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Dynamic Tear Tests of 3-In.-Thick Aluminum Alloys

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ABSTRACT

The Dynamic Tear (DT) test was developed for characterization of the fracture-resistance properties of metals over the entire range of strength and toughness. The fracture-extension-resistance curve (R curve), which is determined by DT test procedures, indicates the fracture state (elastic or plastic) and the level of resistance to crack extension in terms of the required energy per unit extension.

R curves were determined for four aluminum alloys in 3-in. thicknesses. These materials had been tested by standard fracture-mechanics procedures. R curves for full thickness and for 1-in. and 0.625-in. section sizes are compared to results of K_{Ic} tests. The R-curve data are also presented in terms of an equation involving specimen cross-section dimensions and a constant which is related to the R-curve slope.

PROBLEM STATUS

Final report on one phase of a continuing NRL problem.

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DYNAMIC TEAR TESTS OF 3-IN.-THICK ALUMINUM ALLOYS

INTRODUCTION

Recent recognition that many structural applications require materials with a reserve of resistance to fracture extension has given impetus to research in the area of over-yield fracture mechanics. Such materials are not amenable to analysis of fracture-extension processes by methods based on linear-elastic theory. The Dynamic Tear (DT) test (1) was developed several years ago to characterize fracture properties of structural materials over the full range of resistance to fracture extension. In the absence of analytical methods for failure-safe design using plastic materials, the DT test, together with larger test models and associated structural-mechanics analysis diagrams, has provided methods for assurance of safety of structures from catastrophic crack extension (1 — 5).

Recent developments of fracture-extension-resistance curves (R curves) for 1-in.-thick materials determined by DT test methods (6 — 9) permit characterization of structural metals by basic parameters. Further studies (10) indicated that an equation involving specimen cross-section dimensions and a constant related to the intrinsic resistance of the material to crack extension can be used to define R-curve slopes using specimens that are much smaller than full thickness. This report presents the results of R-curve determinations for 3-in.-thick aluminum-alloy plates with full-thickness and subthickness specimens, with emphasis on the relationships between R curves and other fracture-resistance parameters.

MATERIALS AND PROCEDURES

The test materials were four plates of 3-in.-thick aluminum alloys 5083-H321, 5086-H32, 6061-T651, and 7005-T6351, which were obtained from the Metals Properties Council. Linear-elastic fracture-mechanics tests were conducted for the same materials by Nelson and Kaufman (11).

The DT test specimen is an edge-notched bend bar. Specimens scaled for 1-in. thickness (12) and for 5/8-in. thickness (13) have been standardized for Navy use (Fig. 1); the 5/8-in.-thick configuration is currently being standardized in ASTM. Crack-starter flaws for the specimens are either brittle electron-beam welds or sharp-tip notches; tests* have shown that the flaws are equivalent. Pendulum-type test machines are used where possible, and drop-weight machines are used when required by the size or geometry of the test piece. Fracture energy is measured directly in pendulum machines, by the use of calibrated compression blocks to measure residual energy in drop-weight machines, and by integration of force-time records measured by instrumented tups for both machine types.

*Unpublished data.

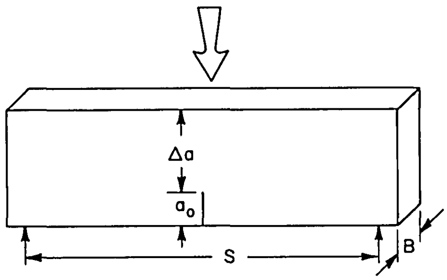

Fig. 1 — Dynamic-tear test specimen. The dimensions are scaled by the thickness of the test material. The table shows the standard configurations presently in use.

B	Δa	a_0	S
3	5	3	26
1	3	1.75	16
0.625	1.125	0.5	6.5

The DT R-curve models the characteristic behavior of ductile metals under conditions of crack propagation. Because the initial phases of crack extension involve a transition from flat fracture to some degree of shear fracture, the energy requirements for crack extension increase as the crack propagates. The R curve is a plot of energy per unit crack extension vs crack length, and the R-curve slope indicates the rate of required energy increase. It has been shown (9) that R-curve slope depends only on the fracture-extension resistance of the material; geometrical effects are predictable.

R-curve tests were conducted for the TL orientation (14) in the full thickness and in 1-in. and 5/8-in. thicknesses. Specimens were configured in the range of values of Δa/B shown in Table 1. Subsize specimens were machined from both surfaces and from the center of each test plate. Tensile tests using standard 0.505-in.-diameter specimens were conducted for corresponding locations of each alloy. A complete set of tests was conducted at 80°F; additional values of DT energy were measured at 30°F with standard 1-in. DT specimens for comparison to the existing body of data at that temperature. Full-thickness tests were conducted by the drop-weight method. Specimens of 1-in. thickness were tested in a single-pendulum testing machine of 10,000-ft-lb capacity, whereas 5/8-in.-thick specimens were tested in a double-pendulum machine of 2000-ft-lb capacity and in a drop-weight machine of the same capacity.

Table 1
Configurations of the Dynamic-Tear-Test Specimens

3-in. Thick (Full Thickness)				1-in. Thick				5/8-in. Thick			
Notch Depth (in.)	B (in.)	Δa (in.)	$\frac{\Delta a}{B}$	Notch Depth (in.)	B (in.)	Δa (in.)	$\frac{\Delta a}{B}$	Notch Depth (in.)	B (in.)	Δa (in.)	$\frac{\Delta a}{B}$
3	3	3	1	1	1	1	1	0.5	0.625	0.625	1
3	3	5	1.67*	1	1	2	2	0.5	0.625	1.125	1.8*
3	3	7	2.33	1	1	3	3*	0.5	0.625	1.75	7.8
3	3	10	3.33					0.5	0.625	2.375	3.5

*Standard specimen configuration

DISCUSSION OF RESULTS

The results of R-curve tests and tensile tests of the subject materials are presented in Tables 2 — 4. DT energy values measured with standard 1-in.-thick specimens at 30° F and at 80° F are nearly identical (Table 2), so that there is no effect in this temperature range.

Table 2
Standard 1-in. Dynamic-Tear-Test Results

Alloy	DT Energy (ft lb)				
	30° F				80° F
	A (Surface)	B (Surface)	C (Center)	Avg	Avg
5083-H321	970	950	690	870	880
5086-H32	1710	1720	1130	1520	1507
6061-T651	470	530	290	430	467
7005-T6351	490	470	430	460	463

One factor that was immediately apparent from the DT data is the gradient of fracture resistance through the thickness of three of the four plates. Only the 7005-T6351 plate had uniform fracture properties through the thickness. For each of the three remaining plates, fracture-resistance properties are comparable for both surfaces, whereas the plate center has significantly lower properties. The gradient effect is illustrated in Fig. 2 for the 5086-H32 alloy by R curves for the 1-in.-thick specimens. In Fig. 2 the R-curve slope is considerably lower for center material than for surface material. Tensile-test data (Table 4) did not reveal any differences in plate properties through the thickness, except for a small gradient in the 7005-T6351 plate.

DT R curves for the four aluminum alloys are presented in Figs. 3 — 5 for 3-in.-thick (full-thickness) specimens, 1-in.-thick specimens, and 5/8-in.-thick specimens respectively. Because of the gradient effect, R curves determined by 1-in.- and 5/8-in.-thick specimens are shown in terms of average values. In Fig. 3 an apparent anomaly of crossing R curves can be explained in terms of thickness-vs-strength relationships. One notes that in Fig. 3 the curve for 7005-T6351 is flat, indicating that elastic behavior is expected. This was, in fact, the only alloy for which a valid K_{Ic} could be measured (11). Alloy 6061-T651 had approximately the same K_Q value as alloy 7005-T651, but it also had a lower yield strength and failed to satisfy the rising load requirement. For full thickness, a rising R curve which intersects the flat R curve of alloy 7005-T6351 is expected for alloy 6061-T651, as shown in Fig. 3. For tests involving subthickness specimens, R curves with positive slopes are expected for all four alloys, as shown in Figs. 4 and 5. R-curve tests with subthickness specimens indicated nonelastic behavior, for the thickness tested, by rising R curves. R curves for all tests of the 5083-H321 and 5086-H32 alloys had positive slopes. This indicates a high level of resistance to plastic fracture extension, as was also shown by the behavior of these materials in K_{Ic} tests (11).

Table 3
Dynamic Tear Tests of 3-in.-Thick Aluminum Alloys

B (in.)	Δa (in.)	5083-H321 Energy (ft lb)				5086-H32 Energy (ft lb)				6061-T651 Energy (ft lb)				7005-T6351 Energy (ft lb)			
		A (Surface)	B (Surface)	C (Center)	Avg	A (Surface)	B (Surface)	C (Center)	Avg	A (Surface)	B (Surface)	C (Center)	Avg	A (Surface)	B (Surface)	C (Center)	Avg
0.625	0.625	40	42	30	37	59	65	47	57	22	27	22	24	22	23	22	23
	1.125	131	131	88	117	201	197	134	177	68	71	58	66	74	72	71	72
	1.750	312	312	302	309	472	452	392	439	152	152	162	155	192	162	162	172
	2.375		612	452	558	1010	892	692	864	282	312	282	292	322	332	362	338
1	1	120	140	90	117	240	230	180	216	89	89	70	83	90	100	80	
	2	420	430	300	384	712	730	500	648	210	210	180	200	260	260	250	
	3	950	1000	690	880	1690	1690	1240	1507	470	510	420	467	500	540	410	
3	3			2066				3320				1070				1620	
	5			4100				9450				2000				2550	
	7			8700				-				4950				3700	
	10			13600				26100				-				5500	

Table 4
Tensile-Test Properties of 3-in.-Thick Aluminum-Alloy Plates

Alloy	Location*	YS (ksi)	UTS (ksi)	RA (%)	El (%)
5083-H321	A	31.5	48.6	30	17
	B	31.9	49.6	27	18
	C	32.8	50.3	19	16
5086-H32	A	28.1	43.2	36	17
	B	28.6	43.5	36	20
	C	28.5	44.0	29	18
6061-T651	A	41.5	46.9	33	13
	B	41.4	46.8	30	14
	C	41.7	46.5	28	13
7005-T6351	A	48.5	55.6	37	16
	B	46.7	52.7	42	17
	C	51.2	58.5	29	13

*A and B indicate surfaces; C indicates center.

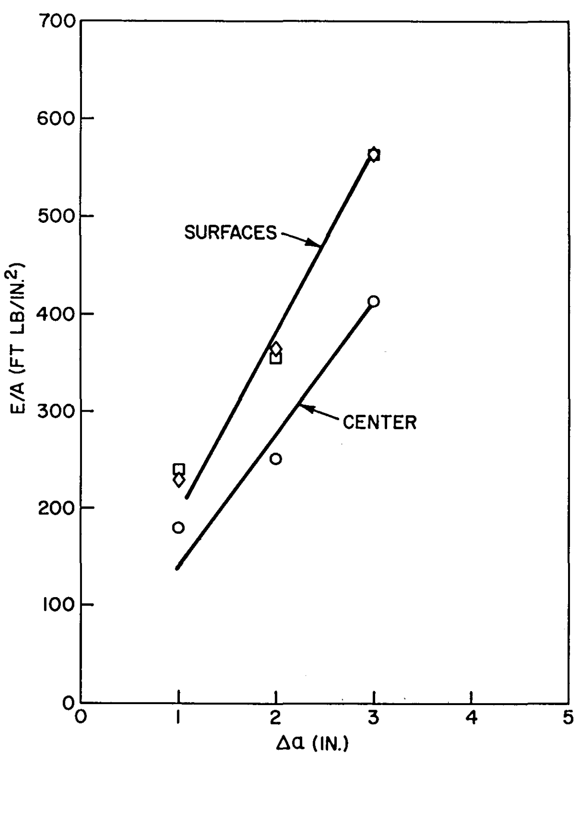

Fig. 2 — Gradient of fracture properties between surface material and center material for 3-in.-thick 5086-H32 alloy, as shown by R curves for 1-in. thickness

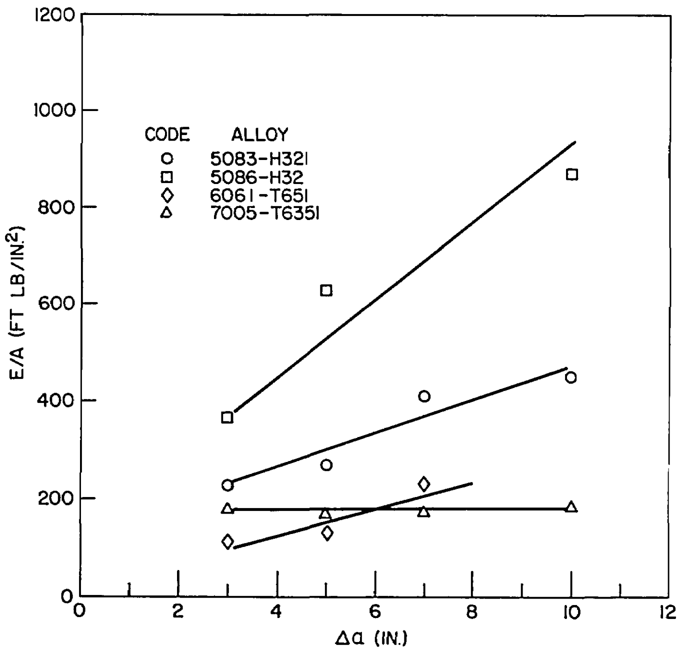

Fig. 3 — R curves for full-thickness (3-in.) aluminum alloys. The flat R curve for the 7005-T6351 alloy indicates plane-strain levels of fracture resistance.

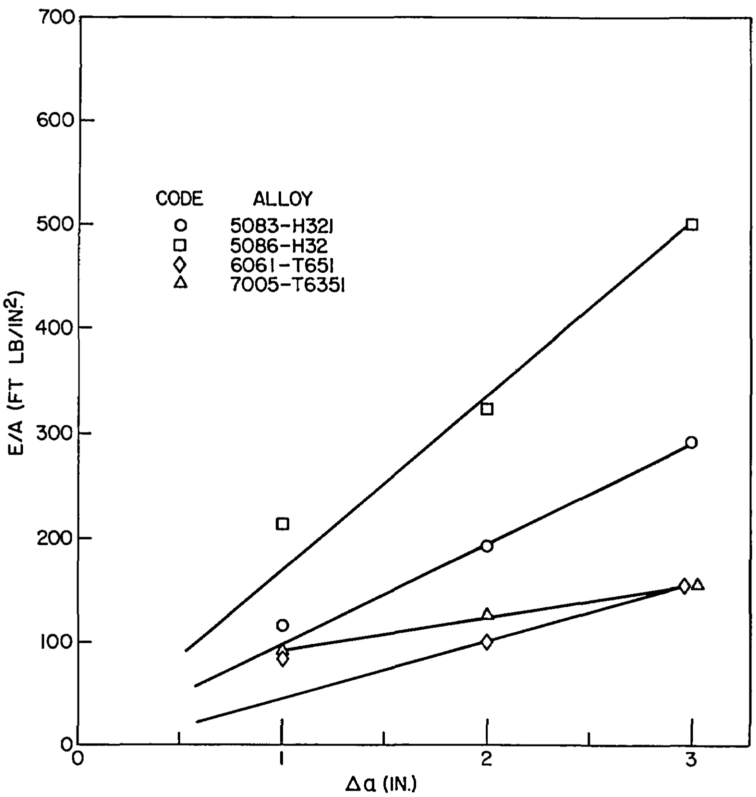

Fig. 4 — R curves determined with 1-in.-thick specimens. Note the positive slope of curves for all alloys.

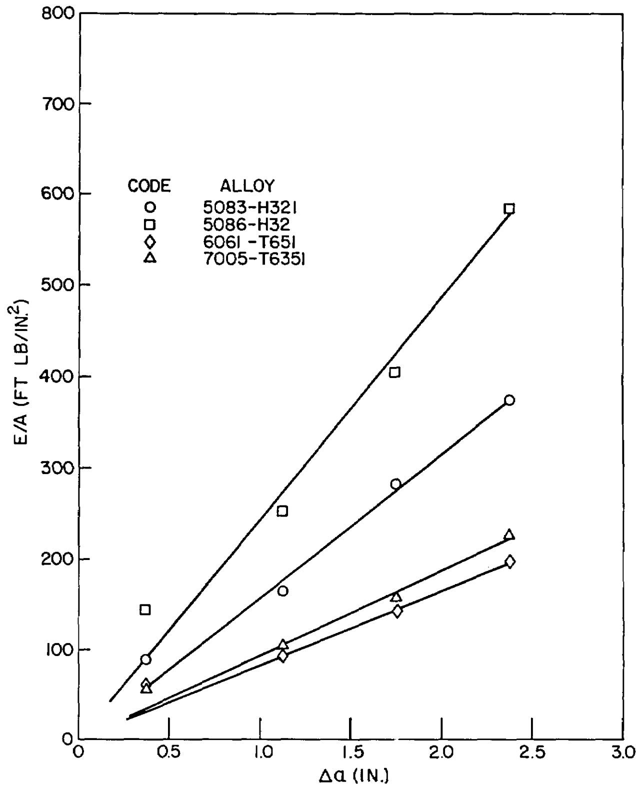

Fig. 5 — R curves determined with 5/8-in.-thick specimens

The 7005-T6351 alloy offered a unique opportunity to study the effect of constraint on R-curve slope. For full thickness a flat R curve is expected because of the plane-strain condition required for valid K_{Ic} measurement. As mechanical constraint is decreased by testing smaller section sizes, R-curve slope should increase. Figure 6 compares R-curve slopes by plotting E/A vs $\Delta a/B$, the specimen aspect ratio. The results are entirely as predicted. The full-thickness R curve is flat, whereas the slopes of the R curves for the 1-in. thickness and for the 5/8-in. thickness become steeper with decreasing thickness.

Earlier work with R curves of aluminum alloys was the basis for an equation defining fracture properties of metals (7). The equation is $E = R_p (\Delta a)^{1.8} B^{0.7}$, where R_p is a constant that describes the properties of the metal and Δa and B are as defined in Fig. 1. The factor R_p was calculated for each DT test for each alloy. Values of R_p were then averaged to give a characteristic number for the material (Table 5). The accuracy of the method is demonstrated in Fig. 7 by plotting E/R_p vs $(\Delta a)^{1.8} B^{0.7}$; this procedure separates dimensional parameters from measured values and gives an indication of the closeness of the fit. Log-log coordinates are used to separate the data points for comparison purposes and to emphasize that results of small-specimen tests can be used to predict full-thickness test results. In effect this procedure compares predicted values with measured values. The good fit to a 1:1-correspondence line illustrates that the method applies over an extremely wide range of DT energy for a given alloy. Values of R_p were not calculated for full-thickness tests of the 7005-T6351 alloy because the equation does not apply for the plane-strain condition.

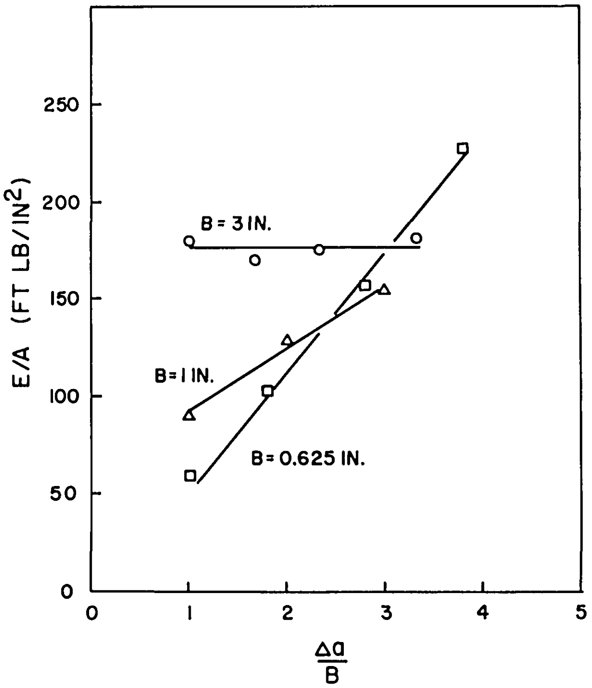

Fig. 6 — Comparison of R-curve slopes for different specimen thicknesses for the 7005-T6351 alloy

Table 5
Comparison of Parameters for Defining Fracture-Extension Resistance

Alloy	R_{sb}	K_{MCSF}	R_p^*	$R_p^\dagger$
5083-H321	1.14	3.67	128	115
5086-H32	1.54	6.38	214	197
6061-T651	0.70	1.42	73	63
7005-T6351	0.79	1.89	82	71

*Calculated from $E = R_p(\Delta a)^{1.8} B^{0.7}$
†Calculated from $E = R_p(\Delta a)^2 B^{0.5}$

For use of the equation in practical applications, it is convenient to simplify the analytical work to change the equation to $E = R_p (\Delta a)^2 B^{0.5}$ by rounding off the exponents. The energy values and specimen dimensions were substituted in this equation, and R_p was calculated for each material as before (Table 5). A plot of E/R_p vs $(\Delta a)^2 B^{0.5}$ (Fig. 8) shows that, except for large values of Δa in full thickness, the equation with rounded-off exponents is sufficiently accurate for engineering use.

Comparison of the parameters measured in K_{Ic} tests (11) of all four alloys with the R_p values shows that all factors rank the materials in the same order. Table 5 lists the parameters of interest: R_{sb} = specimen strength ratio, which is the ratio of maximum crack-tip stress to the tensile yield strength, K_{max} or the equivalent $K_{MCSF} = 2.5(K_{max}/\sigma_{ys})^2$, as noted in Ref. 11, and R_p. The materials are ranked in the same order by all

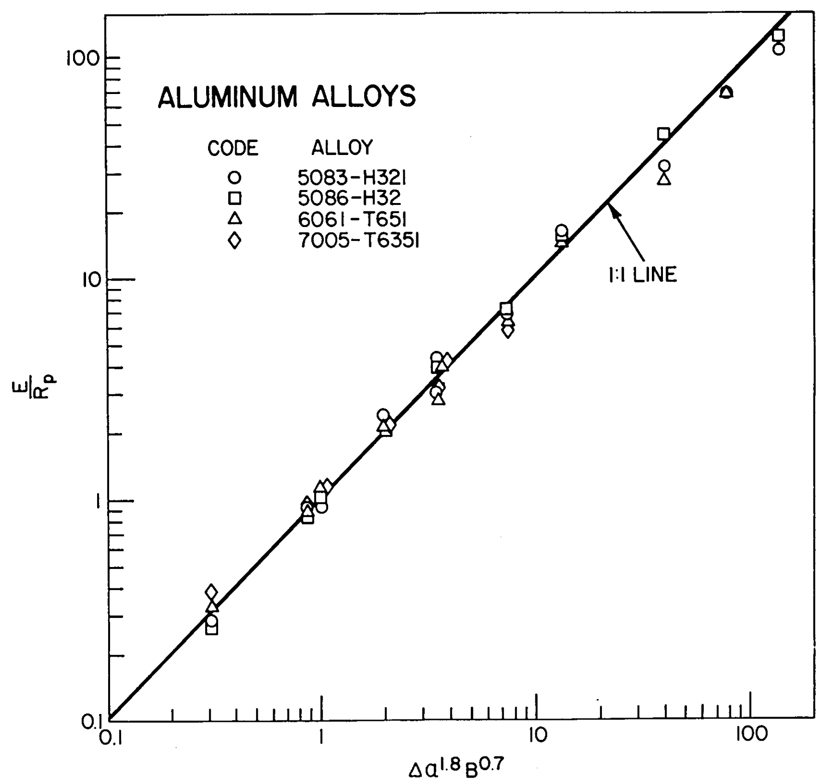

Fig. 7 — Accuracy of $E = R_p(\Delta a)^{1.8}\ B^{0.7}$ in defining the effects of specimen geometry on measured energy in the DT test. This equation can be used to predict DT energy or R-curve slope for full-thickness materials from subthickness specimens.

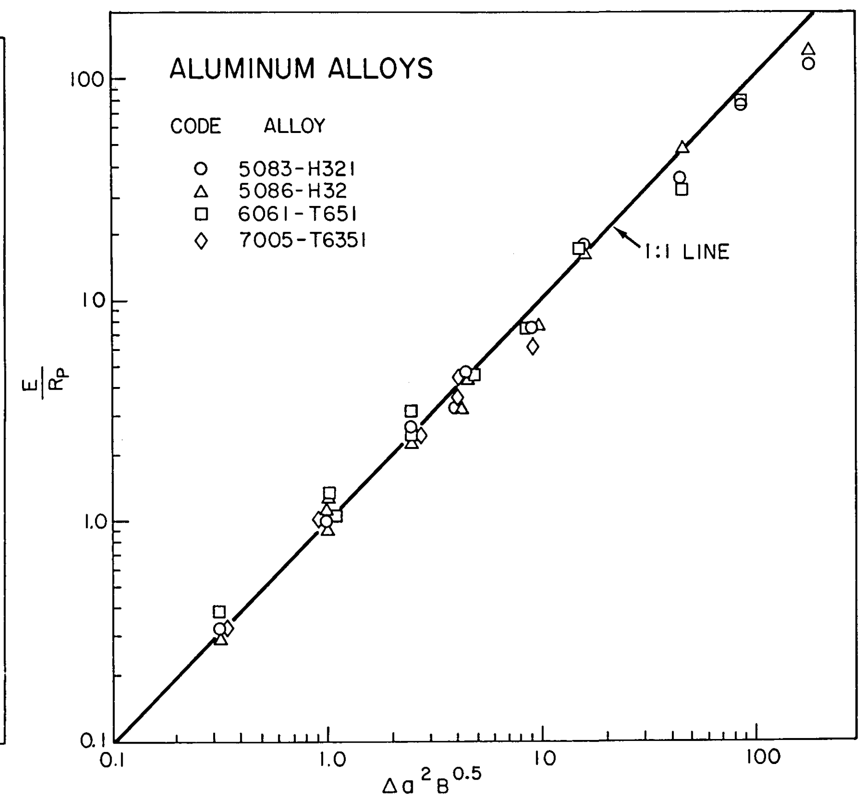

Fig. 8 — Accuracy of $E = R_p\ (\Delta a)^2\ B^{0.5}$

three parameters; additionally, plots of K_{MCSF} and R_{sb} vs R_p (Fig. 9) show that a correspondence exists. This is to be expected, since all three parameters attempt to measure the same physical property. Three pertinent factors should be noted at this point:

- Of the three parameters, R_p is the only one that describes resistance to crack extension; the other two are based on observations of crack initiation.
- Of the three parameters, R_p is the only one that is independent of geometry effects.
- Of the three parameters, R_p is by far the easiest and least expensive to obtain.

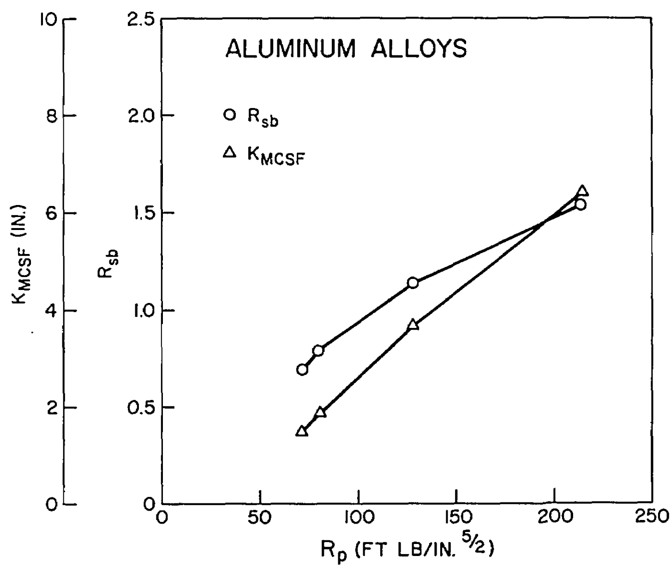

Fig. 9 — Correspondence of parameters for defining fracture resistance of ductile materials

Predictions of the fracture state — elastic, elastic-plastic, or plastic (9) — can be made from the DT test and associated Ratio Analysis Diagram (RAD). Plotting the R_p values on the aluminum RAD (Fig. 10) shows the expected fracture performance for each material. The K_{Ic}/σ_{ys} lines divide the RAD for analysis of the 3-in. thickness as follows:

$$\frac{K_{Ic}}{\sigma_{ys}} < 1.1 \qquad \text{— Elastic; } K_{Ic} \text{ fracture}$$

$$1.1 < \frac{K_{Ic}}{\sigma_{ys}} < 1.73 \text{ — Elastic-plastic}$$

$$\frac{K_{Ic}}{\sigma_{ys}} > 1.73 \qquad \text{— Plastic fracture}$$

Average R_p values and K_{max} or K_{Ic} values are shown for each material. The 7005-T6351 alloy is predicted to have elastic fracture properties by the location of the R_p point, as was the case. Both of the 5000-series alloys have plastic fracture properties and did not give valid K_{Ic} numbers. One notes that K_{max} for each alloy was considerably lower than the R_p value in the RAD; this shows that use of K_{max} for lower-bound-type calculations of fracture conditions leads to underestimated assessments of the metal tolerance for sharp cracks and high stress levels.

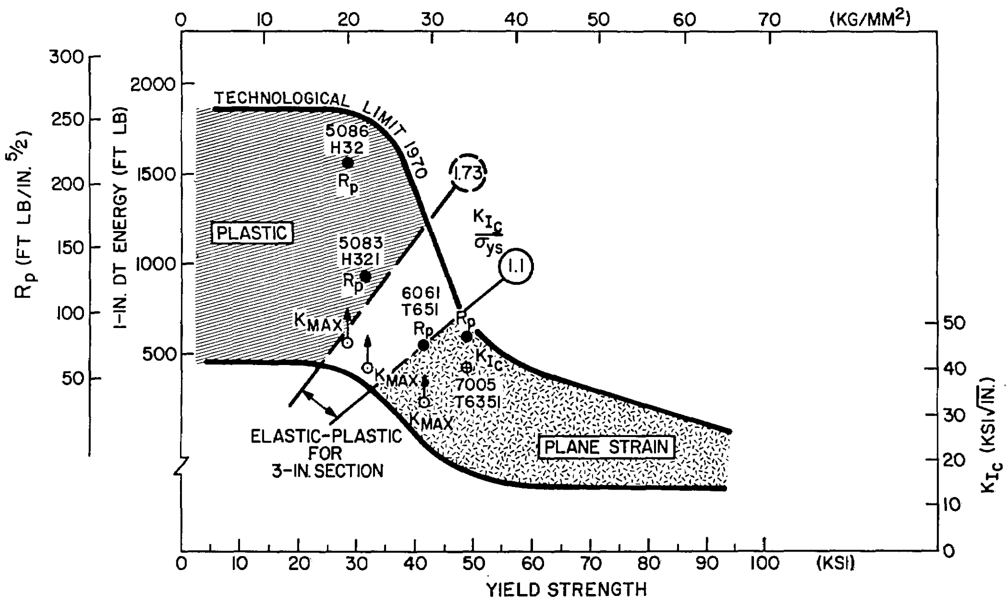

Fig. 10 — Ratio Analysis Diagram for aluminum alloys scaled to define fracture states for 3-in.-thick materials. The data plotted, K_{max} and average R_p, are compared to show that K_{max} underestimates the true fracture properties of the materials to a large degree.

It is interesting to note that the *average* R_p value for the 6061-T651 alloy lies on the boundary line for valid plane-strain numbers. The K_Q for this material met all criteria except that of rising load. Because of the fracture gradient, it can be visualized that crack initiation in the center of the K_{Ic} specimen, which had the lowest resistance, was followed by arrest of the crack in the surface material, which had elastic-plastic properties. The rising load was necessary to cause the fracture to extend in the elastic-plastic surface material.

CONCLUSIONS

From the DT tests of 3-in.-thick aluminum alloys and comparisons with the results of K_{Ic} tests of the same materials, the following conclusions can be drawn:

- R curves for aluminum alloys accurately predict the fracture behavior. The same predictions are obtained from both full-thickness and subthickness tests.
- For three of the four materials tested in this study, gradients in fracture properties through the thickness existed. These gradients were not observed by tensile tests or by full-thickness K_{Ic} tests.
- A previously developed equation which permits definition of fracture resistance by a parameter R_p, which is not dependent on the geometry, applies for these aluminum alloys.

- Comparison of R_p with parameters determined in K_{Ic} tests showed that R_p, specimen strength ratio, and the quantity 2.5 $(K_{max}/\sigma_{ys})^2$ ranked the materials in the same order, and that a correspondence existed between R_p and each of the other parameters.
- Analysis of R_p and K_{max} or K_{Ic} data on the RAD showed that DT tests accurately predict the structural performance of each test material, as well as the results of K_{Ic} tests. In the case of the 6061-T651 alloy, the surface-to-center gradient in fracture toughness that was revealed by the DT test was probably responsible for the failure of the material to meet the requirements for a valid K_{Ic} test (15).

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13. ABSTRACT

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