NRL Report 7313

Fracture Extension Resistance (R-Curve) Concepts for Fracture-Safe Design with Nonfrangible Titanium Alloys

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August 16, 1971

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CONTENTS

ABSTRACT

New procedures have been evolved to characterize the fracture extension resistance of nonfrangible structural titanium alloys. Fracture extension resistance is defined by the increase in plastic work energy required to propagate a crack. The resistance parameter is the R-curve slope of the metal.

Characteristic R-curve features are presented for titanium alloys ranging from frangible to high fracture toughness types. The R-curve slope determines the plastic work energy expended for fracture extension in structures, as confirmed by Explosion Tear Test results. The R curves are defined by the use of the Dynamic Tear test specimen. Indexing the R-curve slopes to the Ratio Analysis Diagram (RAD) for titanium provides definition of the metal capabilities for use in structures of low, intermediate, and high compliance features. This integration of strucutral aspects with the mechanical and metallurgical aspects of the RAD should provide for significant advances in generalized fracture-safe design of titanium structures using nonfrangible alloys.

PROBLEM STATUS

This is one report of a series concerned with defining parameters applicable to the problem of fracture-safe design. Work on the problem is continuing.

AUTHORIZATION

NRL Problem M01-25
Project RR 007-01-46-5432

Manuscript submitted June 3, 1971.

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FRACTURE EXTENSION RESISTANCE (R-CURVE) CONCEPTS FOR FRACTURE-SAFE DESIGN WITH NONFRANGIBLE TITANIUM ALLOYS

NOMENCLATURE

R	resistance to fracture extension
K	stress-intensity factor
K_c	critical value of K for unstable crack extension under the plane stress state
K_{Ic}	critical value of K for plane strain crack extension at slow loading rates
K_{Id}	critical value of K for plane strain crack extension at dynamic loading rates
K_Q	questionable or invalid values of K due to excessive plastic deformation of the crack tip
a	depth of surface or edge crack
Δa	fracture extension increment
σ_{ys}	yield strength of material
B	thickness dimension of specimen or plate
C_v	standard Charpy-V notch test
DT	Dynamic Tear test
E/A	energy per fracture area measured in DT test
R_p	constant which defines resistance to plastic fracture in terms of DT energy
RAD	Ratio Analysis Diagram
Ratio	refers to lines of constant K_{Ic}/σ_{ys} on RAD
ETT	Explosion Tear Test
LEFM	linear elastic fracture mechanics

INTRODUCTION

The requirements of high-performance structures for light-weight, high-strength metals in fairly thick sections can be met by many titanium alloys. However, there is a general lack of information for designing with titanium alloys that are not brittle. Although some progress has been made, a general lack of material property information and structural service experience exists for heavy-section titanium alloys compared to the data bank of information available for design with steels and aluminum alloys.

The Ratio Analysis Diagram (RAD), Fig. 1, displays the capability for fracture-safe design with titanium alloys that have been evolved to date (1). Dynamic Tear (DT) and linear-elastic fracture mechanics (LEFM) plane strain K_{Ic} test values provide the fracture toughness indexing to the RAD. The upper and lower limit lines refer respectively to the highest and lowest values of fracture resistance that can be expected over the entire strength range of available materials. It is important to recognize that K_{Ic} characterization of fracture toughness is applicable to only the RAD regions below the K_{Ic}/σ_{ys} ratio line which relates to the section size of interest. As an example, for 1.0-in.-thick plates the applicable ratio is 0.63. Materials of DT (or K_{Ic}) energy values indexing to ratios below 0.63 would be frangible. Metals which fracture at DT test energy values above this ratio line do not fracture in a plane strain mode and therefore cannot be characterized by K_{Ic} parameters. It is well established that structural metals exhibit a transition from high to low levels of fracture resistance as a result of increased strength level. This effect, termed the "strength" transition, is best illustrated by the Technological Limit line on the RAD. From the RAD it can be seen that the strength transition corresponds to the 110 to 140 ksi yield strength range.

Early studies to determine the significance of DT values in the nonfrangible (plane stress or ductile fracture region) were conducted using the Explosion Tear Test (ETT). A very large increase in resistance to fracture extension was shown to develop for titanium alloys which were indexed by the DT test to the ductile fracture region of the RAD. The increase in fracture extension resistance was demonstrated by a large amount of plastic strain (bulging) developing in the presence of a 2T (length twice plate thickness) through-thickness flaw in the ETT plate. Similar demonstrations were made for steels and aluminum alloys in relation to their respective strength transition plots.

These studies involved correlation between a parameter measured by a practical low-cost laboratory fracture test (the DT test) and a large plate structural prototype test. The ETT effectively "modeled" a part of a structure (say a cylinder) containing a large flaw. Evidence of large plasticity (deformations of the test plate) indicated that the metal would require gross plastic overload for fracture extension. Conversely, fracturing or shattering of the plate without evidence of plastic deformation indicated that in the presence of the 2T flaw the metal was frangible (brittle) and that unstable crack extension would occur at elastic stress levels.

The early studies were interrupted by investigations of the limits of LEFM applicability, which led to locating the ratio lines in the bottom regions of the diagram, i.e., the frangible region. Recently we have returned to the problem of defining the significance of DT energy values which lie above the brittle fracture region. The first objective was to investigate the basic reason for the excellent correlations between the DT test and the ETT. While it was obvious that this reason had to be related to the increase of fracture extension resistance of the metal, there was no way of accurately representing this effect in terms of a generalized parameter.

These studies were initiated for steels (2) and aluminum alloys (3) and culminated in determining that the parameter of primary consequence is the slope of the fracture extension resistance (R curve) as expressed by an energy increment for fracture extension. A detailed presentation of the basic theory and experimental approach is presented in Ref. 2. For purposes of this report, we shall provide a summary of the findings as evolved from the steel and aluminum studies. These are:

1. Frangible metals develop unstable fracture due to a lack of increase in fracture extension resistance over that required for the initial unit extension — a nonrising R curve is featured.

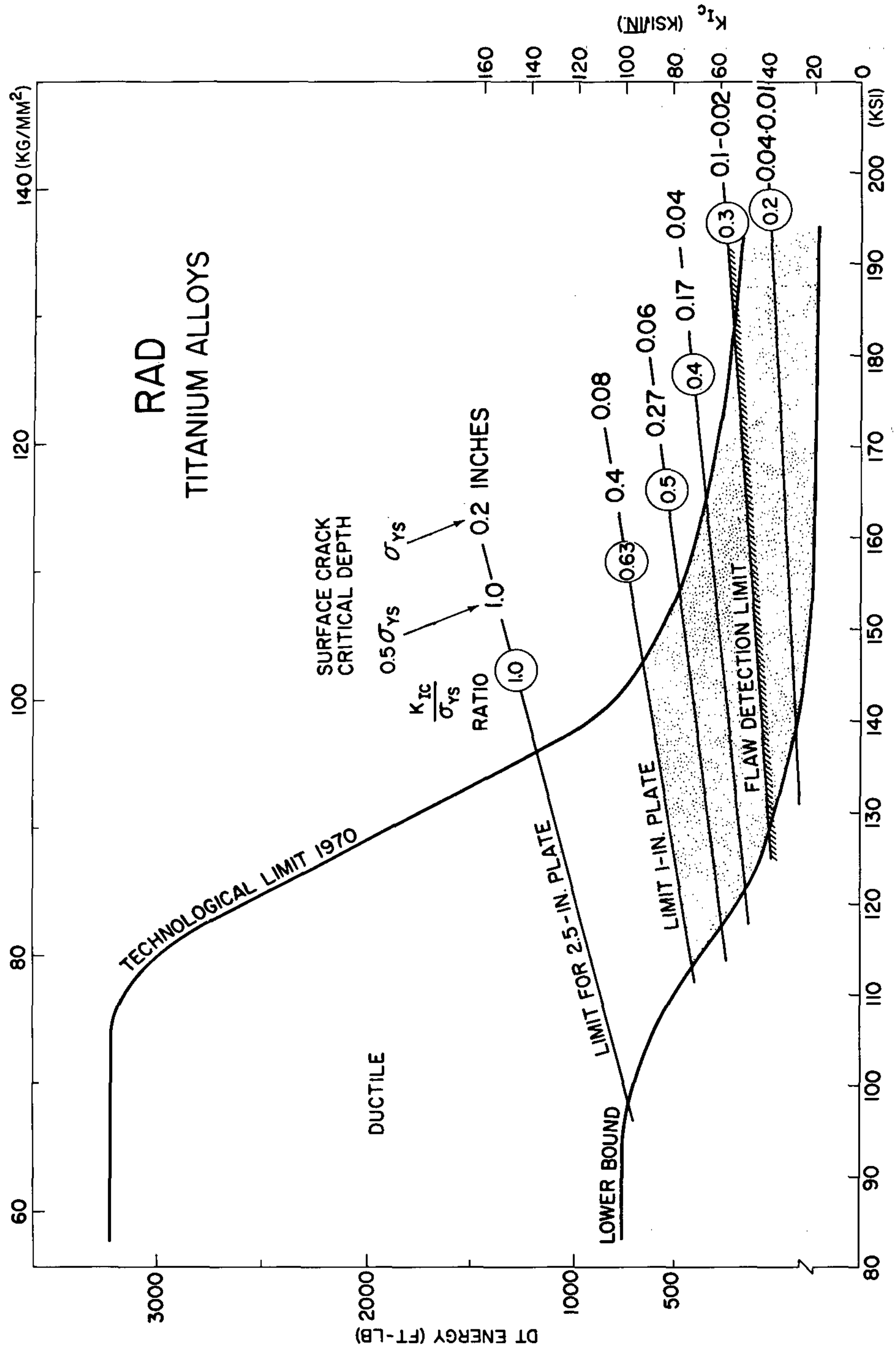

Fig. 1 - Ratio Analysis Diagram (RAD) for structural titanium alloys

2. Nonfrangible metals developed an increasing resistance to fracture extension — hence, a positive R-curve slope which may range from a slight rise for low-toughness metals to a high rise for high-toughness metals.

3. DT tests of short and long fracture run features provide E/A values which may be plotted versus crack extension Δa to define the R-curve slope.

4. The R-curve slope is the parameter which relates the DT energy values and the performance in the ETT.

5. In a more generalized sense, the R-curve slope should serve as the index for evolving analytical procedures of flaw size-plastic stress relationships for fracture extension.

6. The requirement for increasing the R-curve slope in structures depends on the compliance, flaw size, and energy available. For large flaws, high stresses, and high-compliance structural features, a material of high R-curve slope may provide sufficient resistance to fracture. Conversely, a material of low R-curve slope may provide an ineffective energy resistance barrier to fracture for small flaws, high stresses, and low-compliance structural features.

7. To define R-curve slopes, the test specimen must allow a significant fracture extension path of approximately several times the section thickness. This is defined as a plane stress configuration. Test specimens such as K_{Ic} type, Charpy V (C_v), and notched tensile bars have a plane strain configuration which prevents the development of the natural transition of stress state. Accordingly, such specimens are not suitable for determining the R-curve features of a metal.

This report presents data on an investigation of R-curve features for titanium alloys ranging from frangible to high fracture toughness types. Procedures based on plane strain and plane stress DT test specimen configurations have been developed for normalization of thickness constraint effects on fracture extension resistance. From analysis of the R-curve data, an expression is evolved which relates DT specimen geometry-fracture energy aspects to a material-dependent constant R_p. Indexing of the R-curve slope to the RAD provides for defining structural regimes of high, intermediate, and low compliance. Such a definition is the necessary first step to evolving quantitative RAD interpretation procedures for fracture-safe design with ductile titanium alloys.

In general, this report is concerned with evolving for titanium alloys a new approach to defining effective strength of flawed structures for ductility conditions which are outside the restricted limits of LEFM.

CONCEPT OF THE DT TEST CONFIGURATION FOR DEFINITION OF R-CURVE CHARACTERISTICS

One of the most basic requirements in fracture research is that the test specimens must model the behavior of structures which contain flaws. A second requirement is that the test specimens must provide fracture resistance measurement capabilities which are appropriate for the ductility level of the metal. In analyzing the significance of fracture test data, it must be recognized that the behavior of structures is derived from both the type of mechanical force system and the type of metal. The mechanical aspects involve the relative compliance characteristics which determine the stored energy available for fracture propagation. The metallurgical aspects involve the relative ductility characteristics which determine the energy absorption capacity (resistance) to fracture initiation and extension. These two factors act in concert to determine how the structure will respond to loading in the presence of flaws. The essence of fracture-safe design is the assessment of these interactions.

There are broad varieties of metal-type/structure-type combinations for which the bases of fracture-safe design relate directly to the conditions for fracture initiation. Accordingly, the specimen modeling must relate to conditions for initiation of fracture. There are equally broad varieties of metal-type/structure-type combinations for which the bases of fracture-safe design must be found in the conditions for extension of the fracture. For these cases, the specimen modeling must relate to the extension aspects.

The basic aim which determined the design of the DT test was the measurement of fracture extension energy. The general geometry of the test is similar to the fracture mechanics edge-notch-bend test. The thickness B of the test establishes the maximum attainable mechanical constraint for both methods. The sharp crack, or sharp tip notch, must be of sufficient depth so that the full mechanical constraint of the section size is attained. This feature is common for both tests. Correlations of DT fracture energies and K_{Ic} values have been documented for titanium alloys which feature a nonrising R curve (4). Such correlations should be expected because of the common geometric features. The first event (initiation) of crack extension is the significant aspect for measurement of valid K_{Ic} or K_{Id} characteristics. While the DT fracture extension energy is low for such metals, it increases with an increase in the K_{Ic}/σ_{ys} ratio because the related plastic zone size increase is common for both tests. In effect, the DT test is an inexpensive method for indexing the K_{Ic}/σ_{ys} ratio for frangible metals. The correlations with fracture mechanics tests involving increased thickness, B, dimensions provide for indexing to K_{Ic}/σ_{ys} ratios in excess of those which relate to DT specimens of small thickness dimensions.

The foregoing discussions described the use of the DT test in measurements of plane strain fracture toughness. The relatively long fracture extension path of the DT test also provides for measurement of plane stress fracture toughness. This feature may be understood in terms of the effects of test specimen configurations. Figure 2 presents schematic drawings for three types of fracture test configurations. The top schematic drawing labeled 1 illustrates a fracture mechanics test which is configured and instrumented to detect the conditions for the initial extension of a crack. Frangible metal is thus characterized by the K_{Ic} or K_{Id} parameters. A ductile metal of steeply rising R-curve features would be "characterized" by a K_Q (invalid) measurement.

The schematic drawing labeled 3 at the bottom of the figure represents the standard DT test geometry noted as a plane stress configuration. The feature of this configuration is the provision of sufficient fracture extension path to allow the development of plane stress fracture toughness to whatever degree that is characteristic of the metal. The drawing indicates the fracture extension transition from a small plastic zone at the crack tip (plane strain) to a large plastic enclave (plane stress), which is characteristic of a ductile metal.

The schematic drawing labeled 2 at the center of the figure illustrates a "reduced-run" version of the DT test. It is defined as a plane strain configuration because the growth of the plastic enclave is largely prevented by an inadequate length for fracture extension. There is no intent to claim that the conditions are fully equivalent to the plane strain constraint acting at the crack tip. The intent is to obtain an energy absorption measurement, by practical procedures, which is related to a condition which approaches plane strain constraint.

The graph at the top of Fig. 2 illustrates schematically the rise of the energy per unit fracture area (E/A) measured by the three test methods. The E/A value for the plane stress DT configuration should show an additional increase, which is related to loss of constraint as the plane stress state evolves. The three curves of the figure represent metals of frangible (flat curve), shallow-rise, and steep-rise R-curve characteristics. The slopes indicate the Δa rate of transition to lower levels of constraint, i.e.,

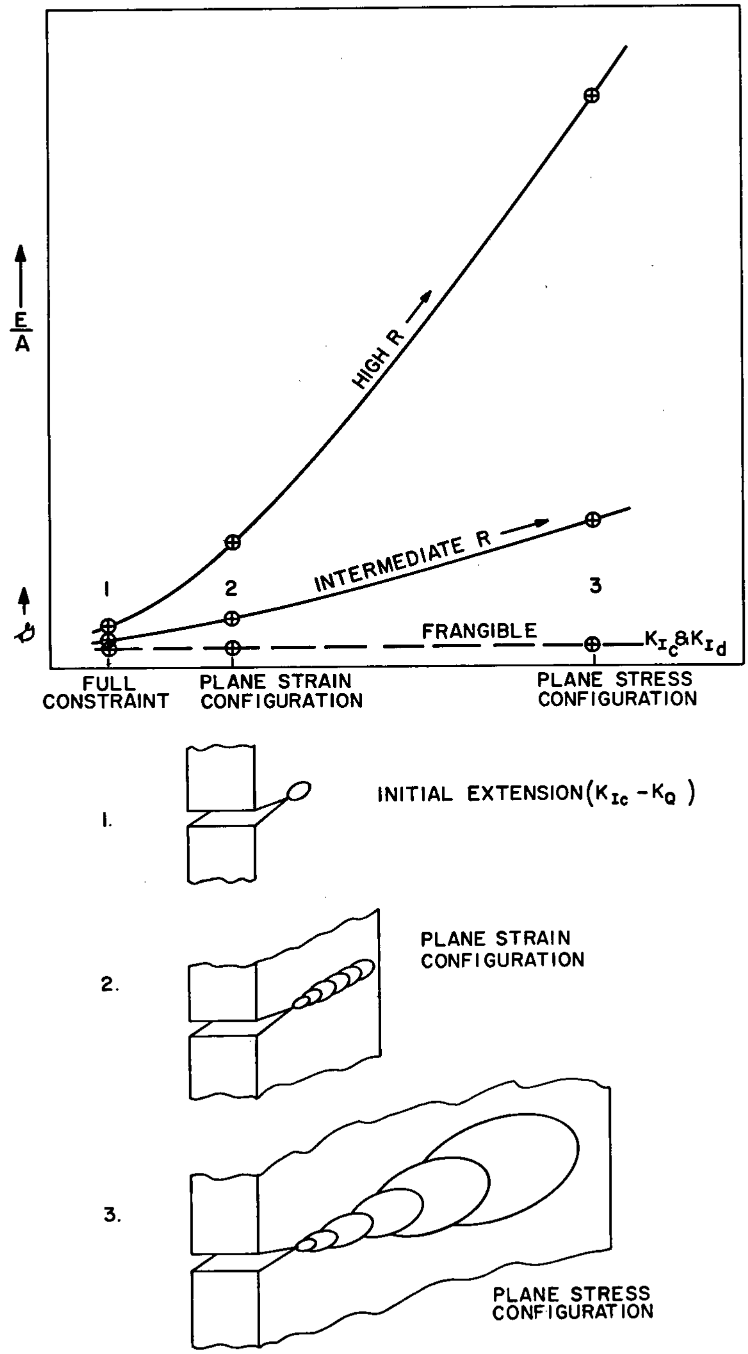

Fig. 2 - Definition of R-curve features by various tests, including (1) fracture mechanics tests which measure only features of initial crack extension, (2) the plane strain DT test specimen configuration, and (3) the standard DT test which represents a plane stress specimen configuration. The solid curves indicate increasing R, typical for alloys of intermediate and high resistance to fracture extension.

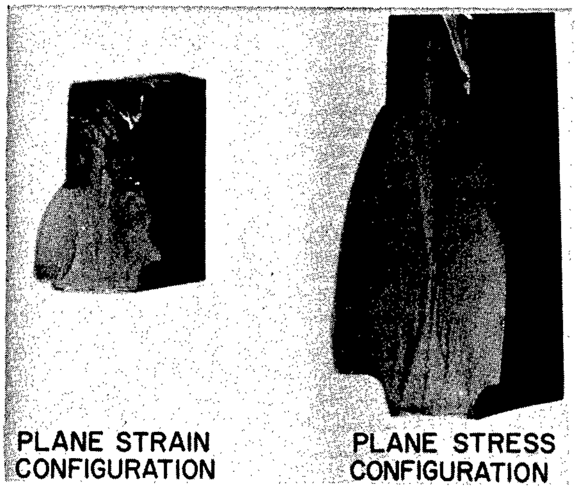

Fig. 3 - Illustration of the change in fracture appearance features of the DT test for the plane strain and plane stress specimen configurations. The fractures are typical of the plane strain to plane stress transition due to increased length of crack run for an alloy of high toughness.

rate of transition to plastic fracture. A practical procedure for measuring the R-curve slopes evolves from comparing the E/A values of the two DT test configurations labeled 2 and 3 in Fig. 2.

The changes in fracture appearance of the DT test in the two configurations are indicated by Fig. 3. The illustration relates to a titanium alloy of high-fracture toughness, steeply rising, R-curve characteristics. This is evident by the development of a full-slant fracture for the standard DT test configuration. However, the full-slant fracture features were not present in the plane strain configuration due to the limited fracture path length. It must be cautioned at this point that due to texturing effects fracture appearance is not as reliable an indicator of fracture resistance for titanium alloys as it is for steels and aluminum. While the same interpretations of fracture appearance may be made for most purposes, a few exceptions have been observed. Full shear fracture is not always accompanied by through-thickness yielding and gross lateral contractions for the titanium alloys, nor is full shear limited to the case of ductile fracture. Thus, the transition from brittle to ductile fracture with respect to amount of flat vs slant fracture for section thickness variations is not as well defined at this time for titanium alloys as it is for other materials. However, the materials selected for this study do feature increasing slant fracture with decreasing mechanical constraint.

DT TEST INVESTIGATIONS OF R-CURVE CHARACTERISTICS

We shall now present experimental data which involve the use of the DT test in several configurations to illustrate the R-curve aspects of various titanium alloys. Documentation of the basic significance of the two-configuration DT test approach emerges from this broad range of studies. Moreover, the meaning of DT energy values in the plane stress portion of the Ratio Analysis Diagram (RAD) becomes clear (1).

To study the R-curve features of these titanium alloys, the DT test specimen configuration was modified by introducing variations of fracture length for a given thickness.

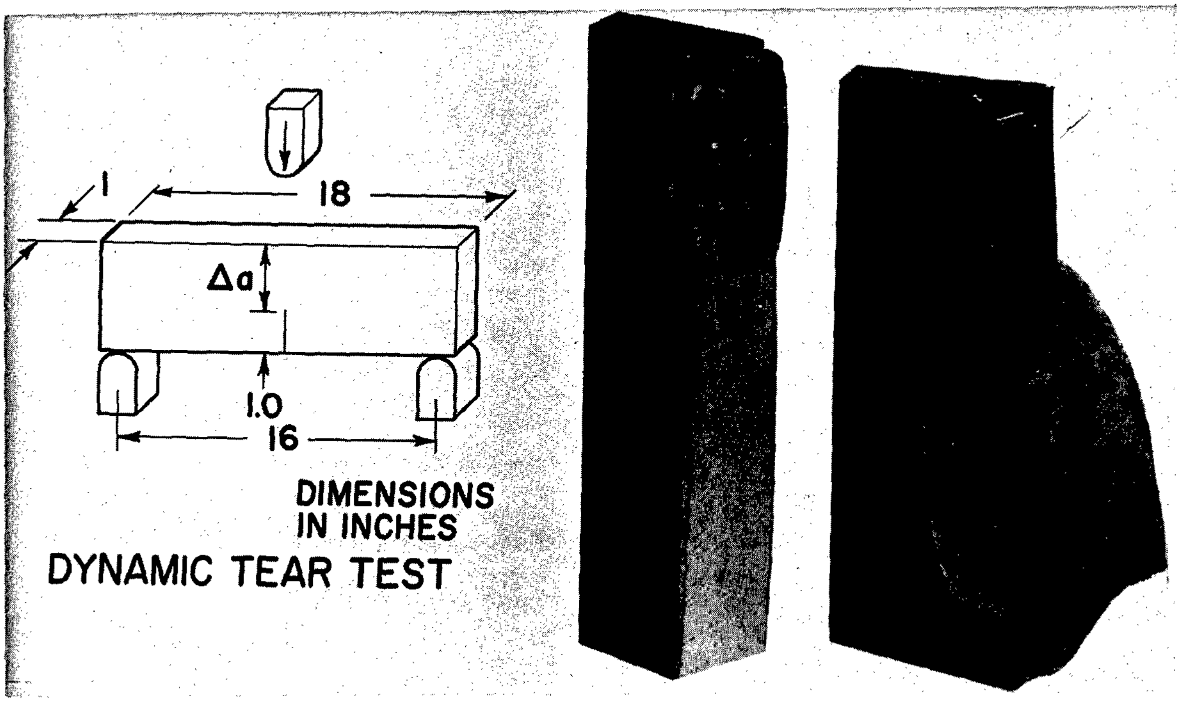

Fig. 4 - Schematic illustration of 1-in. DT specimen in which the fracture length (Δa) was varied to define R-curve features. Fracture surfaces of the standard 1-in. DT specimen configuration are illustrated for a frangible (left) and high-fracture-toughness titanium alloy (right).

Figure 4 illustrates the details of the test specimen design. The alloys selected for R-curve studies were 1-in.-thick plates, representing a wide range of yield strength and DT fracture toughness.

The mechanical properties of the titanium alloys used in this study are given in Table 1, and the chemical compositions are given in Table 2. A graphical representation of the range of properties is shown by plotting these data on the titanium RAD, Fig. 5. Eight of the alloys of this study involve plane stress fracture properties, as is shown by the location of the data points above the 0.63 ratio lines. This line is the upper limit of plane strain fracture toughness for 1-in.-thick plates. The reference code for these eight materials indicates the relative position of the alloy in the ductile region of the RAD, i.e., low (L), medium (M), and high (H). Alloy F-1 lies below the 0.63 ratio line and, therefore, should be characterized by the plane strain fracture toughness (K_{Ic}) scale.

The method of RAD plotting should be explained at this point. The section thickness B determines the maximum constraint that can be developed at the tip of a through-thickness crack (or plate-edge crack). The edge crack of fracture mechanics test specimens and of the DT test "models" a through-thickness crack. As the K_{Ic}/σ_{ys} ratio value increases, the crack tip plastic zone size also increases, i.e., increasing ratio signifies increasing metal ductility. Since a given section thickness provides a fixed value of mechanical constraint, there is a limit to the plane strain K_{Ic}/σ_{ys} ratio value that can be measured — for a 1-in. thickness this limit is 0.63. As the intrinsic metal ductility begins to exceed this ratio value, the mechanical constraint becomes inadequate for measurement of valid plane strain fracture toughness. With an additional increase in metal ductility, unstable brittle fracture cannot develop in such a plate, and some degree of yielding will occur, i.e., plane stress.

Table 1
Mechanical Properties of Test Materials

Composition	Code	YS (ksi)	UTS (ksi)	RA (%)	El (%)	Room Temp. DT Energy (ft-lb)	Remarks
Ti-6Al-6V-2Sn-2Mo	F-1	175.5	183.0	2.5	2	388	1750°F/1 hr/WQ + 1200/2 hr/AC
Ti-6Al-6V-2Sn-2Mo	L-1	138.1	161.3	11	7	899	As rolled
Ti-6Al-4V-2Mo	L-2	126.0	141.0	21	10	1037	As rolled
Ti-6Al-3V-1Mo	L-3	116.5	128.4	28	11	1052	As rolled
Ti-6Al-4Zr-2Mo	L-4	111.8	131	30	9	1109	As rolled
Ti-7Al-2Cb-1Ta	M-5	110.6	117.8	22	11	1443	As rolled
Ti-2Al-4Mo-4Zr	M-6	86.5	102.9	40	21	1509	As rolled
Ti-6Al-2Cb-1Ta-0.8Mo	H-7	114.5	125.5	28	12	2296	As rolled
Ti-6Al-4V	H-8	116.2	127.3	41	18	3050	As rolled

Table 2
Chemical Composition of Test Materials

Code	Al	V	Cb	Ta	Sn	Zr	C	N	Fe	Si	Mn	Mo	O	H
F-1	6.0	6.1	—	—	2.0	—	0.023	0.011	0.06	—	—	2.1	0.08	0.007
L-1	6.0	6.1	—	—	2.0	—	0.023	0.011	0.06	—	—	2.1	0.08	0.007
L-2							Not Available							
L-3	5.9	3.1	—	—	—	—	0.022	0.007	0.05	—	—	1.0	0.07	0.006
L-4							Not Available							
M-5	6.6	—	2.6	1.3	—	—	0.026	0.008	0.1	—	—	—	0.07	0.003
M-6	1.9	—	—	—	—	4.0	0.027	0.011	0.19	—	—	3.9	0.09	0.002
H-7	6.3	—	2.1	1.0	—	—	0.020	0.006	0.08	0.02	0.01	0.76	0.069	0.005
H-8	5.7	4.0	—	—	—	0.008	0.022	0.010	0.07	—	—	—	0.07	0.005

The ratio lines of the RAD define the section size that is required to develop plane strain. The absence of ratio lines above 0.63 in Fig. 6 indicates that the higher ratio values, depicted in the conventional RAD, have no meaning for plates of 1-in. thickness — hence, these are not shown. The significance of DT energy values, which lie above the 0.63 ratio line, is that they represent increasing resistance to plastic (plane stress) fracture. The index of increased resistance is the energy level of the DT value with respect to the ratio line value at the specified strength level, i.e., the energy span between the two values. This procedure represents a simplification; fracture resistance of these metals involves both σ_{ys} and DT energy, as will be discussed later. This indexing procedure for the test materials designates increasing resistance to fracture extension from L-1 (lowest value) to H-8 (highest value) in ascending order.

The RAD location of alloy F-1 signifies that plane strain fracture toughness K_{Ic} is the appropriate characterization parameter and that unstable fracture extension should result, following the "first event" of initial extension at the crack tip. The R curve for this alloy should be "flat" (nonrising). The test data confirmed these expectations — the E/A values for specimens of short- and long-run geometrical features remained constant at a low value, 120 ft-lb/in.^{2}, Fig. 6. The fracture appearance was flat, without evidence of shear lips, for all test configurations.

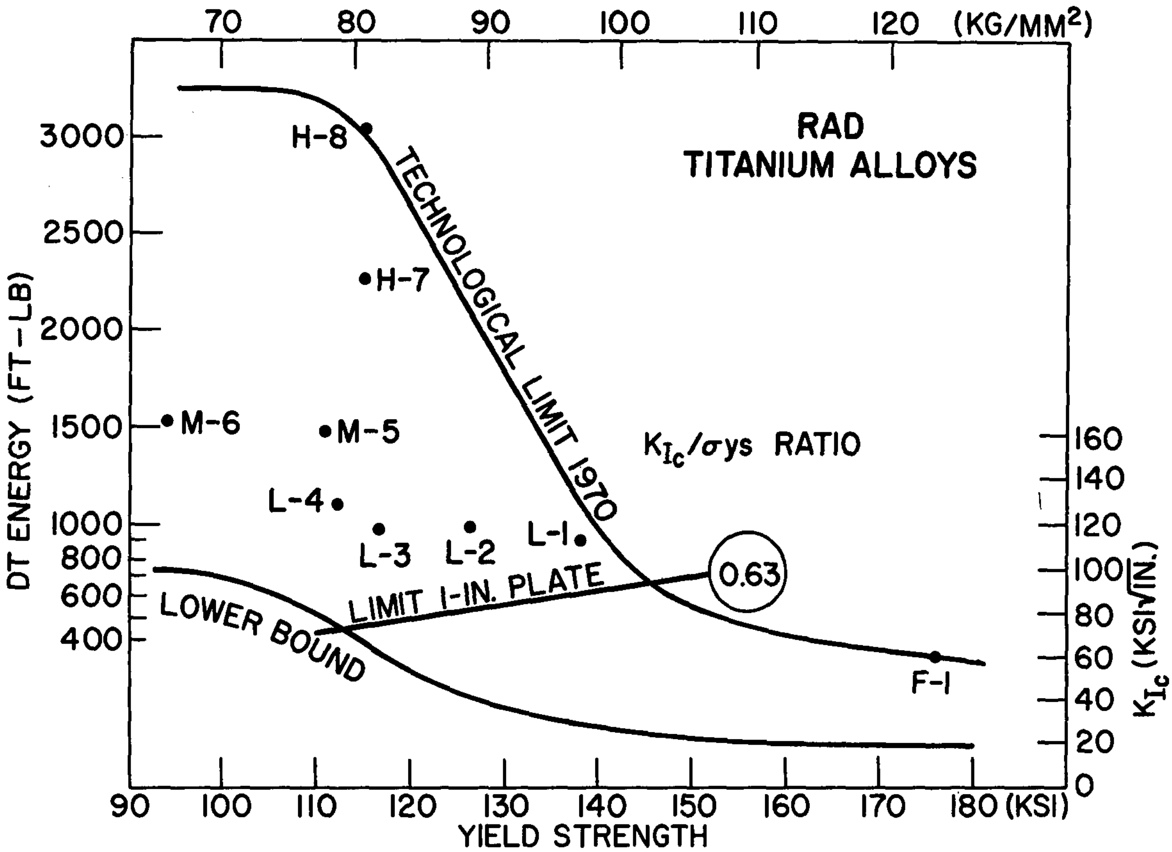

Fig. 5 - Location of the titanium alloys of this study in the plane stress and plane strain regions of the RAD. The K_{Ic}/σ_{ys} ratio line of 0.63 relates to the limit of frangible behavior for 1-in. thickness according to the expression $B = 2.5(K_{Ic}/\sigma_{ys})^2$.

The RAD location of alloy H-8 high in the plane stress region signifies a high level of plane stress fracture resistance. The R curve for this material would be expected to exhibit a steep slope, deriving from gross blunting of the crack tip and the formation of a large plastic enclave. The expected large increase in E/A with tear extension length is illustrated for alloy H-8 in Fig. 7. Changes in fracture appearance with increases in fracture extension result from the changes in DT configuration from the plane strain to the plane stress type. The series thus serves to "model" the natural processes of transition (decreasing mechanical constraint) from plane strain to plane stress with fracture extension. Each specimen provides an average E/A value for the limit of the allowed extension; i.e., the R curve is defined by integrated average values of E/A.

The RAD location of alloy L-1 low in the plane stress region signifies low fracture extension resistance. The R curve would be expected to exhibit a low slope, deriving from the slight blunting of the crack tip and the formation of a small plastic enclave. The expected behavior of this alloy is confirmed by the data presented in Fig. 8. The shallow R curve is indicative of a much slower buildup of E/A with increasing Δa as compared to the high toughness H-8 alloy described in Fig. 7. The fracture surfaces pictured above the curve demonstrate that this material does not attain conditions of full-slant fracture, as should be expected from the limited rise of the R curve. Thus, the fracture extension resistance is only marginally above that of frangible materials. These various features are predictable from the RAD location, barely above the 0.63 ratio line for plane strain.

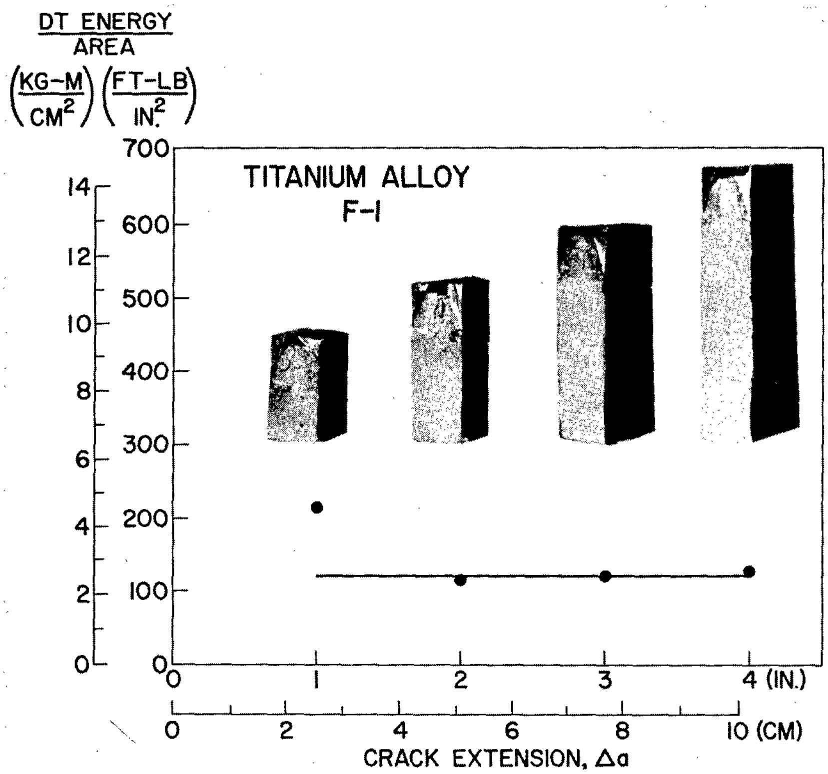

Fig. 6 - R-curve features and fracture appearance for a frangible alloy. Note the flat R curve and lack of a transition from flat plane strain fracture with increased Δa which is typical for brittle material.

The characteristic R curves (E/A vs Δa) for the nine titanium alloys included in this study are shown in Fig. 9. The R-curve relationships with respect to crack tip blunting and plastic enclave features described for the preceding examples apply to the alloys which show rising R curves. This is indicated by the intercept values which rise with increased slope of the R curves.

A comparison of the L-3 and L-4 alloys indicates identical R curves and different values of yield strength. These aspects are independent parameters for different alloys and for different orientations in the same material. The DT energy value is directly related to the R-curve slope; i.e., alloys of different yield strengths will feature the same R-curve slope if the DT energy values are the same.

On the RAD of Fig. 1, a constant critical flaw size-stress level condition is denoted by a constant K_{Ic}/σ_{ys} ratio line; increases in yield strength require increases in K_{Ic} to maintain the ratio at a constant value. The slope of the ratio line with respect to the DT energy scale signifies that increased DT energy absorption is required to offset the effects of higher K levels resulting from increases in yield strength. Similarly, increased fracture extension resistance (R-curve slope) is required to offset the increased level of allowable plastic stresses (acting on a given flaw) which result from increasing yield strength. This requirement must be met by increasing the DT energy value as a function of increasing yield strength.

In simple terms, the prevention of fracture extension for a specified flaw size will require increased R-curve slope (increased DT energy) due to the increase of allowable

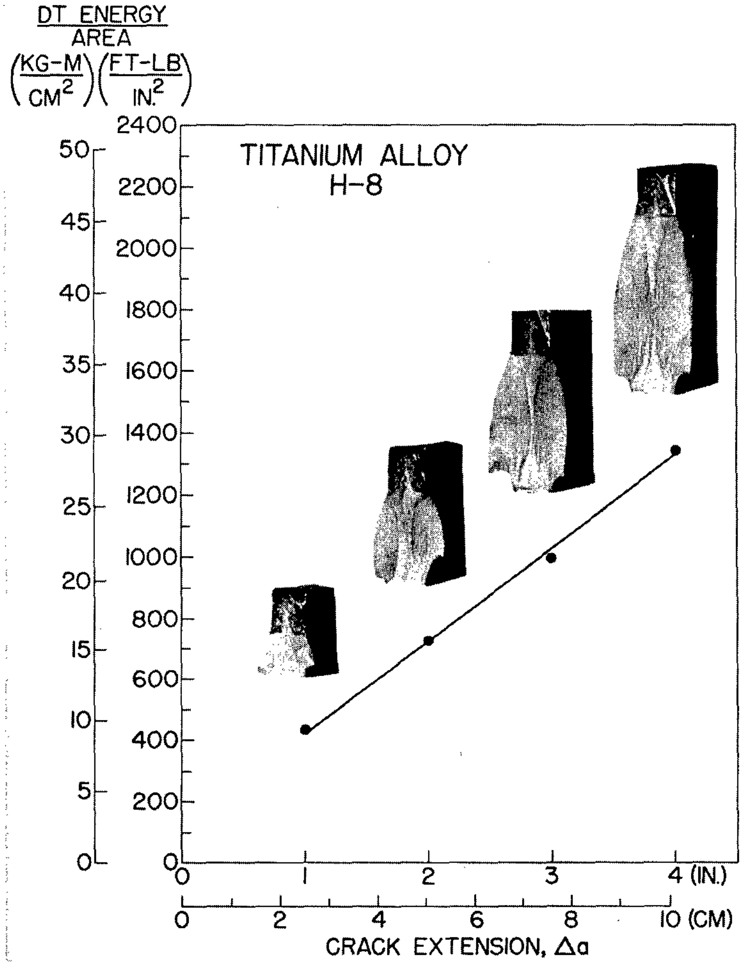

Fig. 7 - R-curve features and transition from plane strain to plane stress fracture with fracture extension for a high toughness alloy

stress levels which result from increased yield strength. The analytical definition of specific design requirements for fracture extension resistance (in terms of R-curve slopes or the equivalent DT energy) must be related to flaw size, allowable stress level, and compliance characteristics of the structure. These relationships must be evolved by correlations with structural prototype tests, for reasons which are explained later.

Note that the significance of the DT data points must be related to section size. All DT data of Fig. 1 are for 1-in. DT specimens. If the 1-in. DT specimen is taken from a 2.5-in. plate, the appropriate ratio line which relates to the plane strain limit for the plate is 1.0. Table 3 defines the plane strain fracture toughness limits in terms of K_{Ic}/σ_{ys} ratios for given values of thickness. These thickness-related limits are plotted as ratio lines in the RAD of Fig. 1. Constraint effects due to section size are analyzed in this fashion and represent a basic consideration in the use of the RAD. The degree of plane stress fracture toughness for the 2.5-in. plates should then be related to the energy values which lie above 1.0 ratio line.

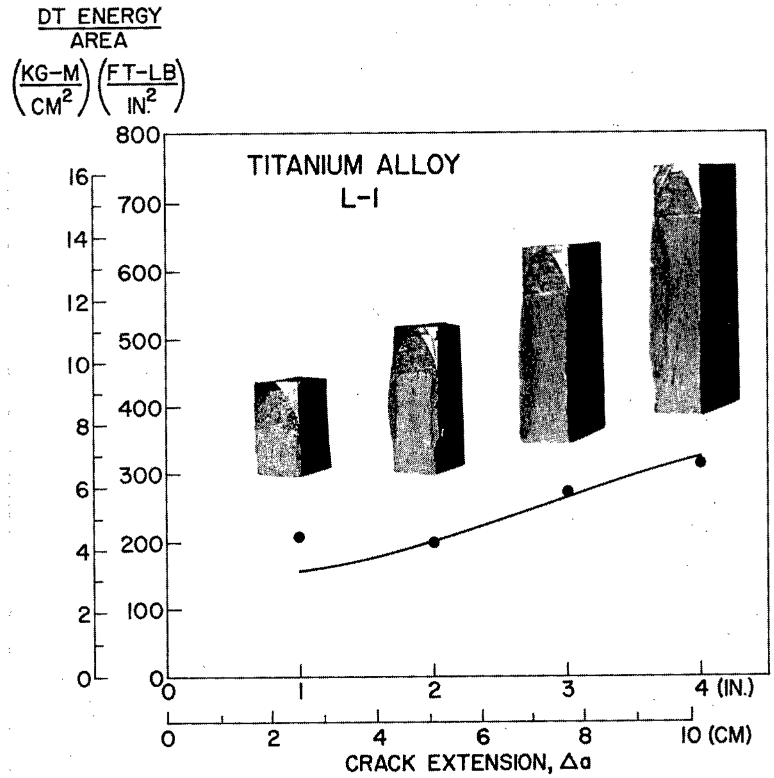

Fig. 8 - R-curve features and fracture appearance for an alloy of low resistance to fracture extension

Table 3
Plane Strain Limits for Through-Thickness Cracks
(Plate Thickness B $\geq 2.5(K_{Ic}/\sigma_{ys})^2$)

Plate Thickness B (in.)	Maximum Ratio K_{Ic}/σ_{ys} Value for Plane Strain ($\sqrt{\text{in.}}$)
0.5	0.45
1.0	0.63
1.5	0.77
2.0	0.89
2.5	1.00
3.0	1.09
4.0	1.26
6.0	1.54
10.0	2.00

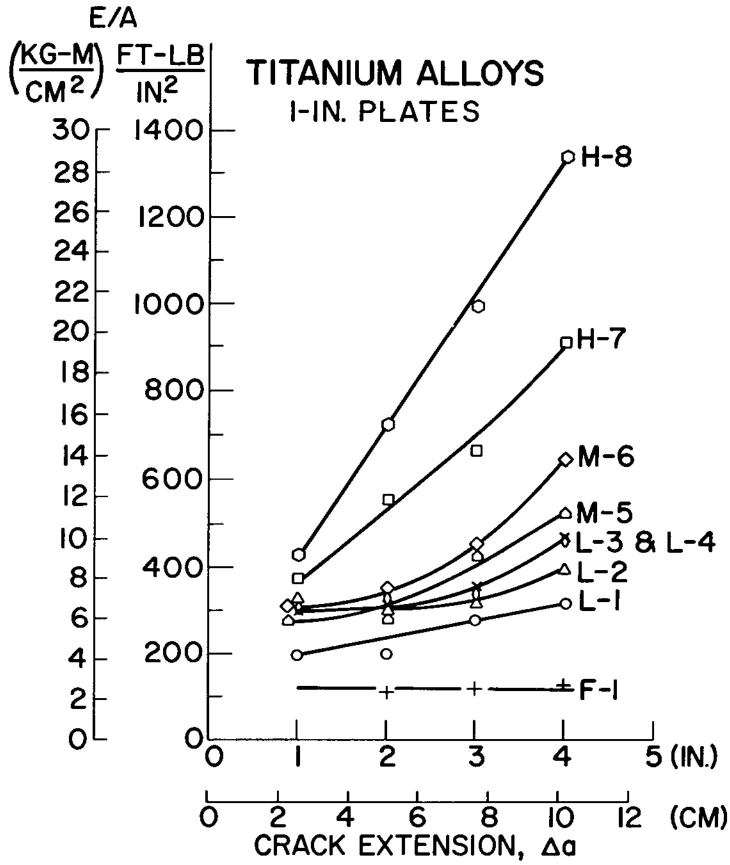

Fig. 9 - Summary of R-curve features for titanium alloys ranging from frangible (F-1) to high fracture toughness (H-8)

ANALYSIS OF R-CURVE DATA

An analysis of the R curves was made by plotting the data on log-log coordinates, which results in the straight-line relationships shown in Fig. 10. The slopes of the lines vary between only 1.4 and 1.8 for these eight alloys with an average value of 1.6. A relation is thus inferred where the energy $E = R_p(\Delta a)^{1.6} f(B)$. The term R_p is a constant that defines the position of the curve on the log-log plot, which is different for each alloy, Δa is the crack extension, and the exponent 1.6 is the average slope of the log-log plots. The $f(B)$ term represents a function of the specimen thickness B. The R curves (E/A values) for the 1-in.-thick titanium alloy plates are related to Fig. 10 by dividing the E value by the fracture area of the specimen, i.e., $R = E/A = R_p(\Delta a/B) f(B)$.

These data all relate to a single value of thickness; establishment of generalized relationships, including the thickness B, requires tests involving wide variations of both Δa and DT test specimen thickness. The $f(B)$ relationships which are currently being established for steels appear to be approximately $B^{1/2}$. The equation for steels is $E = R_p B^{1/2} (\Delta a)^2$. The B relationships for titanium alloys will be the subject of future research.

The ability to express the characteristic R-curve features by an empirically derived equation, involving only specimen dimensions and a material-dependent constant R_p, is most valuable since it will permit characterization of materials in any thickness and resistance level by a single procedure.

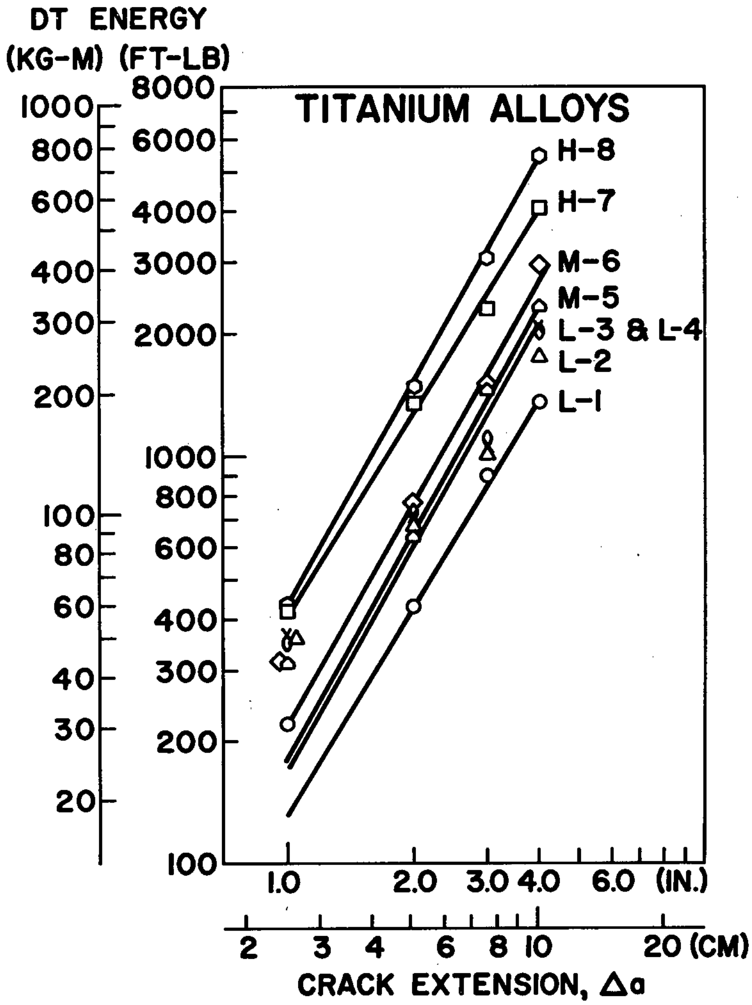

Fig. 10 - Log-log plot of R-curve data presented in Fig. 9. The straight-line relationships can be expressed by the equation $E = R_p(\Delta a)^{1.6} f(B)$, where E is the DT energy, R_p is a material-dependent constant signified by the position of the relationship in the plot, Δa is length of crack extension, and B is thickness. The $f(B)$ term requires establishment through R-curve studies involving different B values.

The foregoing analyses do not imply that the resistance to fracture extension increases indefinitely with extension. The analyses apply only for the extension interval which involves the fracture mode transition from plane strain constraint at the crack tip to the characteristic plane stress mode of the metal. The R-curve rise which derives from this transition provides the "barrier" to fracture extension, and the analyses relate directly to this factor. Following completion of the fracture mode transition, the R curve should "saturate," i.e., level out to a characteristic fixed level of resistance to continued extension (see introductory discussions).

The R-curve E/A plots do not level off because the fracture run is not extended significantly past the point of attainment of the characteristic plane stress fracture mode for the metal. Thus, the E/A value represents an average of the plane strain and plane stress portions of the fracture. To attain a leveling off additional fracture extension would be required, so that the average E/A value would be determined primarily by the plane stress portion of the total fracture.

It is emphasized that the characteristic fracture mode is in fact attained by the standard DT specimen. This fact has been confirmed by extensive comparison of the fracture mode displayed in the ETT (with a fracture run of 8 in. for a 1-in.-thick plate) and the fracture mode attained by the DT test specimens. The fracture modes were found to be identical for both test procedures in all cases. These comparisons confirmed that the DT test provided a proper definition of the plane stress fracture features of the metal and decided the design of the test geometry. The relative slopes of the R curves determined by the described procedures provide an adequate basis for characterizing the fracture extension resistance. Additional refinements, such as following the E/A rise to saturation, would not provide significant improvement in the desired characterization of slopes, as will be described below.

Previous discussions have emphasized that information derived from the characterization of R-curve slopes should provide for correlations with prototype structural tests. These correlations should result in empirical calculation capabilities for fracture-safe design based on critical plastic stresses or plastic strains for fracture extension.

Unfortunately, a generalized analytical approach which would apply to all types of structures is not feasible, except as evolved by structural prototype testing. Generalized analytical approaches, based on first principles, run into complications of structural features which cannot be analyzed directly by mechanical principles. Thus, the structural response must be analyzed on a case basis. For example, such studies are being conducted for steel gas transmission lines and various types of steel pressure vessels. If a proper sequence of similar tests is conducted for different generic structural configurations (flat plate structures, etc.) involving titanium alloys, a generalized analytical framework keyed to simple laboratory tests should emerge.

ENGINEERING SIGNIFICANCE OF R CURVES

Rising R curves of steep slope provide positive evidence that unstable fracture extension in the brittle mode is not possible for the section thickness B represented by the test specimen. Since the effects of increased section size are rapidly becoming understood, the R-curve slopes for specimens of small thickness (say 5/8 or 1 in.) can be translated to predictions of fracture extension characteristics for plate sections of greater thickness in engineering structures. R-curves which are flat or of very low slope indicate that unstable fracture propagation is possible. If fracture instability is possible, there is no need to consider the structural aspects of compliance — either rigid or compliant structures will be subject to fracture initiation at predictable values of K_{Ic} or K_{Id} as applicable. For conditions of low slope, the K_c parameter may apply; however, there are no reliable procedures for analytical definition of the initiation conditions for this case.

Of equal importance is the classification of the significance (or not) of K definitions for fracture initiation. For a metal featuring steeply rising R curves, K parameters for fracture initiation are of no consequence, no matter how elegantly described as being K_Q (where Q is any nonstandard designation) or "lower bound" values. If the fracture resistance cannot be expressed as being a valid K_{Ic} or K_{Id} type, no analytical value can be derived at the present state of knowledge.

INTEGRATION OF R-CURVE DEFINITIONS INTO THE TITANIUM RAD

The titanium RAD integrates the mechanical and metallurgical factors relating to fracture by "zoning" in terms of both aspects. Definition of R-curve factors provides for additional analytical possibilities for these integrations by permitting RAD zoning with respect to structural aspects. The fracture-safe design process requires total integration of all three factors, either sequentially or directly. The feasibility of a direct, integrated analysis has been demonstrated for the steel RAD (2) and the aluminum RAD (3). The same feasibility can now be demonstrated for the titanium RAD.

The plane strain and plane stress DT specimen configurations provide for indexing the significance of the zonal region of the RAD which relates to plastic fracture. When the indexing is to ratio lines, or below, the R curve is flat because unstable, plane strain fracture extension follows the initial instability. This instability corresponds to fragmenting and shattering of the plate specimen for elastic loads in the ETT. Such behavior is illustrated for 1-in.-thick plate noted as frangible in the RAD of Fig. 11. Indexing to increasing values of DT energy above the ratio line region signifies a zone of increasing R-curve slope. The increased R-curve slope corresponds to increased plastic deformation before fracture in the ETT as noted in Fig. 11 for materials of low, intermediate, and high plastic fracture resistance. Thus, the engineering significance of the RAD is amplified while retaining the inherent simplicity of a generalized diagram indexed by practical test procedures.

The metallurgical zoning of the RAD, Fig. 1, which was discussed previously (1) in terms of significance to the ratio lines region can now be related to aspects of fracture extension resistance for the region above the ratio line for the thickness involved.

The R-curve indexing to the RAD adds the feature of zoning with respect to the <u>type of structure.</u> For example, low R-curve slope regions of the RAD represent plane stress fracture resistance which may be adequate for relatively noncompliant structures. With increase in compliance features and total available structural energy, there is a need to select titanium alloys from the high R-curve slope locations of the RAD. Thus, the high R-curve slope regions may be defined as the high-compliance/high-total-energy structural regime. Conversely, the low R-curve slope regions may be defined as the low-compliance/low-total-energy structural regime. Regions below the ratio line, which applies to the specific section size, may be defined as the unstable fracture regime (for any type of structure).

SUMMARY

In Ref. 2, a case was presented for the redirection of fracture research to neglected issues of major engineering importance. These issues involve steels which are neither brittle nor highly ductile — otherwise defined as being of "low-shelf," "low-tearing-energy," or "low-plane-stress fracture toughness" features. In this report, a similar case has been made for titanium alloys. The potential for failure increases with increasing flaw size, applied stress, compliance characteristics of the structure, and total load energy acting on the structure. The metal-type/structure-type relationships must be analyzed to arrive at satisfactory fracture-safe design solutions.

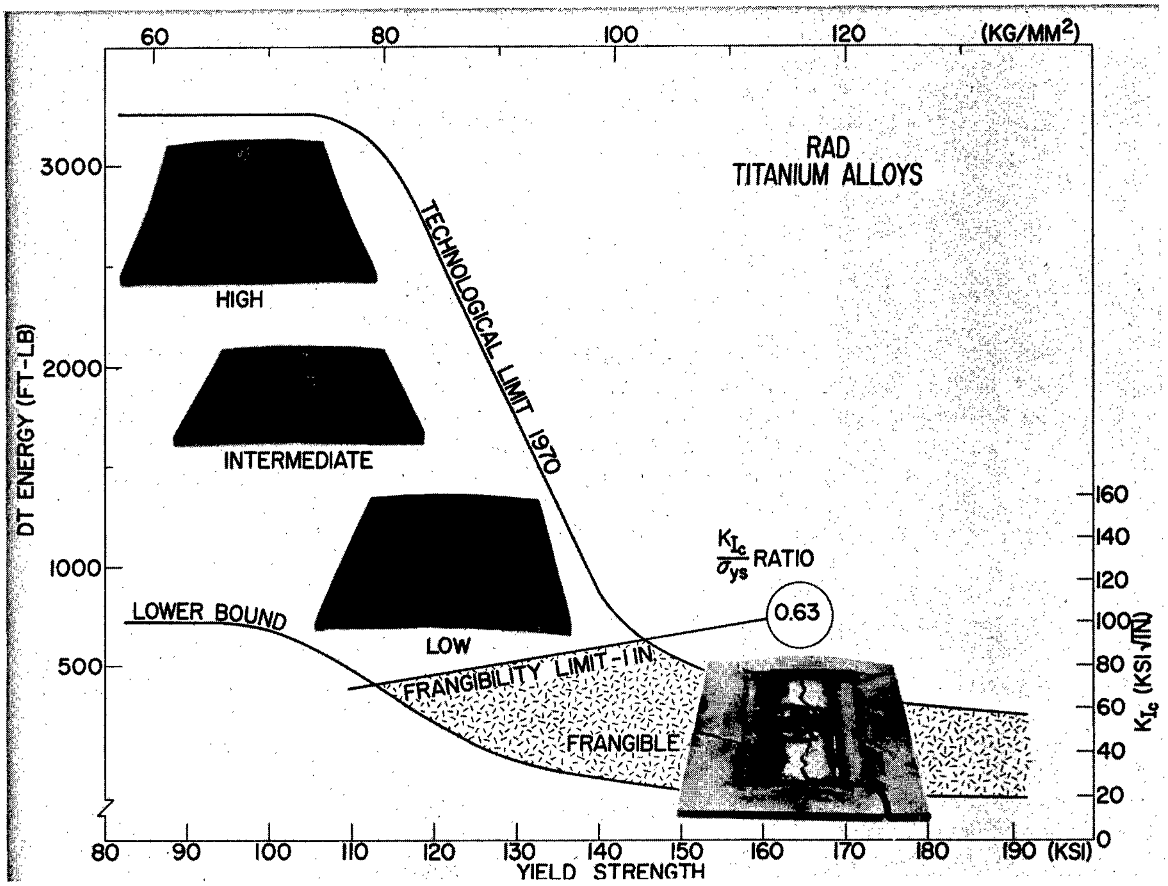

Fig. 11 - Different levels of fracture extension resistance with respect to the RAD position by ETT performance. ETT specimens are sufficiently large and have a long crack run so that a complaint structure is effectively represented. The increase in strain required for fracture in the ETT in the RAD region above the frangibility limit is an index of the fracture resistance of the metal.

The basic parameter of importance to the safety of compliant titanium structures is the specific fracture extension resistance of the material. This parameter is defined by the R curve of the metal which relates the degree of increase in fracture extension resistance (R) with movement of the crack (or tear) away from the initial crack tip. The R-curve features of titanium alloys may range between the two broad extremes of nonrising and steeply rising. A nonrising R curve signifies a condition such that the resistance to fracture entirely depends on the first unit extension, i.e., initiation. After the first unit extension, there is no further increase in fracture resistance, and the fracture process is defined as unstable (fast-brittle fracture). A rising R curve signifies an alloy which breaks down the initial plane strain constraint to plastic flow at the crack tip, in the course of fracture extension. Thus, the mechanical state acting as fracture extension occurs changes from plane strain to plane stress.

The most important consequence of increased R-curve slope is the effect on the energy that must be expended by the structure to extend the fracture during the period of change from plane strain to plane stress. The distance involved in the transition of mechanical states is approximately several times the section thickness, depending on the R-curve slope. Large flaws, high stresses, and high-compliance structural features may be ineffective in breaking through the energy resistance barrier provided by a high-slope R-curve alloy. Conversely, small flaws, high stresses, and high-compliance structural features may easily break through the energy resistance barrier provided by a low-slope R-curve alloy. The objectives of the new research are to establish guiding principles which provide for solving the relationships between structural features and R-curve characteristics for titanium alloys. These solutions cannot be evolved in the absence of test methods which define R-curve features.

Fracture mechanics tests define conditions for initial extension in terms of K factors. Thus, such tests cannot provide a definition of R-curve characteristics. Accordingly, there is a basic requirement for using energy-measuring test methods which index the fracture energy increase with crack (or tear) extension.

The DT test in the standard configuration provides sufficient crack extension distance to index the degree of change in mechanical constraint — plane strain at the crack tip to whatever degree of plane stress that is developed by the metal. Thus, the DT energy value provides an index of the R-curve slope for titanium alloys. The standardized specimen is defined as the plane stress DT configuration because the length of run allows the development of the plane stress state, which is characteristic of the metal. If the metal is brittle and fractures in a plane strain mode, correlations may be made between DT energy and K_{Ic} or K_{Id} parameters. These correlations reflect that the plane stress transition did not evolve for reasons of intrinsic metal properties even though the transition was allowed by the specimen geometry.

The basic virtue of the DT test is that it can index all degrees of transition in mechanical states. This feature also permits direct measurement of the R-curve features by reducing the length of fracture run. When the length of run is decreased to a distance equal to the specimen thickness, a close approach to flat fracture is developed because the plane strain state conditions dominate. The short-run version is thus defined as the plane strain DT configuration.

The primary purpose of this report was to introduce the subject of R curves for titanium alloys and their significance to metal-type/structure-type aspects of fracture-safe design. Thus, the presentation of research experiments was limited to illustrative examples of R curves determined by various DT specimen techniques.

The illustrative examples focused on the selection of titanium alloys from various locations in the RAD. The selections were made on the basis of a spread of strength levels and a spread of DT energy levels. The following results emerged:

1. High-DT energy alloys located in the top region of the RAD are characterized by steep R curves. This should be expected because the high DT energy RAD location signifies a fracture extension transition to high-energy intensity plane stress.

2. Low DT energy alloys located barely above the ratio line limit for plane strain for the section size (0.63 for 1-in. thickness) exhibit very slight R-curve rise. This should be expected because the transition involved is to a low order of plane stress — barely above the plane strain (brittle) level.

3. Alloys of intermediate DT energy level values demonstrate R curves of intermediate rise features.

The R-curve indexing capabilities of the DT test adds another dimension to the use of this versatile test procedure for titanium alloys. Added meaning is provided for the RAD system of fracture-safe design analysis. Previously, this system was of primary importance for analyzing conditions relating to brittle fracture, or for its preclusion. With the additional analytical potential evolving from R-curve interpretations, applications may now be made for conditions of semiductile or ductile fracture, i.e., plane stress. In particular, the RAD system fits especially well to analyses of titanium alloys in relation to structures of high-compliance features. In simple terms, structural requirements involving increasing degrees of fracture extension resistance may be met by moving to metals located in higher regions of the RAD.

Knowledge of the R-curve slopes for the various locations of the RAD represent a "third dimension" to this integrated reference system. For example, alloys which were described as being "barely above the ratio line for the thickness involved" would be illogical candidates for construction of high-compliance structures. The question of "how high above the ratio line is enough" should find its answer in detailed definition of the R-curve slope.

ACKNOWLEDGMENT

The authors express their appreciation to the Office of Naval Research for providing the financial support for the research studies of this report.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

FRACTURE EXTENSION RESISTANCE (R-CURVE) CONCEPTS FOR FRACTURE-SAFE DESIGN WITH NONFRANGIBLE TITANIUM ALLOYS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Special summary and interpretive report

5. AUTHOR(S) *(First name, middle initial, last name)*

R.W. Judy, Jr., and R.J. Goode

6. REPORT DATE August 16, 1971	7a. TOTAL NO. OF PAGES 24	7b. NO. OF REFS 4

8a. CONTRACT OR GRANT NO. NRL Problem M01-25 b. PROJECT NO. RR 007-01-46-5432 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7313 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research) Arlington, Virginia 22217

13. ABSTRACT

New procedures have been evolved to characterize the fracture extension resistance of nonfrangible structural titanium alloys. Fracture extension resistance is defined by the increase in plastic work energy required to propagate a crack. The resistance parameter is the R-curve slope of the metal.

Characteristic R-curve features are presented for titanium alloys ranging from frangible to high fracture toughness types. The R-curve slope determines the plastic work energy expended for fracture extension in structures, as confirmed by Explosion Tear Test results. The R curves are defined by the use of the Dynamic Tear test specimen. Indexing the R-curve slopes to the Ratio Analysis Diagram (RAD) for titanium provides definition of the metal capabilities for use in structures of low, intermediate, and high compliance features. This integration of structural aspects with the mechanical and metallurgical aspects of the RAD should provide for significant advances in generalized fracture-safe design of titanium structures rising nonfrangible alloys.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Titanium alloys						
DT test						
R-curve						
Fracture extension resistance						
Ratio Analysis Diagram						