are rational methods which characterize a single property of the materials. Thus, both the K_{Ic} and DT energy provide an entry to the RAD for assessment of fracture safety of structures. It must be recognized that a limit of applicability for linear-elastic principles is given in terms of the section size, or material thickness. For titanium alloys, the RAD was based on K_{Ic} and DT test results from plate materials of 1-in. thickness, with reasonable extrapolations to include thicker sections up to 3 in. It is necessary to validate these early predictions by extending the experiments to include higher values of K_{Ic} and DT energy from tests involving thicker sections. This report describes the results of K_{Ic} and DT tests on 3-in.-thick titanium alloys for the purpose of corroborating the capabilities of the RAD in this size range.

RATIO ANALYSIS DIAGRAM FOR TITANIUM ALLOYS

The RAD provides a format for analysis of the fracture resistance properties of titanium alloys over the entire range of strength and fracture resistance levels. As a group, titanium alloys have a continuous range of yield strength and fracture resistance levels from very low to very high. To understand the significance of fracture resistance measurements, it is necessary to divide the alloys into three general groupings — plane strain, plastic, and a transition region called elastic plastic — and to analyze each group separately.

Plane strain materials are those that fracture at elastic nominal stress levels; the technology of linear-elastic fracture mechanics applies only to materials of this type. The unique characteristic of plane strain materials is that unstable crack propagation follows any crack initiation event; hence, use of these materials concerns only the prevention of crack initiation. Equations relating crack size and shape, applied nominal stress level, and K_{Ic} exist for several different geometrical configurations. One of the most often used equations for a part-through surface flaw is presented in graphical form in Fig. 1 for engineering purposes. This chart relates critical flaw depths at different applied stress levels to the ratio of K_{Ic}/σ_{ys}. It is important to note that in this and all other fracture mechanics calculations critical flaw size is related directly to this ratio. Therefore, the K_{Ic}/σ_{ys} ratio provides an index of merit with respect to fracture properties.

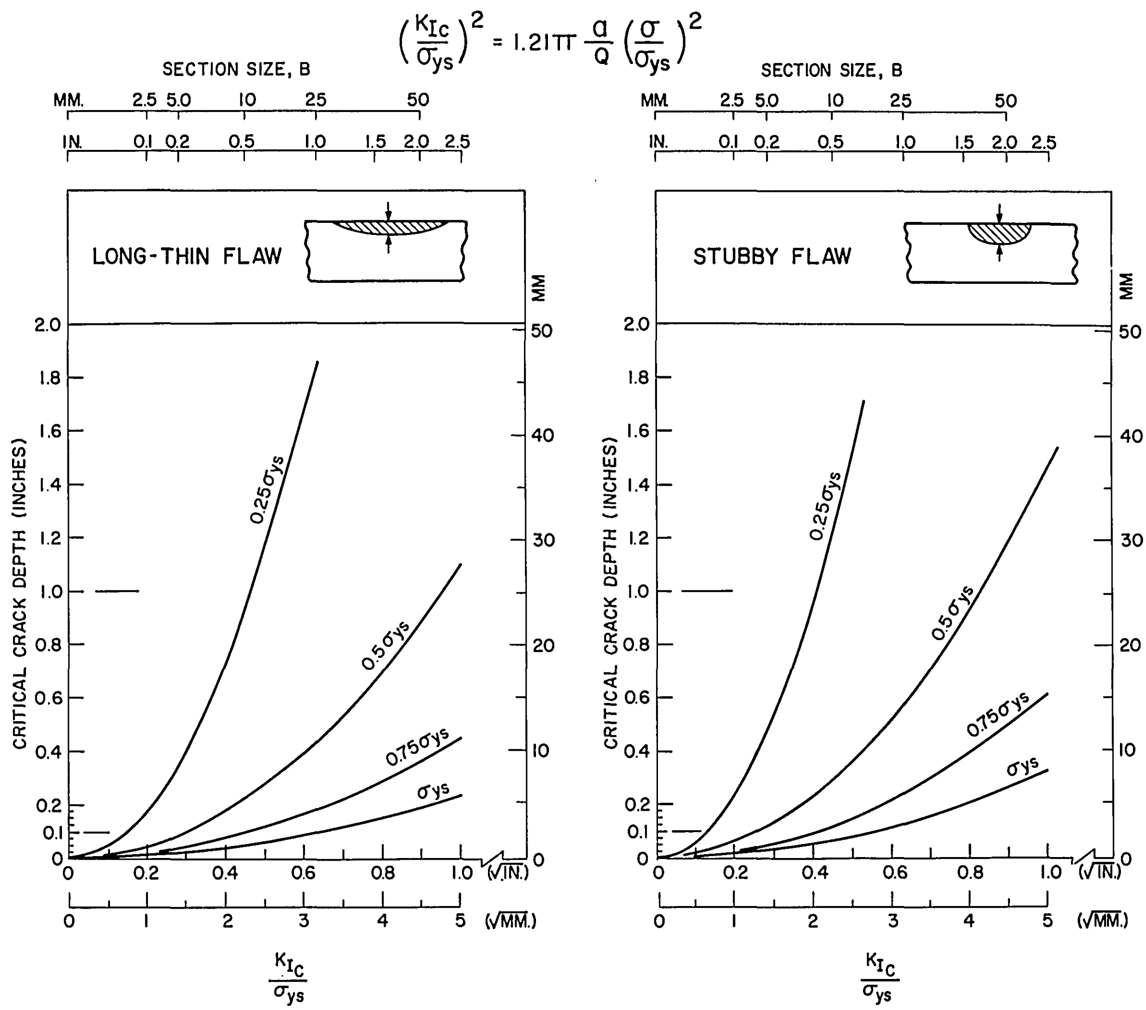

Fig. 1 - Surface flaw equation in engineering diagram form for determination of critical flaw sizes for fracture of brittle metals. Note that the critical flaw size depends on the ratio K_{Ic}/σ_{ys}.

It must also be cautioned that Fig. 1 does not apply directly to all cases — only to plane strain materials. In strict terms, plane strain materials are those that meet the criterion $B \geq 2.5(K_{Ic}/\sigma_{ys})^2$; this specification was established by the ASTM E-24 Committee on fracture as the upper limit of application of linear-elastic fracture mechanics (4). A reference limit, called the Plane Strain Limit, separating plane strain materials from elastic-plastic materials, is established by this specification as a function of material thickness.

The elastic-plastic case is concerned with fracture at medium-to-high elastic stress levels with sufficient crack-tip plasticity to preclude use of strictly elastic analysis procedures. Elastic-plastic criteria involve through-thickness cracks that are large compared to the thickness. A through-thickness crack is illustrated in Fig. 2, along with the appropriate equation for linear-elastic flaw size calculations and an engineering diagram depicting the use of the equation for thick sections. Figure 2 shows that on an increasing fracture resistance (K_{Ic}/σ_{ys}) scale, the elastic-plastic regime is the transition between the plane strain state and the plastic fracture state. The elastic-plastic regime for any given thickness of material is bounded by the plane strain limit and by the general yield limit, which is given by $B \leq 1.0(K_{Ic}/\sigma_{ys})^2$ (Ref. 5), where K_{Ic} is referenced by other test methods. The general yield limit is defined as the ratio value where nominal stresses in excess of yield are necessary to cause fracture extension for flaws of reasonable size, for example, a length 3 times the thickness (3T). The important point is that the fracture stress rises dramatically from 0.3 σ_{ys} at the plane strain limit to σ_{ys} in the narrow elastic-plastic range. This transition effect is relatively insensitive to material thickness factors and is independent of changes in flaw length; i.e., flaw sizes in the range of 2T to 6T do not significantly alter the intercepts on the plane strain limit and yield strength lines.

The third group of alloys is ductile, or plastic, materials, which require nominal stresses overyield to cause fracture extension. The basic characterization tool for plastic materials is the fracture extension resistance curve (R curve) defined by DT test methods (6). No general relations of critical defect sizes and applied stress levels exist because the plastic fracture case is geometry dependent. For each geometrical configuration, different failure criteria and, accordingly, different material requirements exist, and problems in design with plastic materials must be solved on a case-by-case basis.

In the RAD, Fig. 3, all these factors are combined into a single "plotting board" for interpretation of fracture principles from laboratory test results. The RAD framework is formed from the scales of yield strength vs K_{Ic} and DT energy. The most prominent features of the RAD are the limit lines and the system of lines of constant K_{Ic}/σ_{ys} ratio. The Technological Limit (TL) line represents the highest values of fracture resistance measured to date by either K_{Ic} tests or DT tests over the entire yield strength range; the Lower Bound represents the lowest levels of fracture resistance. A reference to the critical flaw size charts, Figs. 1 and 2, is provided by the system of ratio lines constructed from the scales of K_{Ic} and σ_{ys}. As an example, critical sizes for a long, thin surface flaw for half-yield and full-yield loading conditions are shown on the RAD for each ratio line.

The ratio lines also serve to divide the diagram into regions of expected plastic, plane strain, and elastic-plastic fracture behavior for given material thicknesses. The separations are determined according to thickness as shown for 1-in. section size in Fig. 3. The critical boundary between brittle behavior and elastic-plastic behavior is the plane strain limit. The boundary between the elastic-plastic and ductile regimes is the general-yield limit. The division of the RAD into three regions provides an engineering index of the fracture state and thereby serves to indicate the type of a more detailed design approach required for each case.

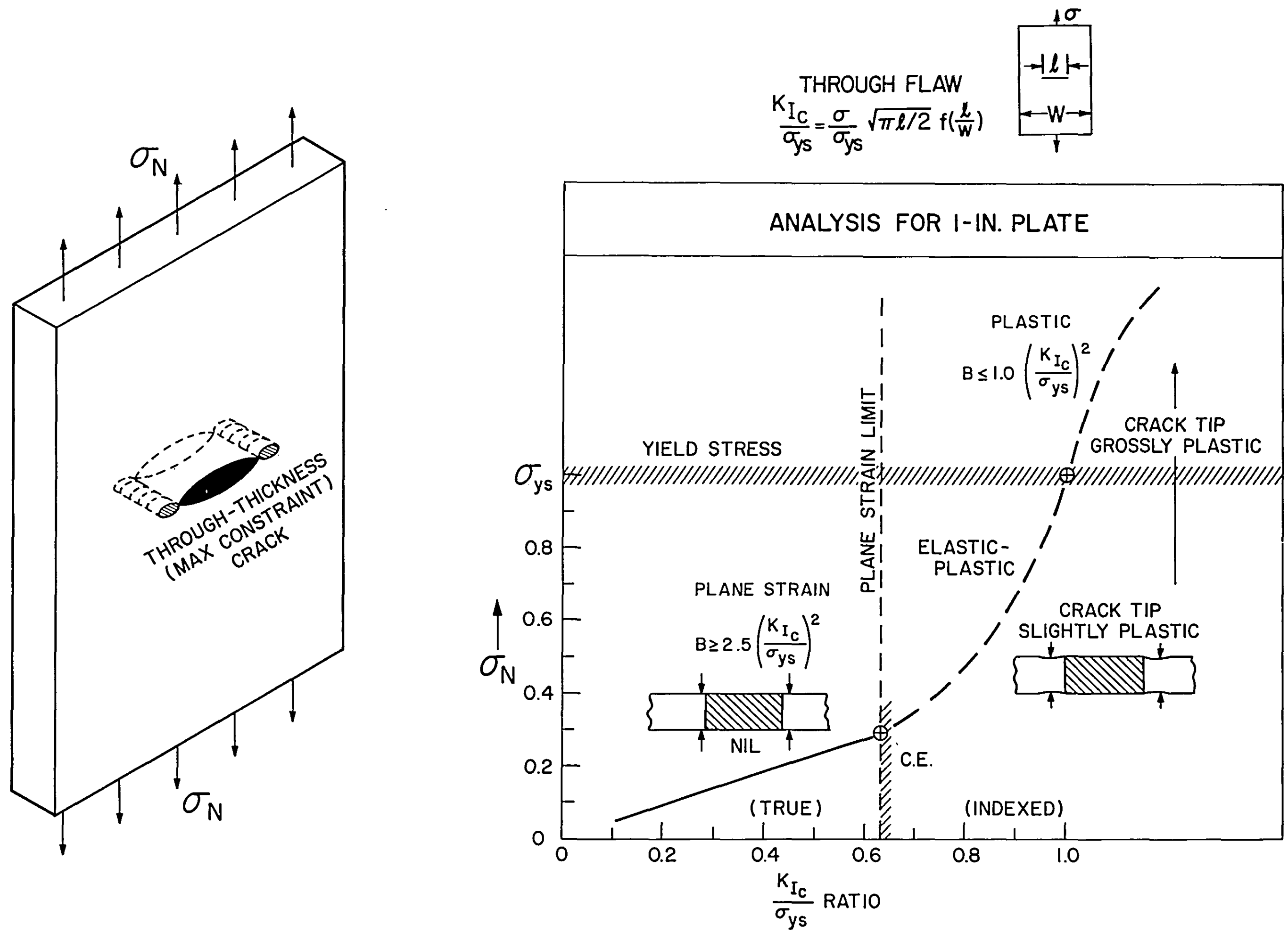

Fig. 2 - Illustration of the significance of elastic-plastic transition from plane-strain to plastic fracture states. Fracture stress for a 3T through flaw is given by the curve. The solid part of the curve is given by the equation at the top, while the dashed part connects the plane strain limit to the yield point.

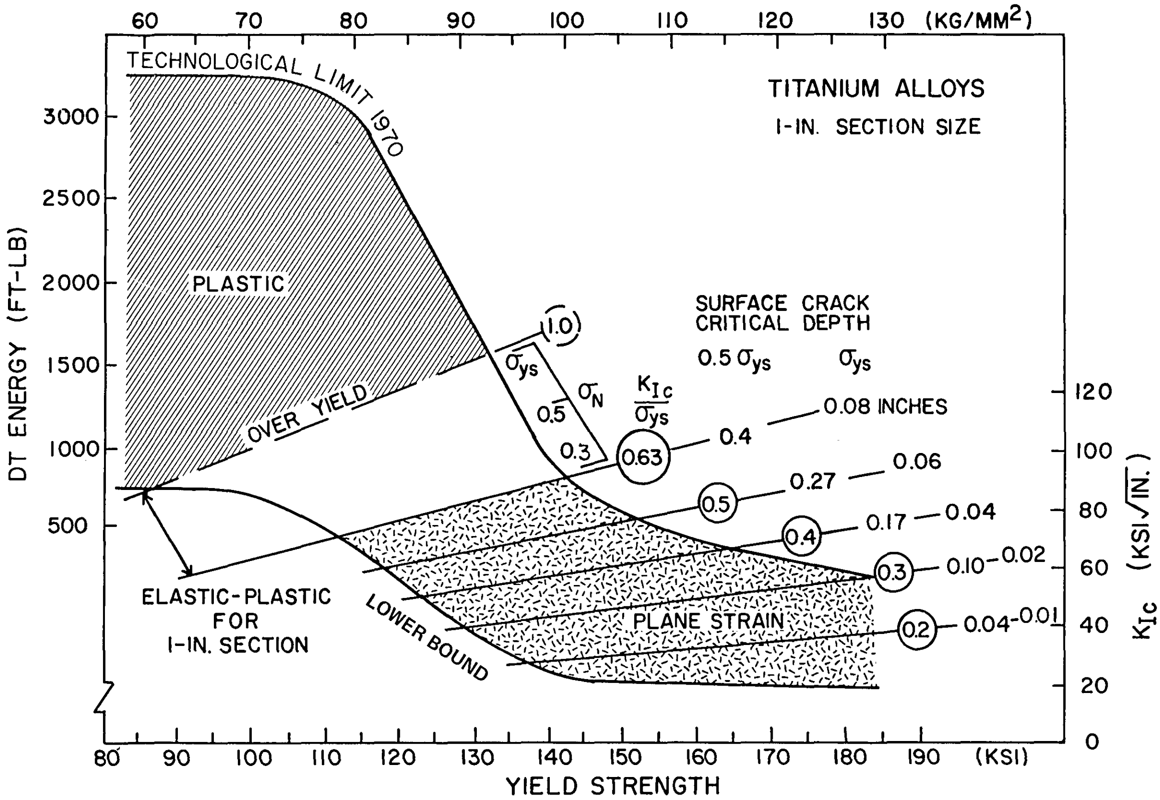

Fig. 3 - Framework of the RAD for titanium alloys for 1-in. thickness

The most important feature of the RAD is that both DT and K_{Ic} data can be indexed to the system of ratio lines. There is a definite advantage to using the DT test for indexing to the RAD; compared to K_{Ic} tests, DT tests are relatively inexpensive in the costs of specimen preparation, in the test procedures, and in the amounts of materials required. An additional advantage to using DT tests is that the entire range of materials from brittle to ductile can be characterized by DT test procedures, while the K_{Ic} test is limited to the plane strain materials.

MATERIALS AND TEST PROCEDURES

The wide variety of near-alpha and alpha-beta titanium alloys in 3-in. rolled-plate form were included in this investigation (Tables 1 and 2). K_{Ic} tests, 1-in.-thick DT tests (7), and tensile tests were conducted for each alloy. Standard 0.505-in.-diam tensile and standard 1-in. DT test specimens were machined from surface and plate center locations; K_{Ic} test specimens included the full plate thickness. Dimensions of the K_{Ic} and DT specimens are shown in Fig. 4. All specimens were oriented in the "WR" or weak fracture direction with respect to anisotropy due to rolling. DT tests were conducted at 30°F, and all other tests were conducted at room temperature.

Specimen preparation procedures, test procedures, and test record analyses for the K_{Ic} tests conformed to ASTM Specification E-399-70T. In many cases, materials in the mill-annealed condition had fracture resistance levels sufficiently high to prevent satisfaction of the thickness specification ($B \geq 2.5(K_{Ic}/\sigma_{ys})^2$; the results of these tests are not reported. To overcome this effect, the plates had to be heat-treated to higher yield

Table 1
Mechanical Properties of 3-Inch-Thick Titanium Alloy Plates — Plane Strain

Nominal Composition	Fracture Resistance						Tensile Yield Strength (ksi)		
	1-in. DT Energy (ft-lb)			K_{Ic} Av (ksi $\sqrt{in.}$)	K_{Ic} Range (ksi $\sqrt{in.}$)	Number of Specimens			
	Surface	Center	Av				Surface	Center	Av
Ti-6Al-4V-2Mo	472	714	593	69	66-71	3	151.7	139.9	147.8
Ti-6Al-4V	587	699	643	89	88-91	3	136.1	130.4	134.2
Ti-6Al-4V	986	1120	1053	100	96-103	4	112.7	112.6	112.7
Ti-6Al-4V	836	1205	1020	101	99-105	4	125.6	122.2	124.4
Ti-6Al-2Mo	1166	1320	1243	110	107-114	2	113.3	115.0	113.9
Ti-6Al-4V-1Mo	1033	1349	1191	117	111-118	4	113.1	112.1	112.8
Ti-5Al-2V-2Mo-2Sn	1250	1330	1267	117	116-118	4	115.4	111.3	114.0
Ti-6Al-2Cb-1Ta-1.2Mo	1352	1534	1443	123	115-131	3	114.8	114.5	114.7

Table 2
Mechanical Properties of 3-Inch-Thick Titanium
Alloys — Elastic-Plastic or Plastic

Nominal Composition	Av 1-in. DT Energy (ft-lb)	Av Tensile Yield Strength (ksi)
Ti-6Al-2Mo	1268	109.5
Ti-7Al-1Mo-1V	1455	107.7
Ti-6Al-2Mo	1455	119.3
Ti-6Al-2Cb-1Ta-0.8Mo	1517	107.4
Ti-6Al-2Cb-1Ta-1.2Mo	1706	107.6
Ti-6Al-2Mo	1706	108.1
Ti-7Al-2.5Mo	2303	109.4

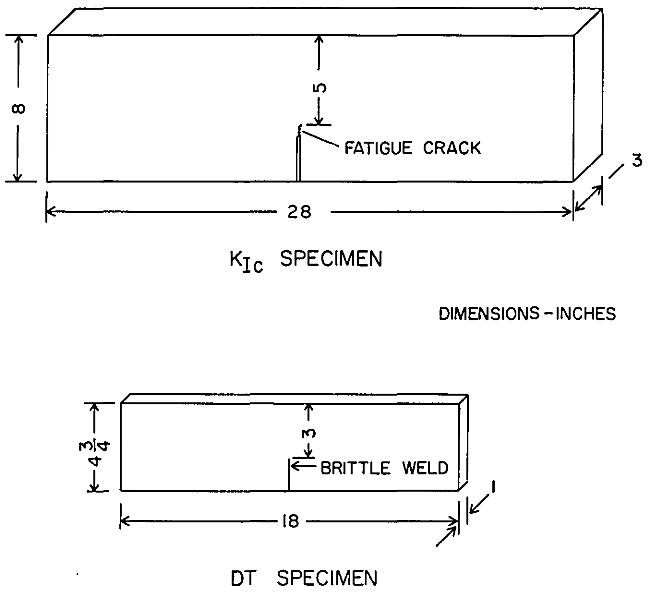

Fig. 4 - Schematic of K_{Ic} and DT test specimens

strength levels so that valid test results could be obtained. In these cases all specimens of a given material were heat-treated at the same time.

DISCUSSION OF RESULTS

The results of the tests are presented in Tables 1 and 2. Table 1 contains the results of K_{Ic}, DT, and tensile tests for materials where K_{Ic} could be measured. Table 2 contains DT and tensile test results for those alloys which failed the thickness requirement.

The characteristic K_{Ic} values reported in Table 1 were determined by averaging the results of two to four specimens; the range of K_{Ic} values is also indicated. Tensile and DT test results in Tables 1 and 2 reflect an average of two specimens at each location. Some significant gradients in fracture resistance properties through the thickness are apparent from DT test results, and gradients in yield strength are also evident to a lesser degree.

The relation of DT energy and K_{Ic} is presented in Fig. 5. A slight downward adjustment of the locus from that extrapolated from 1-in. plate (8) studies was necessary. Previously determined 1-in. plate data are included in Fig. 5 to give a full range of values. The line drawn through the points was determined by a least-square procedure. This line determines the matching of the DT and K_{Ic} scales on the RAD; the nonlinearity of the curve is reflected in the location of the scales on the RAD. The fit of the data in Fig. 5 is very good when all the variables are considered. Much of the scatter can be accounted for by variability of properties from one point to another in a given plate and the observed gradients in fracture properties through the thickness, as well as normal experimental variations.

The significance of the relation between DT energy and K_{Ic} can only be realized by comparing these two indices of fracture resistance on the RAD (Fig. 6). The plane strain limit and general yield limit were determined for 3-in. section size in this figure. The closeness of K_{Ic} and DT values (circles vs triangles) plotted at the average yield strength for each material underscores the accuracy of either method for indexing to the RAD. Note that both values give essentially the same indication of fracture resistance in all cases, as derived from the ratio lines. The flaw sizes that are expected to be critical for given stress levels can be determined for each material by reference to Fig. 1.

The primary difference between the two test methods is cost; a K_{Ic} test costs approximately \$100 or more, whereas a DT test might cost \$10. An even more significant

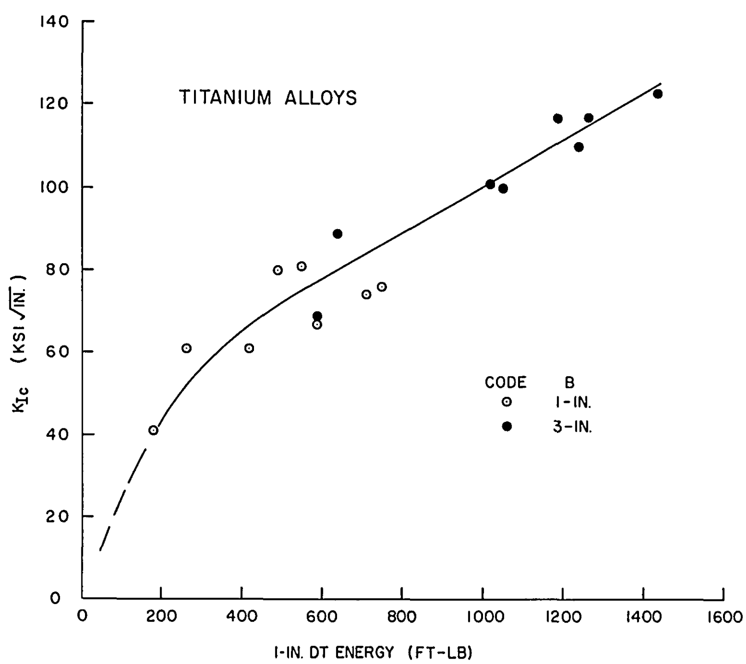

Fig. 5 - Experimental correlation of DT energy and K_{Ic} for 1-in. and 3-in. section sizes

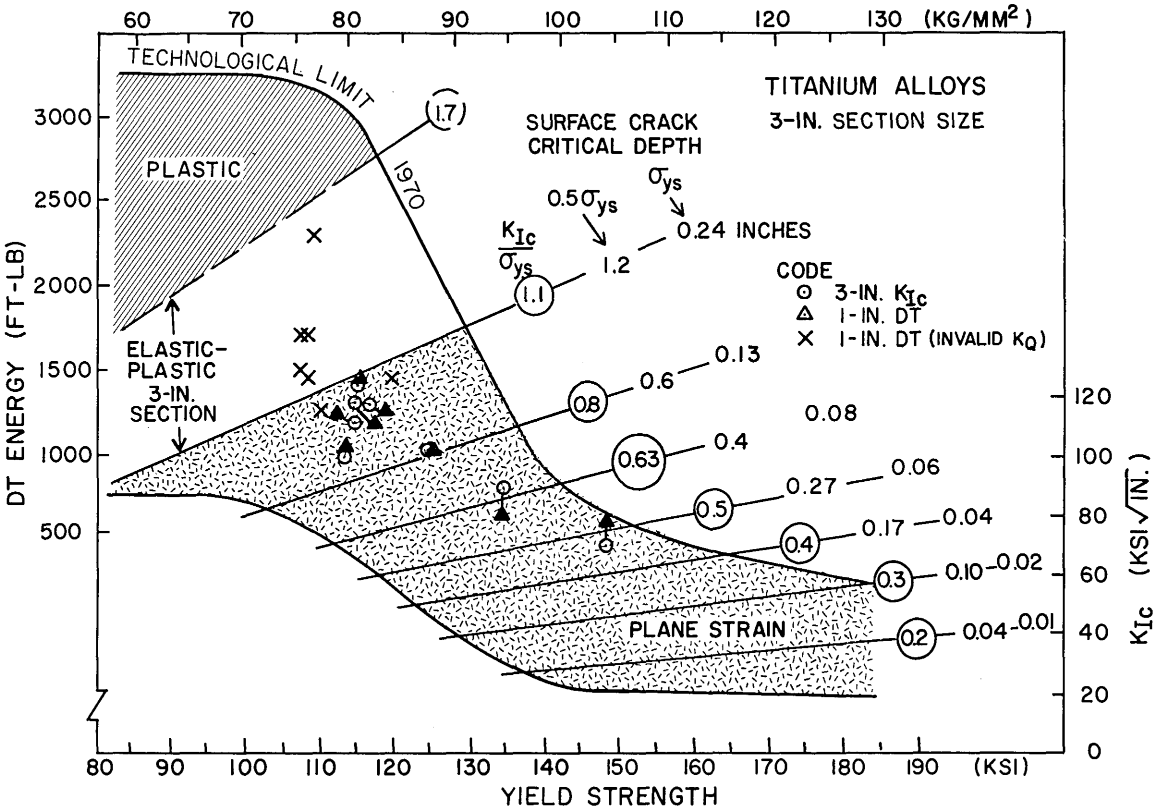

Fig. 6 - Illustration of K_{Ic} and DT energy giving the same indication of fracture resistance on the RAD. Points coded *x* are 1-in. DT energy values for materials for which K_{Ic} could not be measured.

factor emerges from the DT data for materials where K_{Ic} could not be measured in a valid manner. The *x* symbols in Fig. 6 represent average DT energy values for seven materials for which K_{Ic} tests were conducted but the fracture resistance was high enough that the ASTM specifications could not be satisfied, i.e., $B < 2.5(K_{Ic}/\sigma_{ys})^2$ (Table 2). Such values, termed K_Q, are not reported because, as invalid data, they have no capability for defining the fracture resistance of the test materials. In Fig. 6 the data points predict that five of the seven tests would definitely be invalid and that the other two would be very near the plane strain limit line for 3-in. plate ($K_{Ic}/\sigma_{ys} = 1.1$). It should be noted that the behavior predicted for materials very near the line on either side are not greatly different, particularly for thick sections. Therefore, predictions of valid K_{Ic} properties by the two *x* points just below the ratio 1.1 line, when K_{Ic} could not be measured, are not significant discrepancies. In any event, the values fall within the scatter of the correlation plot.

The titanium RAD is illustrated in Fig. 7 and summarizes data for 1-in.-thick titanium alloys. It has been known for several years that a reduction of interstitial oxygen content to low levels is necessary to attain plastic fracture properties in titanium alloys in heavy sections (9). The dashed line across the RAD separates low-oxygen materials (0.08 wt-% or less) from commercial grade alloys and depicts the capabilities of each type as a function of yield strength. Since oxygen is a strengthening agent, low-oxygen materials are not found above 150-ksi σ_{ys} values. Conventional titanium alloys produced to commercial-practice oxygen levels and even Extra-Low Interstitial grades

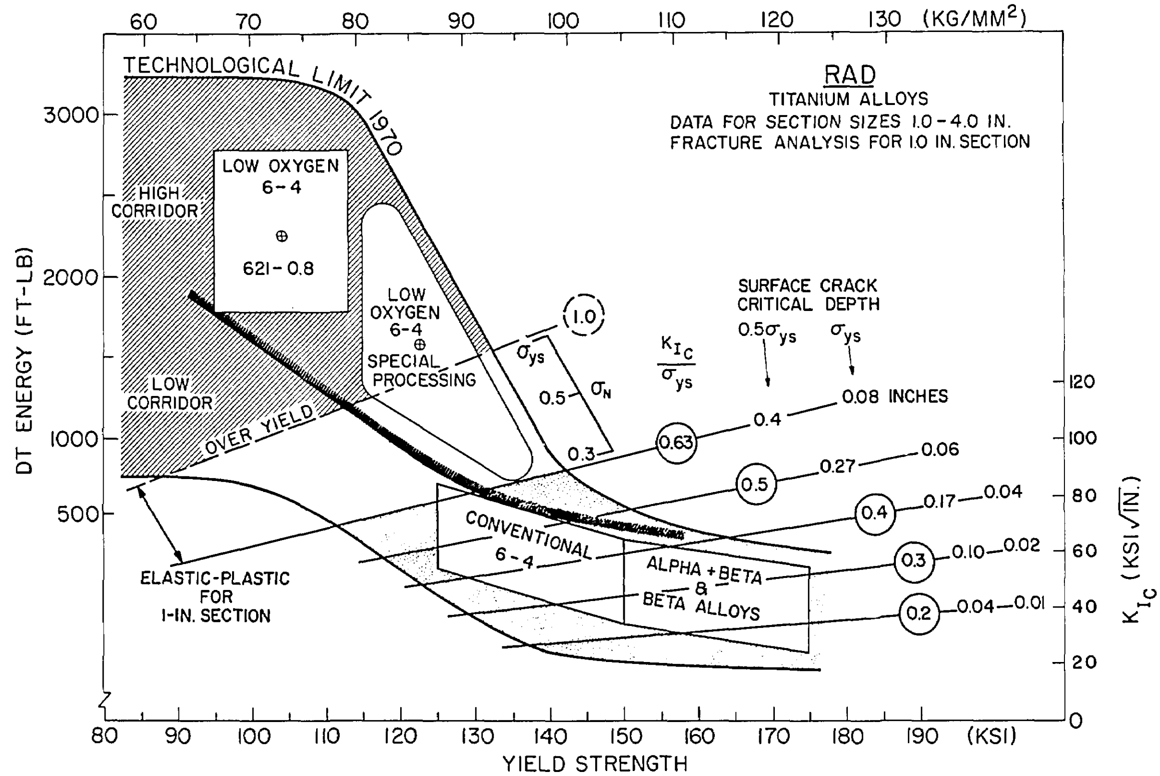

Fig. 7 - RAD for titanium alloys, as prepared for tradeoff analyses involving plate of 1-in. section size. The metallurgical zoning provides for metal selection, depending on structural requirements. For example, at 120- to 130-ksi yield strength a choice may be made for a specific alloy, featuring two levels of oxygen content. The properties are vastly different—plane strain versus plastic fracture states.

occupy the two boxes in the plane strain region of the RAD. To climb from conventional materials to the plastic fracture region of the RAD, it is necessary to reduce both oxygen content and yield strength. In addition, special processing of commercially produced alloys, such as Ti-6Al-4V, is necessary to optimize fracture resistance and yield strength combinations typified by TL line quality materials. Most of the 3-in. plates of this study had low oxygen levels but lacked the special processing necessary to maximize fracture resistance. Whether the properties of 1-in. plates can be duplicated in 3-in. plate is not known at the present time.

SUMMARY

Design of structures using titanium alloys requires a knowledge of the fracture properties of the materials in relation to the imposed loadings to preclude catastrophic failures. A systematic method for making such assessments is provided by the Ratio Analysis Diagram, which is formulated from linear-elastic calculations. Both K_{Ic} and DT test data can be entered on the RAD for indexing purposes. Therefore, it is necessary to have a good knowledge of the relation between these two independent parameters.

Fracture resistance tests of 3-in.-thick plate materials showed that the correlation between the DT energy and K_{Ic} is very good. Combining the data from tests of 3-in.-thick materials with data from earlier studies of 1-in.-thick materials permitted

validation of the RAD interpretations for section sizes up to 3-in. thick. Comparing the data (K_{Ic} and DT energy) on the RAD showed that they are equivalent and that either method could be used for indexing to the RAD; however, because of the much lower cost of DT tests compared to the K_{Ic} tests, DT tests are preferred for general use. Most important, it was shown that the DT test could be used to predict when K_{Ic} tests would be invalid, thereby saving expensive tests that would not have any value.

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13. ABSTRACT

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