NRL Report 7557

Ductile Fracture Equation for High-Strength Structural Metals

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April 3, 1973

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ABSTRACT

Dynamic Tear (DT) test R-curves were developed to define the inherent resistance of structural materials to fracture in terms of the energy-per-unit extension required to cause rapid crack extension. Translation of the R-curve characterizations to useful form for design of structures to preclude fracture has been accomplished by the use of Ratio Analysis Diagram (RAD). R-curve concepts and RADs have been established for steels, aluminum alloys, and titanium alloys.

An equation involving DT test specimen cross-section dimensions and a constant R_p, related to R-curve slope, has been shown to apply for steels and aluminum alloys. Use of this equation permits separation of metallurgical variables and specimen geometry variables for both fracture tests and structural applications and thereby makes possible independent analyses of each aspect. This report summarizes the available R-curve data and analysis methods to illustrate the use of R-curve concepts for fracture-safe structural design.

PROBLEM STATUS

This completes one phase of the problem. Work on other aspects is continuing.

AUTHORIZATION

NRL Problems M01-24 and M01-30
Projects RR 022-01-46-5431 and
62755N-ZF54-544-002

Manuscript submitted January 31, 1973.

DUCTILE FRACTURE EQUATION FOR HIGH-STRENGTH STRUCTURAL METALS

INTRODUCTION

For most complex structures, protection against catastrophic failure depends on the inherent strength of the structural material to arrest crack extension at expected load levels. Higher levels of performance are being sought for many modern structures, resulting in the use of metals of higher strength and consequent lower resistance to crack extension. Welding fabrication methods used for construction of most high-performance structures usually introduce high levels of stress at points of geometric complexity. In the final analysis, the existence of small defects at these regions of high stress must be conceded for such structures; crack growth due to fatigue and environmental effects must also be expected. The tolerance of materials for these sharp defects and high stresses governs the permitted degree of severity of the applied loading and environment. Therefore, the selection of materials with acceptable levels of tolerance for the imposed conditions is the most effective method for guaranteeing the integrity of a structure in its expected operating environment.

The key to selecting materials of acceptable tolerance levels is an accurate and reliable parameter for characterization of fracture properties. There are a number of methods for measuring fracture resistance properties of metals; however, only two tests — K_{Ic} and Dynamic Tear (DT) — are accurate characterization tools. The K_{Ic} parameter applies only for the plane-strain fracture state, which is a condition equivalent to brittle fracture. The DT test and the related fracture-extension resistance (R-curve) analysis can be used to characterize metals of all fracture states — plane strain, elastic-plastic, and plastic. Dynamic Tear (DT) test R-curve characterizations can be directly translated to design criteria by correlating R-curves with larger tests that model generic types of configurations and loadings. For ductile materials this is necessary because (a) fractures must be "driven" by the applied loads and (b) the tolerance of a structure for adverse conditions depends equally on the structural details and on the material's intrinsic resistance to fracture extension.

R-curves have been determined by DT test methods for steels (1), aluminum alloys (2), and titanium alloys (3). Effects of test specimen geometry on measured energy values have been examined in detail, with the result that an equation involving DT energy, specimen dimensions, and a constant that defines the material's resistance to crack extension has been established. This report summarizes the results of R-curve studies to substantiate the validity of the ductile fracture equation and illustrates the application of R-curve concepts to structural design.

BASIC ASPECTS

The characteristic behavior of a metal under conditions of forced crack extension must be determined by methods which focus on crack extension, rather than on crack initiation. Energy dissipation is the mechanism by which cracks can be arrested. R-curve plots of energy-per-unit-crack extension vs the length of the fracture model the crucial early propagation phase of structural failure. For metals covering the full range of fracture states (plane-strain, elastic-plastic, and plastic), the resistance to fracture does not appear to differ significantly at small values of crack extension; however, large differences in fracture resistance become quickly apparent as the moving crack becomes longer. This is illustrated in Fig. 1 by schematic R-curves for metals of high and intermediate R-curve characteristics and for a plane-strain metal. Full-constraint tests based on fracture initiation criteria (typically K_{Ic} tests), as depicted at point 1 in the figure, have very little ability to discriminate between the three metals. Whereas short fracture extension tests of the energy measurement type, such as the Charpy V, point 2, show a limited ability for discriminating between the metals, the tests which measure energy for a significantly long crack extension (DT tests), point 3, accurately define the wide differences in fracture resistance that exist in these metals.

The slope of the R-curve is the index of fracture resistance. Flat R-curves indicate the plane-strain fracture state. A rising R-curve shows that the material undergoes plastic deformation at the crack tip, which is the basic fracture-extension resistance mechanism. The R-curve slope is a measure of the amount of energy required to "drive" the crack per unit extension and thus is the indicator of fracture resistance; i.e., increased slope signifies increased crack-tip plastic deformation.

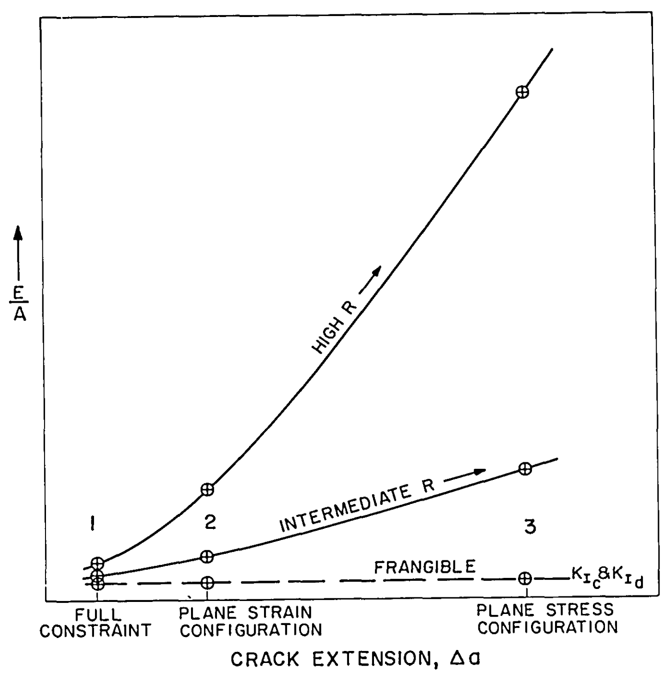

Fig. 1 — Definition of R-curves by various tests including (1) fracture mechanics test which measures initial crack extension, (2) short fracture length specimen and (3) long fracture length specimen. Curves represent three levels of fracture extension resistance (R), as noted.

DYNAMIC-TEAR TEST METHODS

The DT test specimen (Fig. 2) is an edge-notched bar loaded dynamically in three-point bending by machines of pendulum or falling weight type. Test specimens are dimensioned to the thickness of subject materials; standard configurations for 5/8-in. (4) and 1-in. (5) thickness are also shown in Fig. 2. To determine the R-curve by DT test methods, the Δa dimension is varied while all other dimensions and test variables are fixed. The equation of Fig. 2 has been shown to apply for steels and aluminum alloys, with some slight variations in the exponents from one material to another.

DYNAMIC TEAR TEST

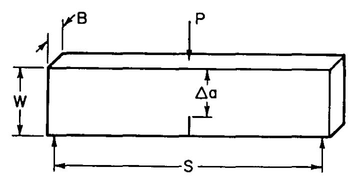

Fig. 2 — Illustration of Dynamic Tear test specimen

ENERGY = $R_p B^Y \Delta a^X$
WHERE R_p = CONSTANT

STANDARD SPECIMENS

B		Δa		W		S	
(IN.)	(CM)	(IN.)	(CM)	(IN.)	(CM)	(IN.)	(CM)
0.63	1.6	1.125	2.9	1.625	4.1	6.5	16.5
1.0	2.5	3	7.6	4.75	12.1	16	41

It must be emphasized at this point that the DT test and associated R-curve analyses are intended for engineering use in providing material characterizations, rather than as a tool for precise scientific investigations. For this reason, every effort to simplify test procedures and to minimize specimen preparation costs has been made. Limits on specimen dimensions have been established to hold energy losses due to deformation at loading points to a very low level.

In studies of DT R-curves involving variations of only the Δa dimension, it was shown that the measured energy E varied as $(\Delta a)^x$ (1-3). In studies involving both Δa and B (6,7) it was shown that the equation $E = R_p (\Delta a)^x (B)^y$, where R_p = constant for a given material, was valid for steels and aluminum alloys. Titanium alloys are a special case, which will be discussed in a later section of this report. There were slight differences in the exponents x and y for steels and for aluminum alloys; however, these differences are minor for most applications. The following sections present the data for high-strength steels, aluminum alloys, and titanium alloys that determine the ductile fracture equation.

Steels

The earliest experiments where DT specimen dimensions were systematically varied (1) involved steels of 1-in. thickness having upper shelf fracture properties that ranged from elastic-plastic to high plastic fracture resistance levels. The data are given in Table 1. In

Table 1
Mechanical Properties of High-Strength Steels

Code	YS (ksi)	UTS (ksi)	EL (%)	RA (%)	STD 1-in. DT Energy (Ft-Lb)	Thickness (In.)	R_p (Ft-Lb/In.$^{5/2}$)	Source (Ref.)
L-1	162	185	14	48	1450	1	189	1,6
L-2	111	117	16	53	2100	1	322	1
L-3	183	201	18	66	2900	1	446	1
M-4	98	108	17	43	2720	1	409	1
M-5	125	141	19	61	4390	1	460	1,6
H-6	144	159	18	61	6650	1	647	1,6
H-7	83	98	24	68	6570	1	925	1
A533B	78	—	—	—	—	6	902	8

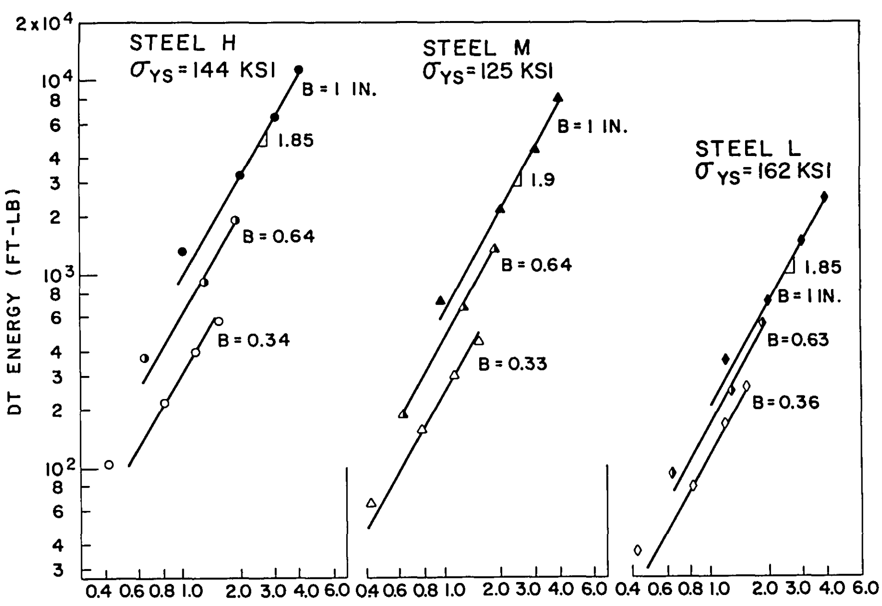

Fig. 3 — R-curves for 1-in. thick steels of High (H), Intermediate (M) and Low (L) levels of resistance to crack extension. The log-log format is used to illustrate the conformance of the data to an equation of exponential form. Note that the short fracture run specimens (lowest data point on each curve) are above the expected energy value.

this study, it was shown that E varied approximately as $(\Delta a)^2$ f(B). Because B = 1 in., f(B) could not be determined. In a later study (6) three of these steels were sectioned to smaller thicknesses (Fig. 3); least-squares curve-fitting procedures gave the best fit to the data as $E = R_p\,(\Delta a)^{1.9}B^{0.8}$. Rounding the exponents gives $E = R_p\,(\Delta a)^2\,B^{1/2}$, the general expression. Application of the second equation also resulted in a very close data fit for all of the steels tested.

Data that show the applicability of the equation over a large range of thicknesses were reported by Loss (8). Full-thickness R-curve tests of 6-in.-thick pressure vessel steel conformed very closely to the scatter band predicted from 5/8-in. DT test results. In all of the steel tests the specimens having a Δa value equal to the plate thickness were in error compared to the remaining data. For this reason, specimens with Δa less than 1.5 × thickness (1.5T) are not recommended and are not included in this report.

Comparisons of data for standard specimen configurations also fit the predictions of the ductile fracture equation reasonably well. In Fig. 4 the correlation between DT energy values measured with standard 1-in.-thick test specimens and with standard 5/8-in.-thick specimens (9) is shown to be 8.0:1. This relation is predicted exactly by the equation $E = R_p (\Delta a)^{1.8} B^{0.7}$, whereas the generalized equation $E = R_p (\Delta a)^2 B^{0.5}$ yields a predicted ratio of 9.0:1. It should be noted that the 5/8-in. DT specimen configuration is currently being standardized by ASTM for use in specification and quality-control applications. Substitution of the dimensions of the standard specimen into the generalized equation reduces it to $E = 1.0\ R_p$, so that the R_p factor can be determined directly by use of this specimen configuration.

Aluminum Alloys

R-curve data for a series of 1-in.-thick aluminum alloys (6) are presented in Table 2. In this study of 1-in. plates, the selection of materials represents the fracture state range from elastic-plastic to high plastic properties. These data also showed that $E \propto (\Delta a)^x f(B)$ where the exponent x varied between 1.65 and 2.0 for the seven materials studied. Data for four aluminum alloys in 3-in. thickness (7) are presented in Fig. 5. In this study, R-curves were determined for full thickness and for section sizes of 1 and 5/8 in. The equation was again demonstrated to apply for the entire range of thicknesses.

An interesting note in the investigation of 3-in.-thick materials was the results of tests of the 7005 alloy, which had plane-strain properties in full thickness, elastic-plastic properties at 1-in. thickness, and plastic properties at 5/8-in. thickness. The R-curves corresponded exactly to this order (Fig. 6) with the full-thickness R-curve flat, and a steeper slope for the 5/8-in. R-curve than the 1-in. R-curve. Full-thickness DT energy values did not fit the equation, which applies only to ductile materials; however, the subthickness specimens corresponded exactly to the equation.

Results of standard 5/8-in. and 1-in. DT tests for aluminum alloys (10) showed the same relation of energy values as was found for steels (Fig. 7). As with the steels, the slope of the line is 8.0, while the slope predicted by the generalized equation is 9.0. Thus, for practical purposes, the results of studies involving steels and aluminum alloys showed that the same equation could be used to describe the dependence of fracture energy on specimen geometry.

Titanium Alloys

DT R-curves were also determined for titanium alloys (3); however, the data did not conform to the equation found for steels and aluminum alloys. Studies of R-curves of 1-in. plates showed the average exponents on Δa to be on the order of 1.6 rather than the 1.8 to 2.0 found for other metal systems. Moreover, some difficulty was found in attempting to attain a good correlation of standard 1-in. and 5/8-in. DT energy values

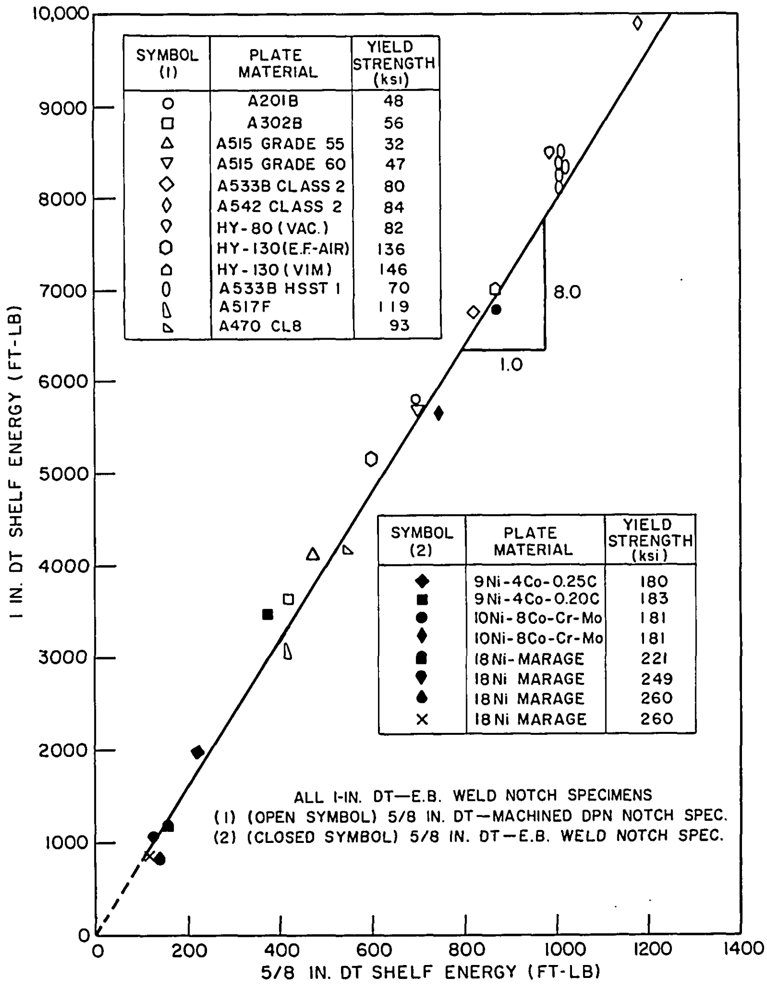

Fig. 4 — Correlation between standard 5/8-in. DT and standard 1-in. DT energy values for steels at upper shelf temperatures for a broad range of steels.

Table 2
Mechanical Properties of Aluminum Alloys

Alloy	YS (ksi)	UTS (ksi)	EL (%)	RA (%)	STD 1-in. DT Energy (Ft-Lb)	Thickness (In.)	R_p (Ft-Lb/In.$^{5/2}$)	Source (Ref.)
2024-T351	49.0	68.8	18		470	1	55	2
5456-H116	31.2	53.8	20	23	710	1	83	2
6061-T651	38.3	44.5	36	26	720	1	86	2
5456-H117	39.6	52.6	14		980	1	105	2
5456-H117	32.5	52.5	19	24	1210	1	135	2
5086-H116	27.2	47.5	21		1330	1	155	2
5086-H117	29.9	44.4	21	36	1830	1	197	2
5083-H321	32.1	49.5	17	25	870	3	115	7
5086-H32	28.4	43.6	18	34	1520	3	197	7
6061-T651	41.5	46.7	13	30	430	3	63	7
7005-T6351	48.8	55.6	15	36	460	3	71	7

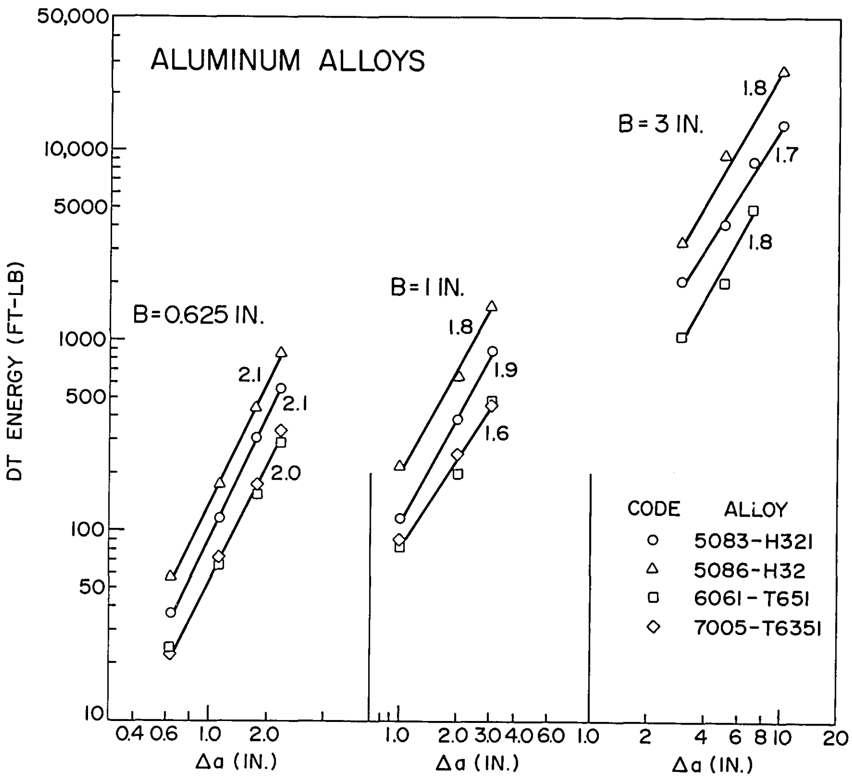

Fig. 5 — R-curve data for 3-in. thick aluminum alloys

measured for a wide variety of alloys. A close scrutiny of the data showed that the apparent scatter could be traced to subtrends for different alloy systems; i.e., a different correlation would exist for different alloy systems.

The cause of these difficulties is the effect of test temperature. Steel data all refer to upper shelf energy values, and aluminum data are unaffected by moderate temperature differences. Titanium alloys exhibit a gradual increase in fracture resistance with increasing temperature as is shown for three different alloys in Fig. 8. Results of both 5/8-in. and 1-in. DT tests evidence the gradual increase; however, the measured energy values for the Ti-6Al-4V alloy (triangles) are the lowest of the group in the 5/8-in. DT test and are the highest in the 1-in. DT test. Attempts to correlate 1-in. DT and 5/8-in. DT test data result in plots such as Fig. 9, which is a replot of the data of Fig. 8. Note that the Ti-621-08 and Ti-6Al-2Mo alloys give one result, whereas the Ti-6Al-4V alloy gives a different result.

Standard DT tests for materials' characterization studies have been conducted at a 30°F reference temperature in past programs to define fracture resistance properties of titanium alloys. It appears from the data above that full-thickness R-curve tests for fracture resistance properties of titanium are to be preferred to tests of reduced section size. In any event, the problems appear to be caused by combined temperature-constraint effects which preclude application of the ductile fracture equation for titanium alloy systems, in general. For specific alloy families, however, the approach may have some validity.

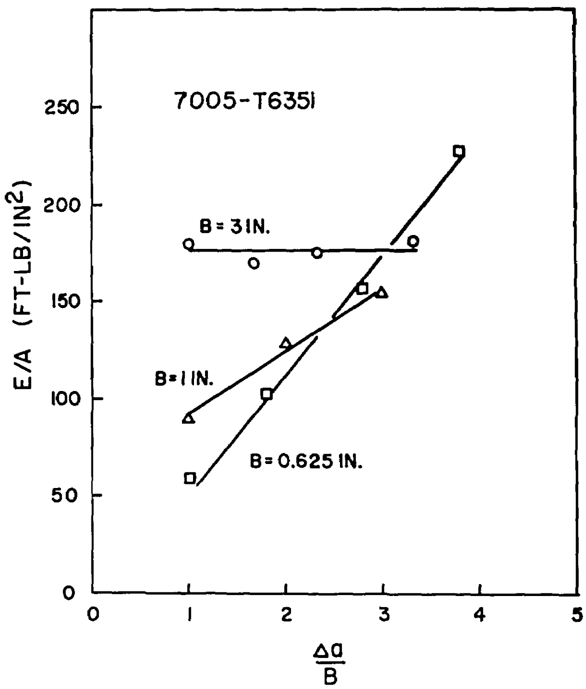

Fig. 6 — R-curves for 7005-T6351 alloy as a function of test specimen thickness. The flat R-curve for full thickness indicates a plane-strain condition, whereas positive slopes for thinner section sizes, as noted, indicate elastic-plastic and plastic conditions. The data are plotted as $\Delta a/B$ to normalize values for comparison.

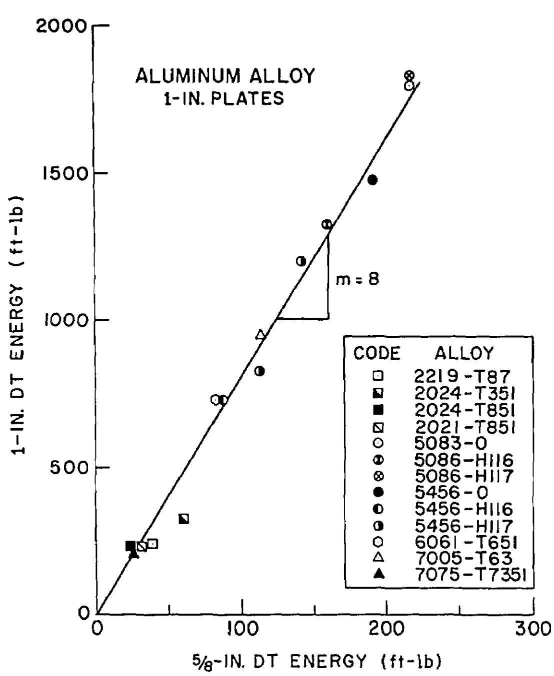

Fig. 7 — Correlation of standard 5/8-in. DT energy and standard 1-in. DT energy for 1-in.-thick aluminum alloys.

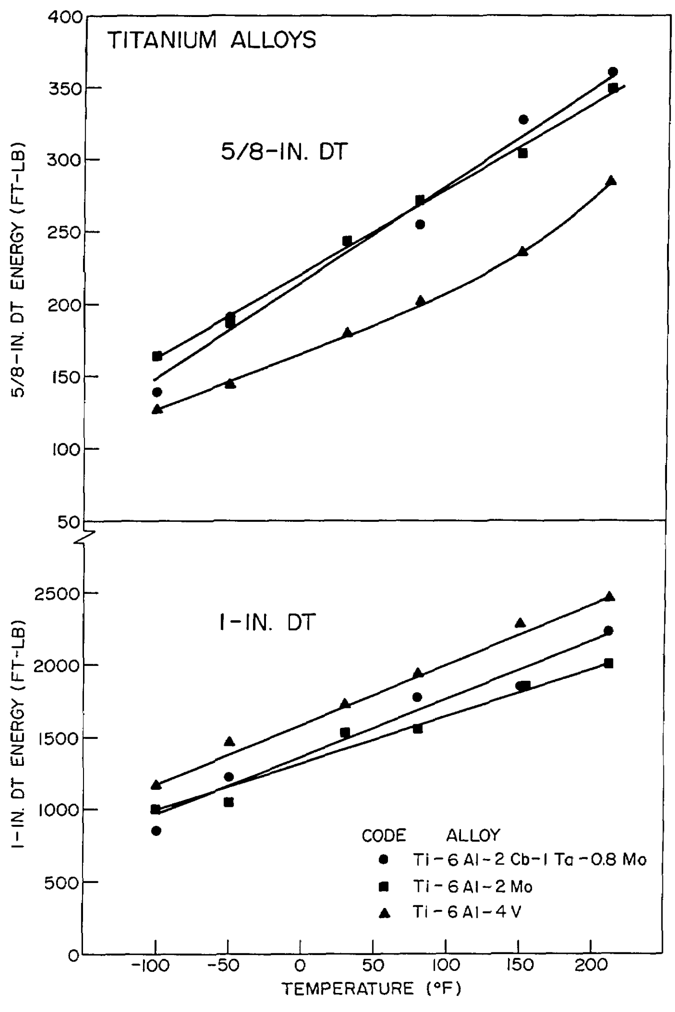

Fig. 8 — Temperature transition curves for three titanium alloys. Note the position of data for Ti-6Al-4V relative to other alloys as measured by 5/8-in. and 1-in. DT tests.

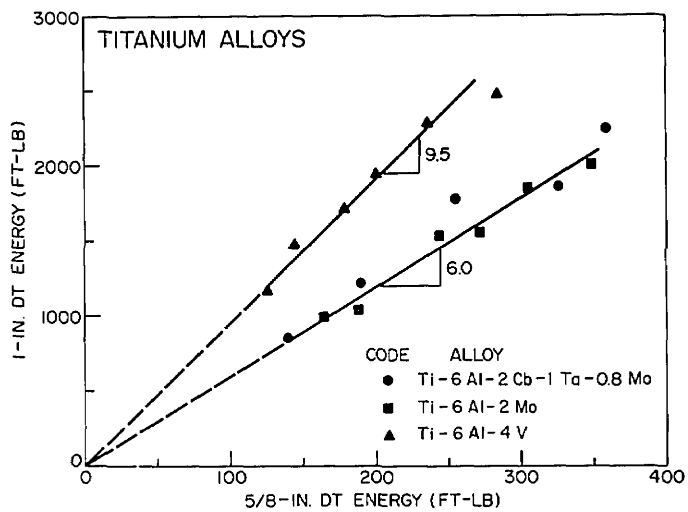

Fig. 9 — Correlation of standard 5/8- and 1-in. DT tests for three titanium alloys

DISCUSSION

To illustrate the conformance of the data to the ductile fracture equation, a plot of predicted vs actual energy that includes all the steel and aluminum data in this report is presented in Fig. 10. In each case, the characteristic R_p value for each material was determined by substituting the measured energy and the specimen dimensions into the equation and calculating the R_p value for each test. All calculated R_p values for a single material, which fit in a ±20% scatter band for each material, were then averaged to give a characteristic R_p value. By using the characteristic R_p value and specimen dimensions, a predicted value of energy was computed for each test. The predicted values are compared to measured values in Fig. 10. The fit of the data to the equation is very good as is shown by the closeness of the points to the 1:1 correspondence line. The data are plotted on log-log scales to emphasize that the equation extends over five orders of magnitude.

The purpose of characterization tests such as DT R-curves is to provide a measure of the fracture resistance properties to be used in design. The Ratio Analysis Diagram (RAD) (11) provides a format for translation of material property characterization data to predictions of structural performance for given conditions. RADs have been derived for steels (12), aluminum alloys (13), and titanium alloys (14).

The RAD framework is formed from the scales of yield strength vs K_{Ic} and DT energy, Fig. 11. The most prominent features of the RAD are the limit lines and the system of lines of constant K_{Ic}/σ_{ys} ratio. The Technological Limit (TL) line represents the highest values of fracture resistance measured to date either by DT tests over the entire yield strength range or by K_{Ic} tests in the elastic fracture range; the Lower Bound represents the lowest levels of fracture resistance. Reference to critical flaw size charts (11) is provided by the system of K_{Ic}/σ_{ys} ratio lines. As an example, critical sizes for long thin surface flaws for half-yield and full-yield loading conditions are shown on the RAD for each ratio line.

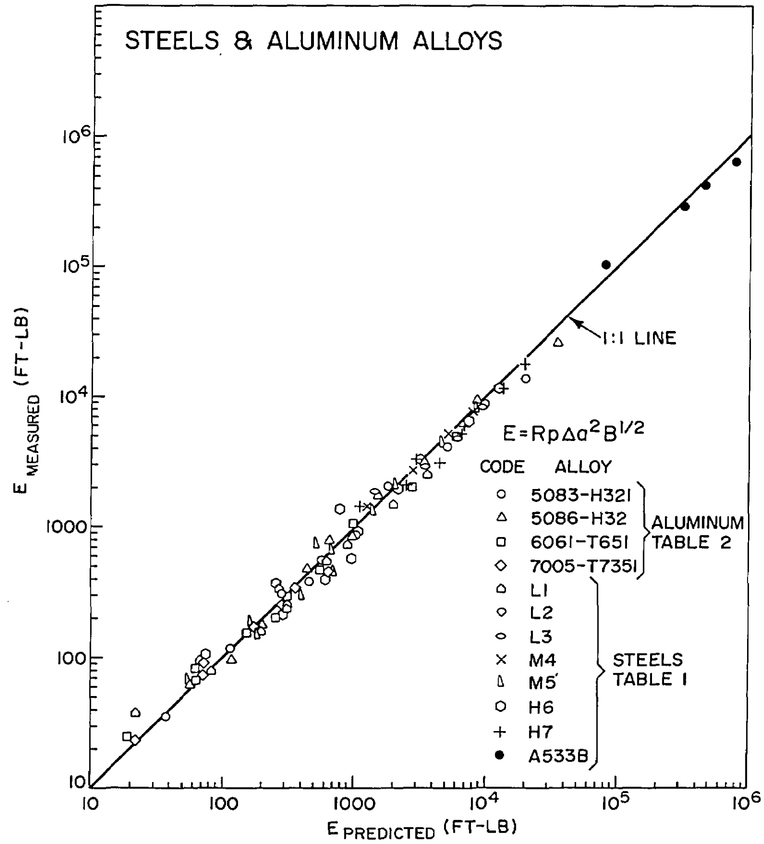

Fig. 10 — Illustration of data fit to equation. See text for details.

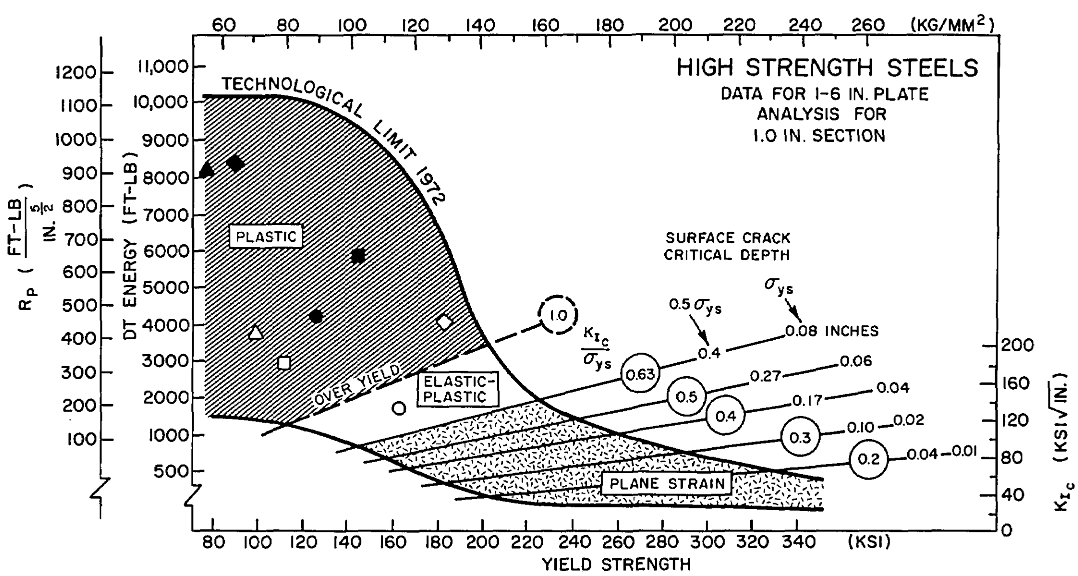

Fig. 11 — Ratio Analysis Diagram for steels. Elastic-plastic boundaries determined for 1-in. thickness. Data are plotted from R_p scale. Note the open circle point in the elastic-plastic zone.

The ratio lines also divide the diagram into regions of expected plastic, brittle, and elastic-plastic behavior for given material thicknesses. The separations are determined according to thickness as shown for the 1-in. section size in Fig. 11. The critical edge between brittle behavior and elastic-plastic behavior is the plane-strain limit. The boundary between the elastic-plastic and ductile regimes is the general-yield limit. Table 3 contains both plane-strain limits and general yield limits as related to section size. The division of the RAD into three regions provides an engineering index of the fracture state and thereby serves to indicate the type of more detailed design approach required for each case.

Of the two entry scales to the RAD, DT energy is to be preferred to K_{Ic} for reasons of the expense of the test method. Standard RADs have been based on use of standard DT tests, while the analysis was adjusted for material thickness from knowledge of the plane-strain limits and general yield limit, which are given in terms of K_{Ic}/σ_{ys} ratio lines.

The ductile fracture equation permits entry of material properties from any plate thickness onto the RAD for analysis of the fracture state. This is done by adding a scale of R_p as calculated from the 1-in. DT energy scale. Since R_p is independent of geometry effects, section size now enters the RAD only in locating the elastic-plastic region. For example, the RADs of Figs. 11-13 are adjusted for 1-in., 1/2-in., and 2.5-in. section sizes, respectively, with all the steel data plotted on the diagram using the R_p scale. Figures 14-16 show the same sequence of section sizes for aluminum alloys.

Table 3
Limits of Applicability of Linear Elastic Fracture Mechanics

Section Size (in.)	Plane-Strain Limit K_{Ic}/σ_{ys} (ksi)	General Yield Limit K_{Ic}/σ_{ys} (ksi$\sqrt{\text{in.}}$/ksi)
0.1	0.20	0.32
0.2	0.28	0.45
0.3	0.35	0.55
0.4	0.40	0.63
0.5	0.45	0.71
1.0	0.63	1.0
1.5	0.8	1.21
2.0	0.9	1.41
3.0	1.1	1.73
6.0	1.5	2.45
10.0	2.0	3.17

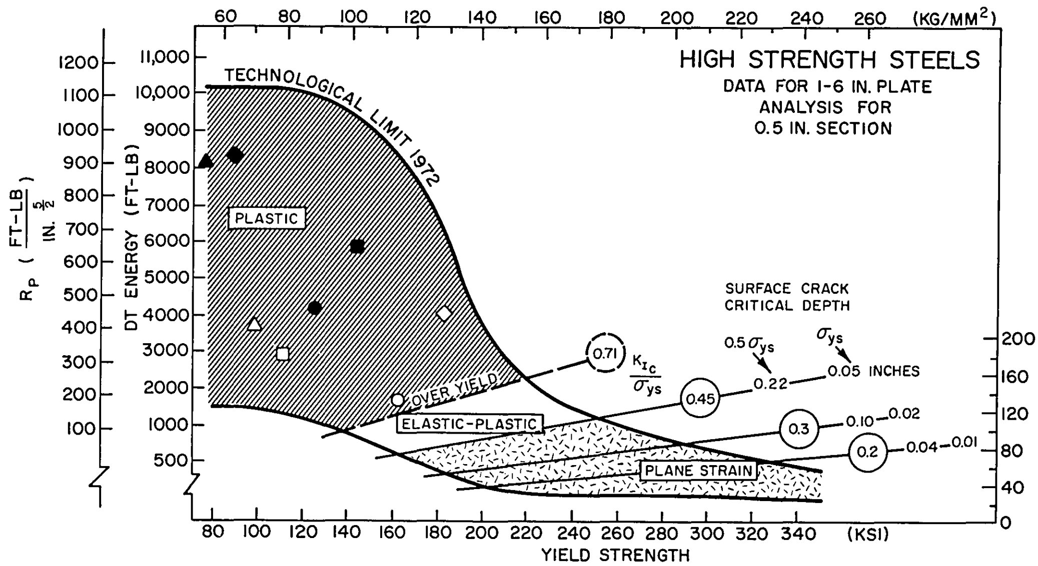

Fig. 12 — RAD for analysis of 0.5-in. section. The open circle point (same R_p as Fig. 11) is now in the plastic fracture region.

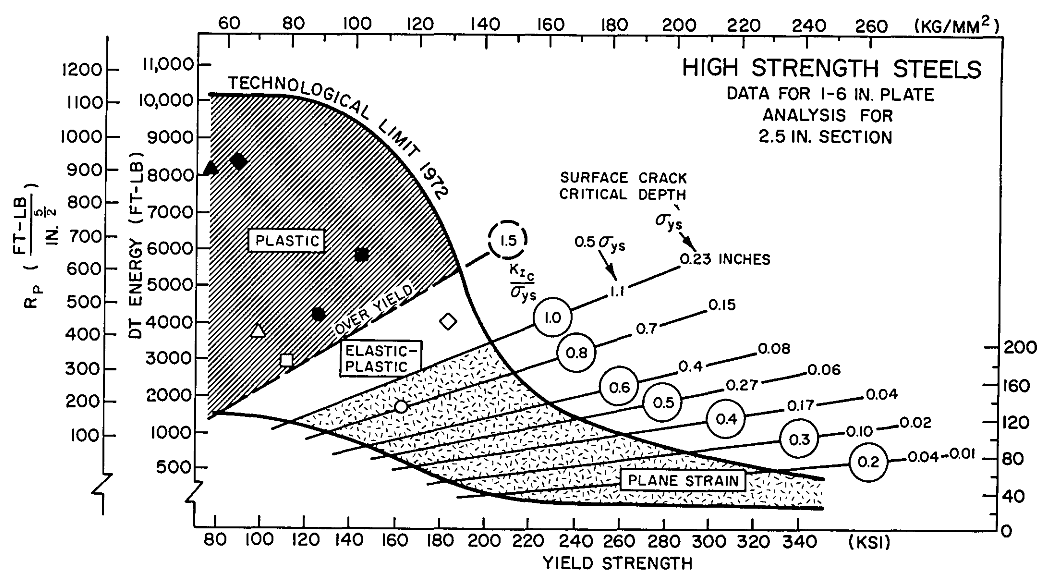

Fig. 13 — RAD for analysis of 2.5-in. section. The open circle point is now in the plane-strain region.

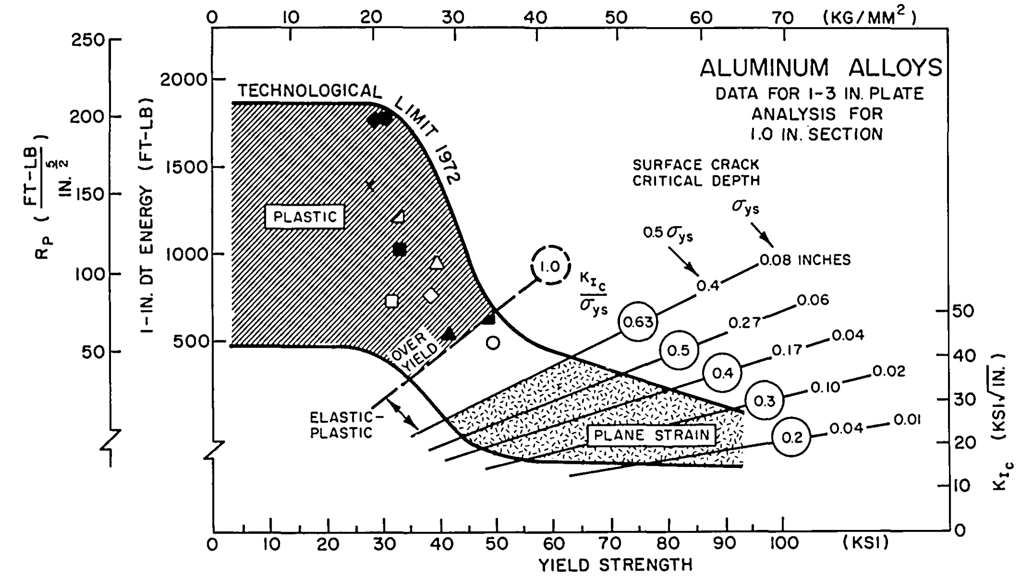

Fig. 14 — Aluminum RAD for analysis of 1-in.-thick materials. Open circle point is for 7005-T7351 — elastic-plastic.

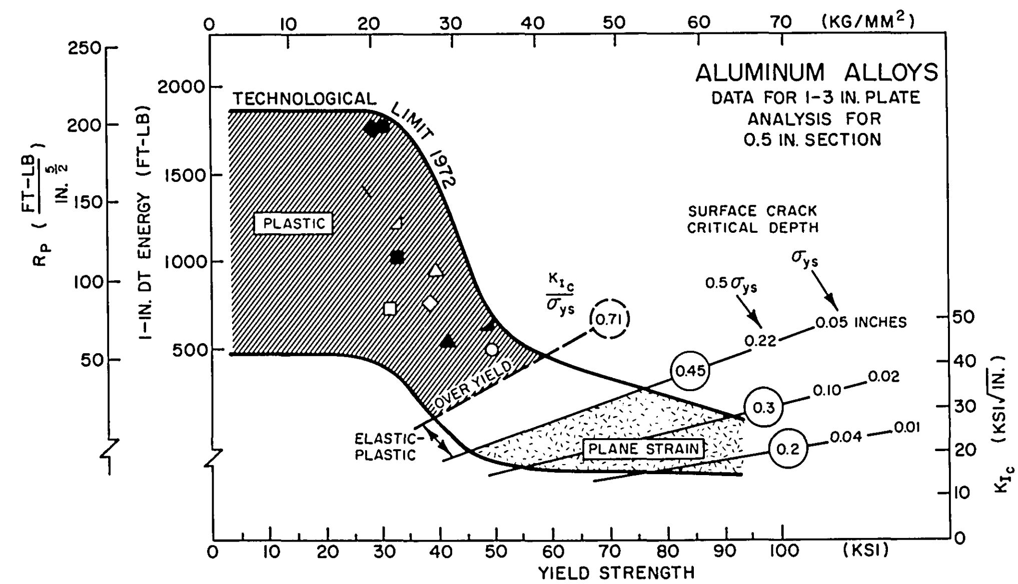

Fig. 15 — Aluminum RAD for analysis of 0.5-in. section. The open circle point is now in the plastic region.

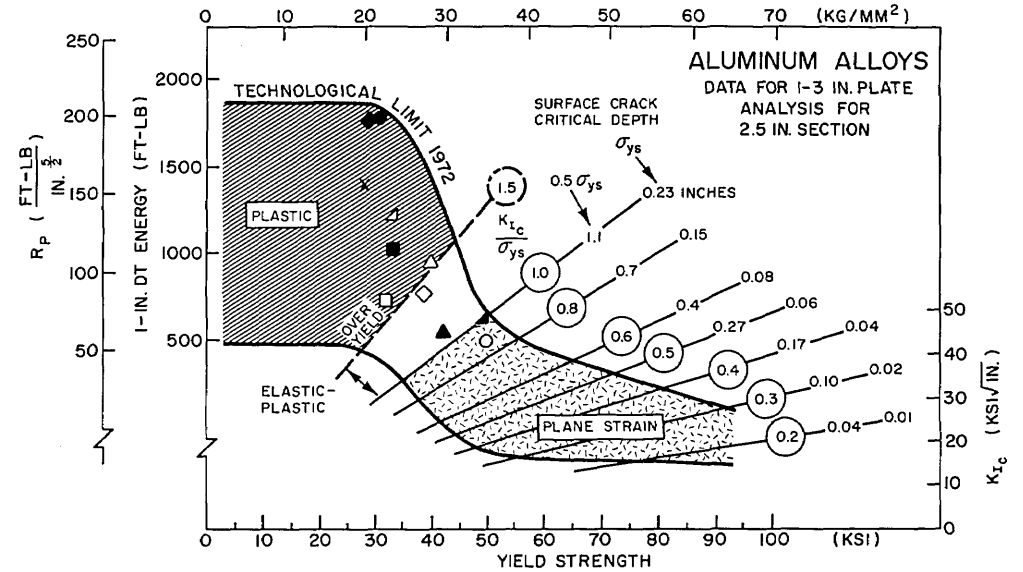

Fig. 16 — Aluminum RAD for analysis of 2.5-in. section. The open circle point is now in the plane-strain region.

To illustrate the value of separating metallurgical variables and mechanical test variables, consider the open circle point on Figs. 11-13. The material for this data point is a 160-ksi yield strength steel produced as 1-in.-thick plate. Since R_p represents only the physical properties of the metal, the point is constant for all three RADs. However, effects of changing section size are such that a different fracture state exists for the same material at each of the selected thicknesses of the RADs (Figs. 11-13):

- At B = 1 in. (Fig. 11), the material has elastic-plastic properties, which is a level of fracture resistance that allows unstable crack propagation at high elastic stress levels with an appreciable amount of crack-tip plasticity.

- At B = 0.5 in. (Fig. 12), the material has plastic properties, for which crack extension requires stresses over the yield strength and a high energy expenditure to "drive" the crack.

- At B = 2.5 in. (Fig. 13), the material has plane-strain properties, a level of fracture resistance that permits unstable crack extension at low elastic stress levels with minimal deformation at the crack tip.

The same range of fracture state levels is shown by the open circle point in the aluminum RADs, Figs. 14-16. The material in this case is the 7005-T6351 produced as 3-in. plate, which was described earlier in this report. Because the effect of section size is so important in determining the fracture state, a parameter for characterizing the fracture resistance properties of ductile materials independently of geometrical effects is essential for evolving a format for interpreting laboratory test results to structural design. Independent analyses of metallurgical and mechanical aspects on the fracture properties of materials are thus made possible by the use of the R_p parameter associated with RAD analysis procedures.

CONCLUSIONS

The following conclusions can be drawn from results of R-curve tests of high-strength materials:

1. The equation $E = R_p\ (\Delta a)^2\ (B)^{1/2}$ accurately defines the dependence of energy measured in the Dynamic Tear test on specimen geometry. The constant R_p is the measure of inherent resistance to extension of fracture.

2. The ductile fracture equation applies equally well for steels at temperatures corresponding to upper shelf fracture conditions and for aluminum alloys. It is not applicable for titanium alloys because of temperature transition effects.

3. Placing an R_p scale on the RAD permits use of the diagram for materials in a wide range of section sizes without the use of extensive experimental correlations to provide entry scales.

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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. 20375	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

DUCTILE FRACTURE EQUATION FOR HIGH-STRENGTH STRUCTURAL METALS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final report on one phase of a continuing NRL Problem.

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

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

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 3, 1973	22	14

8a. CONTRACT OR GRANT NO. NRL Problem Nos. M01-24 & M01-30 b. PROJECT NO. RR 022-01-46-5431 and 62755N-ZF54-544-002 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7557 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

Dynamic Tear (DT) test R-curves were developed to define the inherent resistance of structural materials to fracture in terms of the energy-per-unit extension required to cause rapid crack extension. Translation of the R-curve characterizations to useful form for design of structures to preclude fracture has been accomplished by the use of Ratio Analysis Diagram (RAD). R-curve concepts and RADs have been established for steels, aluminum alloys, and titanium alloys.

An equation involving DT test specimen cross-section dimensions and a constant R_p, related to R-curve slope, has been shown to apply for steels and aluminum alloys. Use of this equation permits separation of metallurgical variables and specimen geometry variables for both fracture tests and structural applications and thereby makes possible independent analyses of each aspect. This report summarizes the available R-curve data and analysis methods to illustrate the use of R-curve concepts for fracture-safe structural design.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
R-curves						
Ductile fracture equation						
Ratio Analysis Diagram						
High-strength steels						
High-strength aluminum alloys						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Security Classification