NRL Formal Report 7262

FRACTURE EXTENSION RESISTANCE (R_CURVE) FEATURES OF NONFRANGIBLE ALUMINUM ALLOYS

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

Strength of Metals Branch
Metallurgy Division

Naval Research Laboratory
June 11, 1971

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) FEATURES OF NONFRANGIBLE ALUMINUM ALLOYS

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

An interim report on a continuing NRL problem.

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

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

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 11, 1971	25	3

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 7262 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, Va. 22217

13. ABSTRACT

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

Characteristic R-curve features are presented for aluminum 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 using the Dynamic Tear test specimen in two configurations involving a "short" and standard fracture extension length. Indexing the R-curve slopes to the Ratio Analysis Diagram (RAD) for aluminum provides a definition of the capabilities of the metal 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 significantly advance the generalized fracture-safe design of aluminum structures using 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
Aluminum alloys Fracture extension resistance Dynamic Tear test R curve Fracture tests Fracture-safe design Interpretations of fracture tests						

CONTENTS

ABSTRACT

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

Characteristic R-curve features are presented for aluminum 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 using the Dynamic Tear test specimen in two configurations involving a "short" and standard fracture extension length. Indexing the R-curve slopes to the Ratio Analysis Diagram (RAD) for aluminum provides a definition of the capabilities of the metal 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 significantly advance the generalized fracture-safe design of aluminum 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 February 17, 1971.

LIST OF SYMBOLS

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, K_x	questionable or invalid values of K due to excessive plastic deformation of the crack tip
a	depth of surface or edge crack, or half length of surface 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
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

FRACTURE EXTENSION RESISTANCE (R-CURVE) FEATURES OF NONFRANGIBLE ALUMINUM ALLOYS

INTRODUCTION

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 transition, termed the "strength" transition, is best represented by the Ratio Analysis Diagram (RAD) summarization of fracture toughness characteristics, shown in Fig. 1 for the generic families of aluminum alloys. From the RAD the strength transition can be seen to correspond to the 30- to 60-ksi yield strength range.

Dynamic Tear (DT) and linear-elastic fracture mechanics (LEFM) plane strain K_{Ic} test values have been used to provide the fracture toughness indexing to the RAD. However, 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. For example, for 1.0-in.-thick plates the applicable ratio level is 0.63. Materials of DT (or K_{Ic}) energy values indexing to ratios below 0.63 would be frangible (brittle). Metals which fracture at DT test values above this ratio line do not fracture in a plane strain mode and therefore cannot be characterized by K_{Ic} parameters.

Early studies of the significance of DT values on the nonfrangible (plane stress or ductile fracture region) were conducted using the Explosion Tear Test (ETT). These investigations showed that a very large increase in resistance to fracture extension was developed for aluminum 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 the development of a large amount of plastic strain (bulging) in the presence of a 2T flaw in the ETT plate. Similar demonstrations were made for steels and titanium in relation to their respective RAD, strength-transition plots.

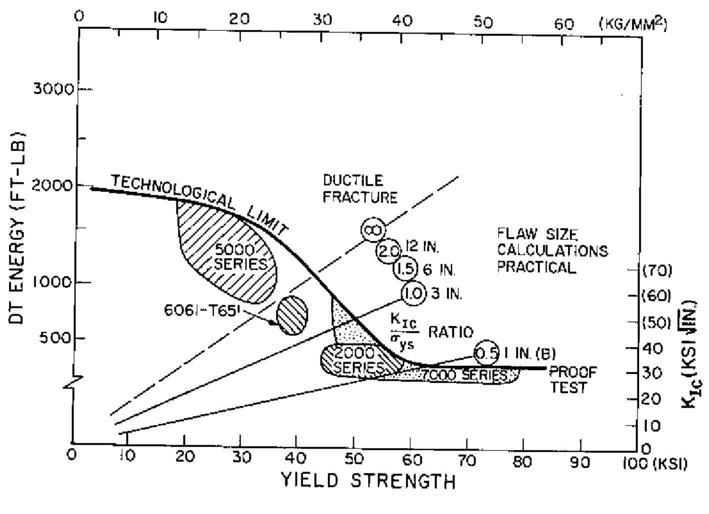

Fig. 1 - Ratio Analysis Diagram (RAD) for generic families of structural aluminum alloys

These studies may be recognized as involving a correlation between a parameter measured by a practical low-cost laboratory fracture test (the DT test) and a structural prototype test involving a large plate. That is, the ETT "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 the metal was frangible and that unstable crack extension would occur at elastic stress levels.

These early studies were interrupted by investigations of the limits of applicability of LEFM, 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 ratio line region. The first objective was to investigate the basic reason for the excellent correlations with the ETT. Obviously this reason had to be in the increase of fracture extension resistance of the metal, but there was no way of accurately representing this mechanical effect in terms of a generalized parameter.

These studies were first begun for steels and culminated in determining that the parameter of primary consequence is the slope of the fracture extension resistance curve (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. 1. For purposes of this report, a summary of the findings as evolved from the steel studies is presented:

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

2. Nonfrangible metals develop 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 metals of high toughness.

3. DT tests of short and long fracture run features provide E/A values which may be plotted versus crack extension $\underline{\Delta a}$ 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. Generally, 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 R-curve slope in structures depends on the compliance features, flaw size, and energy available. For large flaws, high stresses, and high compliance structural features, a material with a high R-curve slope may provide sufficient energy resistance barrier to fracture. Conversely, a material with a low R-curve slope may provide an ineffective energy resistance barrier to fracture for small flaws, low stresses, and low-compliance structural features.

7. For purposes of defining R-curve slopes, the test specimen must allow a significant fracture extension path of approximately several times the thickness.

This report presents data on an investigation of R-curve features for aluminum alloys ranging from frangible to high fracture toughness types. Procedures have been developed for the 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 definition is the necessary first step to evolving quantitative RAD interpretation procedures for generalized fracture-safe design involving both frangible and nonfrangible aluminum alloys.

In general, this report is concerned with evolving new procedures for defining the effective fracture extension resistance of metals for ductility conditions which are outside the restricted limits of LEFM.

CONCEPT OF THE DT TEST CONFIGURATION ADJUSTMENT PROCEDURE 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 of the structure which determine the level of the fracture extension force system. 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 is the measurement of fracture extension energy. The general geometry of the test is similar to that of 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 sufficiently deep to attain the full mechanical constraint of the section size. This feature is common for both tests. Excellent correlations of DT fracture energies and K_{Ic} values have been documented (2) for aluminum alloys which feature a nonrising R curve. 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}-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

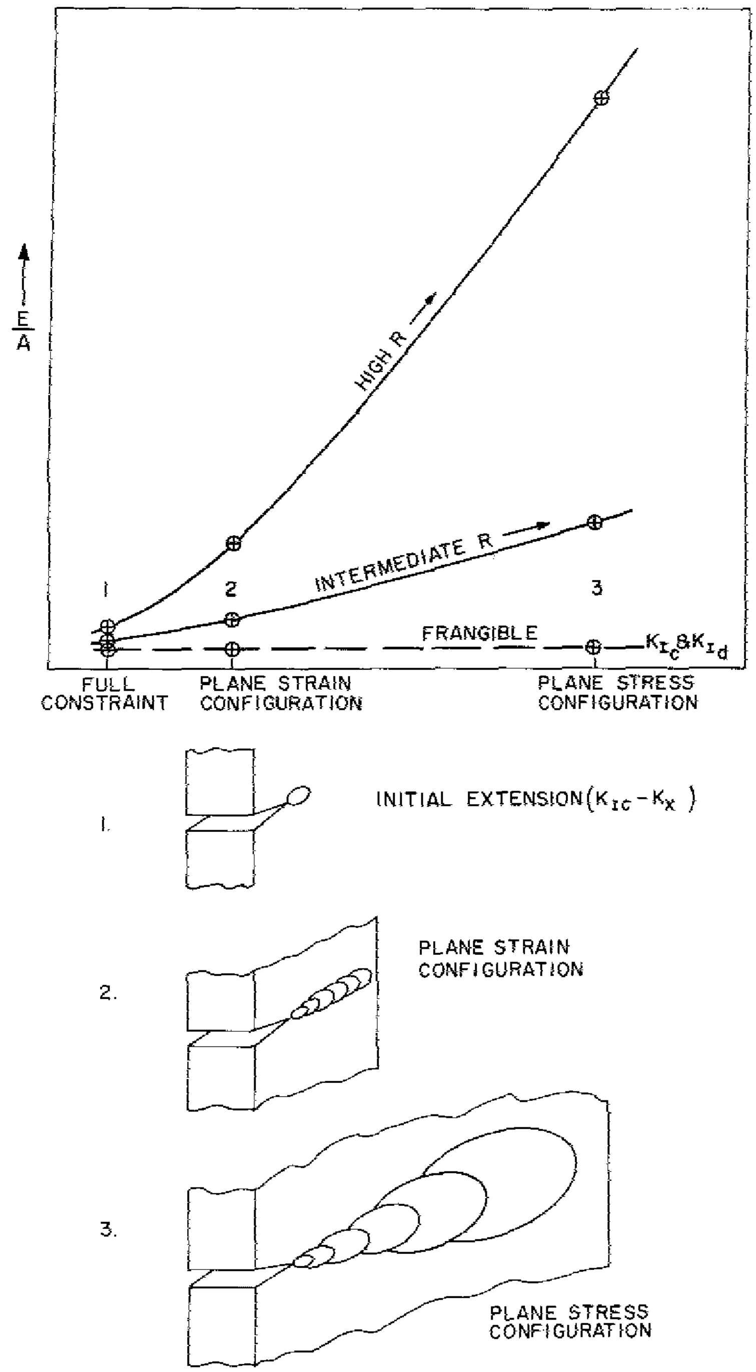

Fig. 2 - Definition of R-curve features by various tests, including (1) fracture mechanics test which only measure features of initial crack extension, (2) the plane strain DT test specimen configuration, and (3) the standard DT test which represents a plane stress specimen configuration. The solid curves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

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. A 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_x (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 that sufficient fracture extension path is provided to allow the development of whatever degree of plane stress fracture toughness 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 due to 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., rate of transition to plastic fracture. A practical procedure for measurement of the R-curve slopes evolves from comparison of 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 an aluminum alloy of high-fracture toughness and steeply rising, R-curve characteristics, which is evident by the development of a full-slant fracture for the standard DT test configuration. However, the full-slant fracture features were not manifested in the plane strain configuration due to the limited fracture path length.

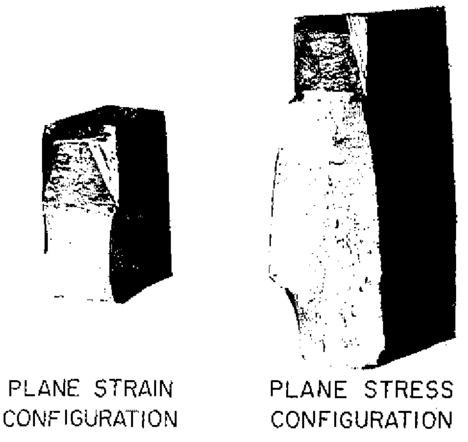

Fig. 3 - Illustration of the change in fracture appearance features of the DT test for the plane strain and plane stress specimen configurations. The fractures are typical of the plane strain to plane stress transition due to increased length of crack run for an alloy of high toughness.

DT TEST INVESTIGATIONS OF R-CURVE CHARACTERISTICS

Experimental data will now be presented which involve the use of the DT test in a wide variety of configurations. These experiments vividly illustrate the R-curve aspects of a wide variety of aluminum 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 (2).

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

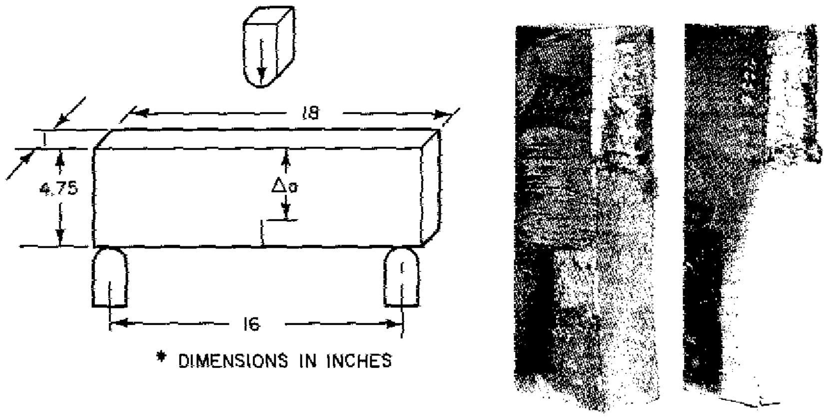

Fig. 4 - Schematic illustration of 1-in. DT specimen in which the fracture length (Δa) was varied to define R-curve features. Fracture surfaces of the standard 1-in. DT specimen configuration are illustrated for a frangible (left) and high-fracture-toughness (right) aluminum alloy.

The mechanical properties of the aluminum alloys used in this study are given in Table 1. A graphical representation of the range of properties is shown by plotting these data on the aluminum RAD, Fig. 5. Seven 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 line. This line is the upper limit of plane strain fracture toughness for 1-in.-thick plates. The reference code for these seven materials indicates the relative position of the alloy in 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 plane strain 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. With increasing K_{Ic}/σ_{ys} ratio value, the crack tip plastic zone size increases, i.e., increasing ratio signifies increasing metal ductility. Since a given section thickness provides a fixed

Table 1
Mechanical Properties of Aluminum Alloys used in R-Curve Studies

Alloy	Code	YS (ksi)	UTS (ksi)	RA (%)	El (%)	DT Energy (ft-lb)
7075-T7351	F-1	65.6	75.0	27	10	210
2024-T351	L-1	49.0	68.8	-	18	470
5456-H116	M-2	31.2	53.8	23	20	710
6061-T651	M-3	38.3	44.5	20	36	720
5456-H117	M-4	39.6	52.6	-	14	1450
5456-H117	H-5	32.5	52.5	24	19	1210
5086-H116	H-6	27.2	47.5	-	21	1330
5086-H117	H-7	29.9	44.4	36	21	1830

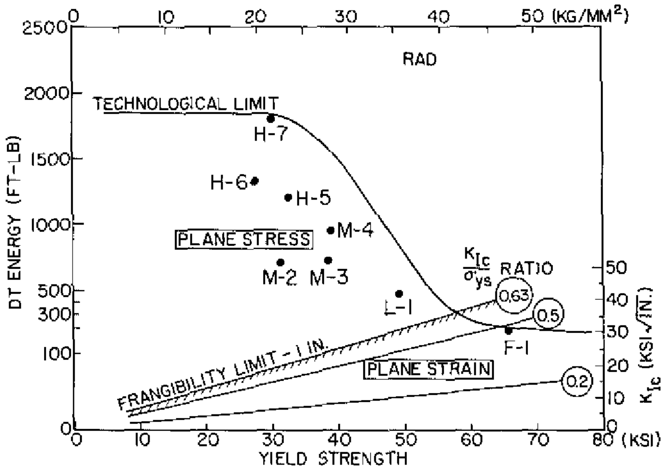

Fig. 5 - Location of the aluminum alloys of this study in the plane stress and plane strain regions of the RAD. The K_{Ic}/σ_{ys} ratio line of 0.63 relates to the limit of frangible behavior for 1-in. thickness according to the expression $B = 2.5(K_{Ic}/\sigma_{ys})^2$.

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 through-thickness yielding (contraction) will evolve, i.e., plane stress.

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. 5 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 indexing procedure for the test materials designates increasing resistance to fracture extension from L-1 (lowest value) to H-7 (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, 75 ft-lb/in.^{2}, Fig. 6. The fracture appearance was flat, without evidence of shear lips, for all test configurations.

The RAD location of alloy H-7 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-7 in Fig. 7. The changes in fracture appearance with increases

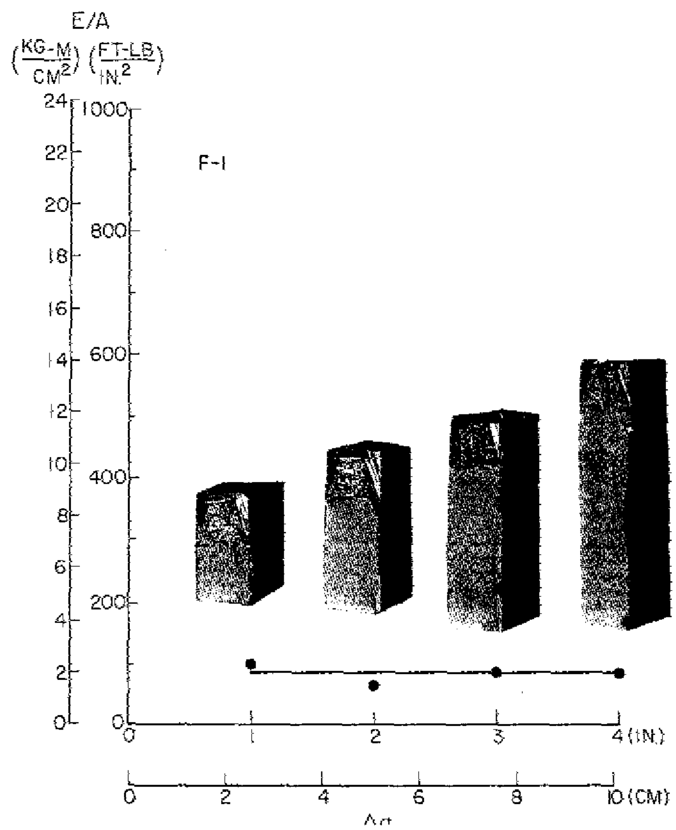

Fig. 6 – R-curve features and fracture appearance for a frangible alloy. Note the flat R curve and lack of a transition from flat plane strain fracture with increased Δa which is typical for brittle material.

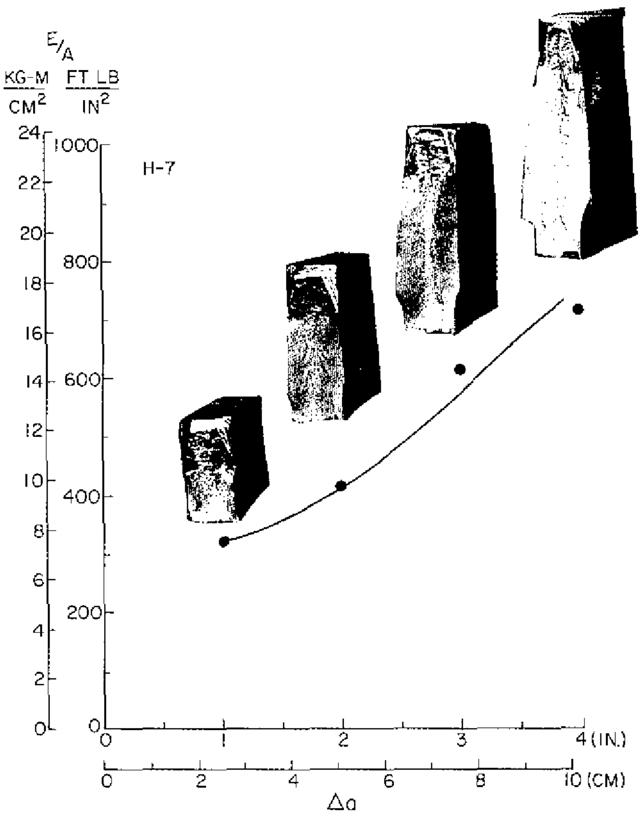

Fig. 7 - R-curve features and transition from plane strain to plane stress fracture with fracture extension for a high-toughness alloy

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. That is to say, 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-7 alloy described above. 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.

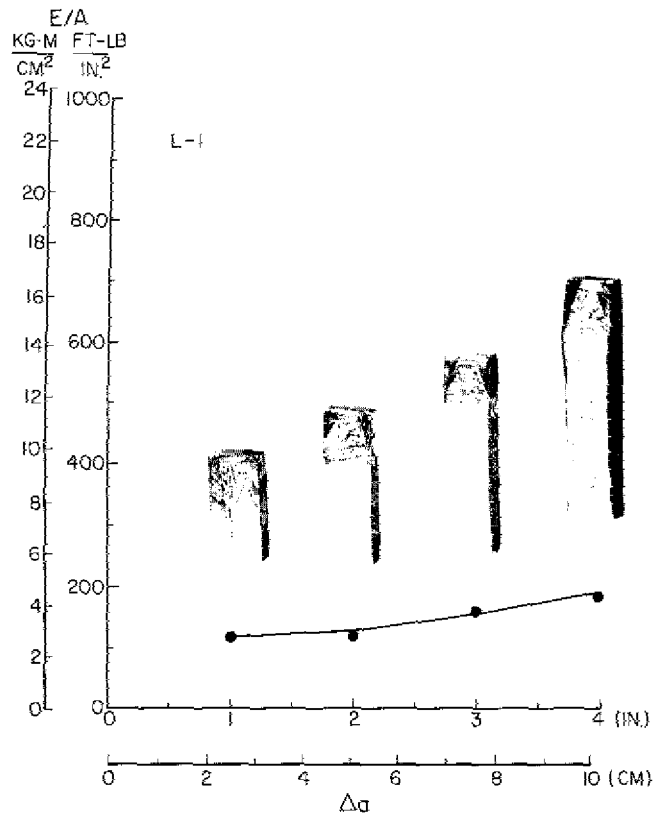

Fig. 8 - R-curve features and fracture appearance for an alloy of low resistance to fracture extension

The characteristic R curves (E/A vs Δa) for the eight aluminum 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 M-2 and M-3 alloys indicates identical R curves and significantly different values of yield strength. These aspects are independent parameters for different alloys and for different orientations in the same material. In this respect, reference is made to the wide variations in DT energy characteristics for the same strength level that is represented by RAD summaries, for the generic alloy families, Fig. 1. The DT energy value is directly related

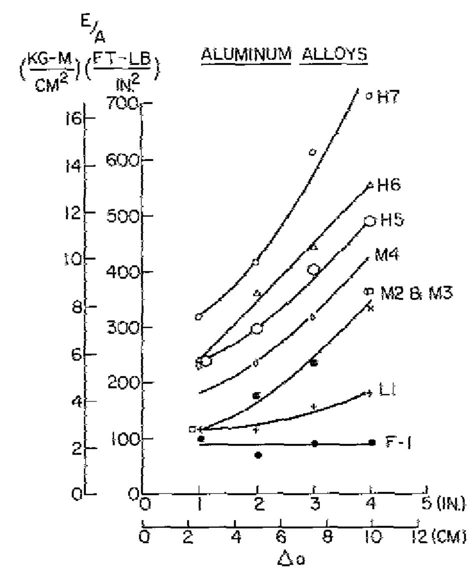

Fig. 9 - Summary of R-curve features for aluminum alloys ranging from frangible (F-1) to high fracture toughness (H-7)

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 increased K levels resulting from increases in yield strength. Similarly, the fracture extension resistance (R-curve slope) must increase 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 an increased R-curve slope (increased DT energy) due to the increase of allowable 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 2 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 the 1.0 ratio line.

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

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

ANALYSIS OF R-CURVE DATA

The R-curve forms of Fig. 2 are evident in the Fig. 9 data plots. An important feature of the characteristic form of these curves is that increases in the R-curve slope are related to increases in the intercept value, defined by the E/A value for the first extension increment (1 in.). Since the characteristic shape of the R curves is known, two data points may be used to establish the R curve for a given alloy. Thus, it is not necessary to conduct extensive tests to plot the full R curve. Two points derived from a plane strain DT-type test and a plane stress DT-type test, Fig. 2, are sufficient to establish the characteristic slope of the curve.

A curve-fitting 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 only between 1.65 and 2.0 for these seven alloys. If the slope is taken as approximately 2.0, a relation is inferred where the energy E varies as

$$E = R_p(\Delta a)^2 f(B).$$

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 2 is the slope of the log-log plot. The f(B) term represents a function of the thickness B of the specimen. The R curves (E/A values) for the 1-in.-thick aluminum alloy plates are related to Fig. 10 by dividing the E value by the fracture area of the specimen, i.e., $R = E/A = R_p \Delta a f(B)/B$.

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 are currently being established for steels; the f(B) term appears to be approximately $B^{1/2}$. Similar studies to establish the B relationships for aluminum alloys will be the subject of future research. Discussion of this factor is beyond the scope of the present report.

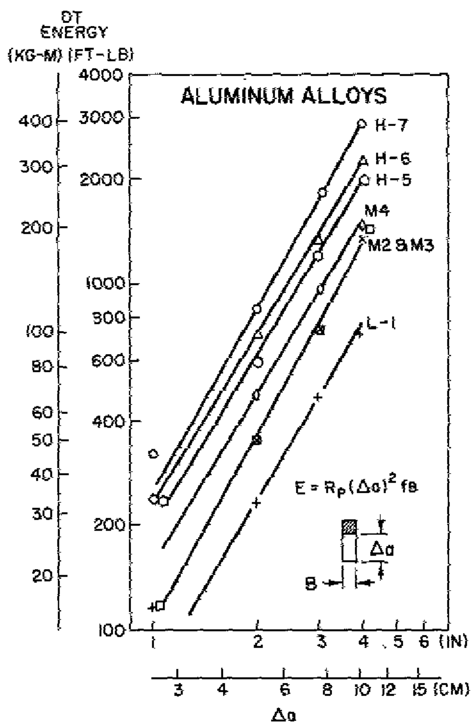

Fig. 10 - Log-log plot of R-curve data presented in Fig. 9. The straight-line relationships can be expressed by the equation $E = R_p \Delta a^2 f(B)$, where E is the DT energy, R_p is a material-dependent constant signified by the position of the relationship in the plot, Δa is length of crack extension, and B is thickness. The f(B) term requires establishment through R-curve studies involving different B values.

The ability to express the characteristic R-curve features by an experimentally 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.

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 accompanies 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.

The R-curve E/A plots do not level off because the modeling by the geometric series of test specimens does not provide exact definition of this aspect. The approximate distance over which increased resistance to fracture extension evolves is indexed by the depth of the internal V of flat central fracture (Fig. 3). The internal V represents a region of plane strain fracture which is eliminated in the course of fracture extension for a highly ductile metal, as shown in Fig. 11a. The disappearance of the V indicates the distance over which the plane strain to plane stress transition is evolved, i.e., the distance over which the constraint effect of the crack tip is decreased. For a metal of low R-curve slope, the V is not eliminated entirely, i.e., mixed-mode fracture is retained. However, a constriction of the flat fracture region is developed over the distance which relates to decrease in the mechanical constraint, Fig. 11b.

The geometric modeling allows the metal to "demonstrate" its characteristic response to a decrease in mechanical constraint. Thus, the natural features of plane strain to plane stress transition which evolve as a consequence of fracture extension are identified and indexed in terms of the R-curve slope.

The section size imposes a definable degree of mechanical constraint at the tip of the original crack; however, the metal determines the rate of change of the mechanical transition. Highly ductile metals undergo a sharp change due to early formation of a plastic enclave of large size. Thus, the R curve is of high level and steep slope. Slightly ductile metals undergo a gradual change due to the formation of a small plastic enclave — the degree of through-thickness yielding (contraction) is small. Thus, the R curve is of low level and slope.

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

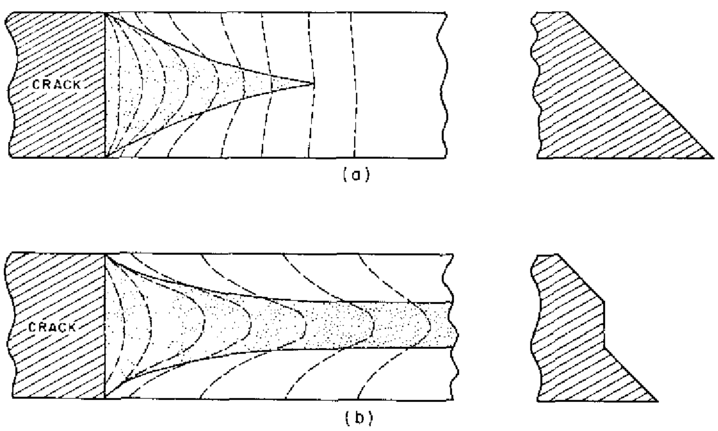

Fig. 11 - Schematic illustration of successive crack front positions (dashed lines) in specimens featuring (a) full slant fracture (high R-curve slope) and (b) mixed-mode, slant plus flat, fracture (low R-curve slope). The V region is eliminated with progressive crack extension for high R-curve slopes. For low R-curve slopes the V region persists with crack extension.

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 (2,3). These comparisons confirmed that the DT test provided a proper definition of the plane stress fracture features (slant fracture or retention of a central flat-fracture region) 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 characterization of the fracture extension resistance. Visual observation of the fracture path length over which the constriction of the central flat region evolves indexes the point of saturation, i.e., no further increase in resistance with extension.

The information derived from the characterization of R-curve slopes should provide for experimental definition of relationships to performance of prototype structural tests. These relationships should result in capabilities for prediction of critical plastic stresses or plastic strains required 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, per se, cannot be analyzed directly by mechanical principles. Thus, it is necessary to analyze the structural response 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 aluminum 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, then 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 ALUMINUM RAD

The aluminum RAD integrates the mechanical and metallurgical aspects relating to fracture extension resistance by "zoning" in terms of both aspects. Definition of R-curve factors provide for additional analytical possibilities for these integrations by zoning with respect to structural aspects. The fracture-safe design process requires total integration of all three factors, either sequentially or directly.

The R-curve slope provides 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 low level of fracture extension resistance results in fragmentation at elastic stress levels. Such behavior (flat break and shattering) is illustrated for 1-in.-thick plate by the point F in the RAD of Fig. 12. Indexing to increasing values of DT energy above the ratio line region signifies increasing R-curve slopes. The increased R-curve slope is a direct indication that fracture extension will require plastic overload as illustrated by the ETT (prototype structural tests) in Fig. 12 for materials of low (L), intermediate (M), and high (H) plastic fracture resistance. The plastic bulging required for fracture extension increases with increased "level" in the RAD, i.e., increased R-curve slope. 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 (2) in terms of its significance to the ratio lines zone, can now be related to aspects of fracture extension resistance for the region above the ratio line for the thickness involved. However, it must be noted that our studies of metallurgical factors for aluminum are not as extensive as for steels and titanium; thus, the following discussion relates to a restricted sampling of the various alloy families.

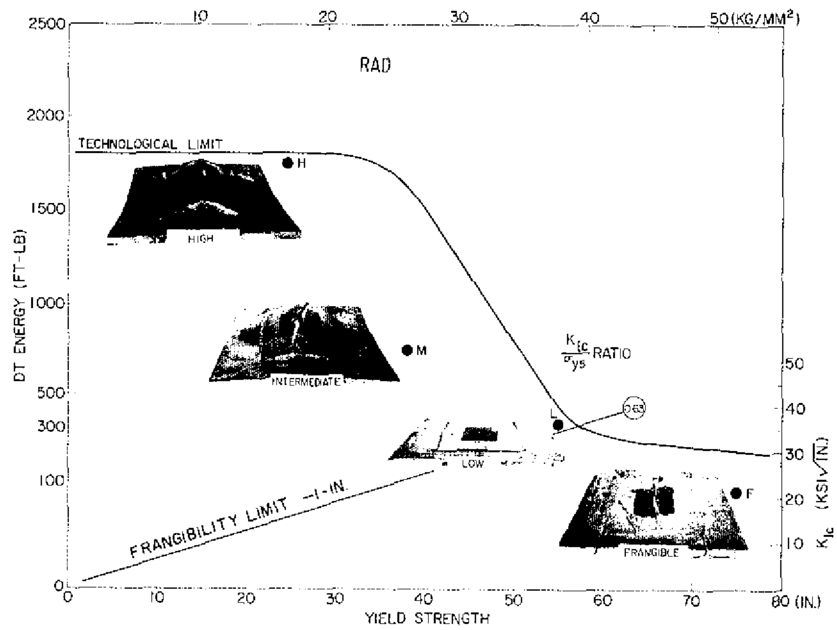

Fig. 12 - Explosion Tear Test (ETT) performance illustrating different levels of fracture extension resistance, which is predictable by the RAD position. ETT specimens are sufficiently large and have a long crack run so that a compliant structure is effectively represented. The increase in plastic (bulging) strain required for fracture extension is directly related to the increase in R-curve slope of the metal.

The 5000 series alloys are characterized by high R-curve slopes to a yield strength of about 30 ksi. For yield strengths in the range of 35 to 45 ksi, the plastic fracture resistance begins to drop rapidly. In this higher-strength range, R curves of intermediate slope would be expected. Yield strengths above 45 ksi would be difficult to obtain in thick sections due to the metallurgical nature of these alloys.

The 6000 series of alloys normally range from about 20- to 65-ksi yield strength. The 6061 alloy of the T-651 temper is the only alloy of this family for which DT and R-curve slope data are available at this time. At about 40-ksi yield strength, it features an intermediate R-curve slope.

The 7000 series of alloys are normally heat treated to develop strength levels in the range of 60- to 80-ksi yield stress. In this range of strength, all the alloys of 1-in. plate thickness would be frangible. Flat R curves are developed indicating frangible (K_{Ic}) characteristics. However, several 7000 series alloys, such as 7005 and 7106, feature yield strength levels in the 50- to 60-ksi range. The RAD plot suggests that careful control of all metallurgical factors should result in material featuring rising R-curve slopes. Therefore, these alloys would not be characterizable by K_{Ic} tests for 1-in.-thick plates.

The 2000 series of alloys normally range from 40- to 65-ksi yield strength; thus, they would be expected to feature rising R-curve slopes in the lower range of yield strength. Flat R-curve slopes and K_{Ic} characterization would be expected for 1-in.-thick plates of the higher strength level.

The R-curve indexing to the RAD adds the feature of zoning which includes the type of structure. For example, low R-curve slope regions of the RAD represent plane stress fracture resistance which may be adequate for the prevention of fracture extension in relatively noncompliant structures. With increase in compliance features and total available structural energy, there is a need to select aluminum 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-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 (for any type of structure) regime.

SUMMARY

In Ref. (1), a general case has been presented for the redirection of fracture research to neglected issues of major engineering importance. These issues involve metals 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 specific case has been made for the use of fracture extension resistance characterization procedures for aluminum alloys so that the full range (brittle to highly ductile) of properties can be defined. The characterization of metal properties should not be restricted to K_{Ic} (brittle) levels because a large fraction of the aluminum alloys system would be left undefined.

The potential for failure increases with flaw size, applied stress, the compliance characteristics of the structure, and the total load energy acting on the structure. The metal-type/structure-type relationships must be analyzed to arrive at satisfactory fracture-safe design solutions.

The basic parameter of importance to the safety of compliant aluminum structures is the specific fracture extension resistance of the alloy. This parameter is defined by the R-curve slope 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 aluminum 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 depends entirely 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 in the course of fracture extension changes from plane strain to plane stress.

Plane strain signifies essentially nil, through-thickness yielding (crack-tip plastic zone size is small). Plane stress signifies some degree of through-thickness yielding, ranging from low to high order, i.e., small plastic enclave dimpling to huge plastic dimpling. Thus, for aluminum alloys the plane stress condition may range from the low-tearing-energy type (low-slope R curve) to high-tearing-energy type (high-slope R curve).

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. 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 aluminum alloys. These solutions cannot be evolved in the absence of test methods which define R-curve features.

Fracture mechanics tests define conditions for initial fracture extension of frangible metals in terms of K factors. Thus, such tests cannot provide a definition of R-curve characteristics of nonfrangible (ductile) metals. 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. 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 the fact that, while the plane stress transition was allowed by the specimen geometry, it did not evolve for reasons of intrinsic metal properties.

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 fracture-energy-over-area (E/A) value for the plane strain configuration may then be compared to the E/A value for the standard plane stress configuration. The slope of the R curve is thus established by plotting the two values against Δa (crack run).

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

The illustrative examples focused on the selection of aluminum alloys from various locations in the RAD. The selections were made on the basis of the 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, demonstrate 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), demonstrate 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 aluminum alloys. Added meaning is provided for the RAD system of fracture-safe design analysis. Previously, this system was of primary importance for analysis of 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 aluminum 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 represents 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 the detailed definition of the R-curve slopes using the two-configuration DT test procedure.

ACKNOWLEDGMENTS

The authors express their appreciation to the Reynolds Metals Company and the Aluminum Company of America for providing the test material used in this study. The Office of Naval Research provided the financial support for the research studies.

REFERENCES

1. Pellini, W.S., and Judy, R.W., Jr., "Significance of Fracture Extension Resistance (R-curve) Factors in Fracture-Safe Design for Nonfrangible Metals," Welding Research Council Bulletin 157, Dec. 1970

2. Judy, R.W., Jr., Goode, R.J., and Freed, C.N., "Fracture Toughness Characterization Procedures and Interpretations to Fracture-Safe Design for Structural Aluminum Alloys," Welding Research Council Bulletin 140, May 1969

3. Pellini, W.S., Goode, R.J., Puzak, P.P., Lange, E.A., and Huber, R.W., "Review of Concepts and Status of Procedures for Fracture-Safe Design of Complex Welded Structures Involving Metals of Low to Ultra-High Strength Levels," NRL Report 6300, June 1965