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Fracture Toughness Characterization Procedures and Interpretations to Fracture-Safe Design for Structural Aluminum Alloys

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CONTENTS

Abstract ii
Problem Status ii
Authorization ii

INTRODUCTION 1

CHARACTERISTICS OF ALUMINUM ALLOYS 1

FRACTURE TOUGHNESS TESTS 2

- Fracture Mechanics Tests 2
- C_v Tests 6
- Notched Tensile Tests 7
- DT Test 7

CORRELATIONS OF FRACTURE TOUGHNESS TESTS 9

- Correlation of DT and C_v Tests 11
- Correlation of Notched Tensile and DT Tests 11
- Correlation of K_{Ic} and DT Tests 11
- Correlation of K_{Ic} and C_v Tests 14

INTERPRETATION OF CORRELATION RELATIONS 15

- Fracture Toughness OMTL Diagram for Aluminum Alloys 18
- Flaw Size Analysis Diagrams 19

RATIO ANALYSIS DIAGRAM 21

SUMMARY 22

ACKNOWLEDGMENTS 24

REFERENCES 24

ABSTRACT

Interpretations of fracture toughness characteristics as measured by various test procedures are presented for structural aluminum alloys. Quantitative definitions of the significance of engineering fracture toughness tests are provided by extension of analytical procedures evolved from fracture mechanics theory. The procedural simplicity of the engineering tests coupled with the analytical capabilities of fracture mechanics theory provides for a significant advancement in fracture-safe design procedures for aluminum alloys covering the full range of yield strength.

The interpretative procedures are evolved from correlations of K_{Ic} with the Dynamic Tear (DT) and Charpy V-notch (C_v) test. An Optimum Material Trend Line (OMTL) diagram is developed which summarizes all the DT fracture toughness data and is additionally indexed according to the K_{Ic} and C_v correlation plots.

Iso-flaw depth lines based on flaw size-stress level calculations for fracture of 1- and 3-in.-thick sections are then placed in overlay on the OMTL diagram. The K_{Ic}/σ_{ys} ratio lines are indexed to the iso-flaw depth lines, and a K_{Ic}/σ_{ys} Ratio Analysis Diagram (RAD) emerges. The RAD provides for simplified, general engineering interpretation of flaw size-stress conditions for fracture. The general fracture toughness characteristics of different aluminum alloy families are simply defined by zones encompassing all the fracture toughness data and their position relative to the K_{Ic}/σ_{ys} ratio lines.

PROBLEM STATUS

This is a special interpretive report covering the results of a wide range of investigations within the Metallurgy Division of NRL and aimed at the general problem of metallurgical optimization and fracture-safe design. The major portions of these investigations are continuing under established problem and subtask categories.

AUTHORIZATION

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FRACTURE TOUGHNESS CHARACTERIZATION PROCEDURES AND INTERPRETATIONS TO FRACTURE-SAFE DESIGN FOR STRUCTURAL ALUMINUM ALLOYS

INTRODUCTION

High-strength aluminum alloys are of interest for structural applications because of their high strength-to-density ratio. Knowledge of the fracture toughness characteristics of these alloys is an important factor in failure-safe design. It has only been in the last few years that meaningful fracture toughness information has been developed for the full strength spectrum of aluminum alloys.

This report presents a summary of fracture toughness characterizations for a variety of commercial aluminum alloys produced as large plates. It also provides procedures for the interpretation of fracture toughness parameters in terms of critical flaw size and stress level factors for sections of 1- to 3-in. thickness. The procedures are the same as those evolved for high-strength steels (1) and titanium alloys (2). The first step in evolving these procedures is based on the correlation of Dynamic Tear (DT) and Charpy V-notch (C_v) tests to fracture mechanics tests in the range where valid plane strain stress-intensity values (K_{Ic}) can be obtained. The second step is based on reasonable extrapolations of the correlations for consideration of conditions of higher fracture toughness. Flaw size-stress level calculations based on plane strain K_{Ic} or plane stress K_c conditions provide the desired interpretation of the C_v and DT tests. Thus, the procedures couple the relatively simple engineering tests with the analytical capability of fracture mechanics theory.

CHARACTERISTICS OF ALUMINUM ALLOYS

Aluminum alloys are classified according to alloy systems and temper, i.e., heat treatment and/or mechanical working. The various alloy systems are number coded according to their primary compositional elements under the guidance established by the Aluminum Assocation:

1XXX - Al

2XXX - Al-Cu

3XXX - Al-Mn

4XXX - Al-Si

5XXX - Al-Mg

6XXX - Al-Mg-Si

7XXX - Al-Zn-Mg

Specific alloy designations, such as 2024 and 7075, describe the major alloy system and indicate additions of other specific alloying elements.

Temper designations of aluminum alloys refer to the heat-treated or worked condition of the material. The H designation (as in 5086-H112) refers to strengthening by

strain hardening with or without subsequent thermal treatment to produce softening. The digits following the H indicate the specific processes involved. The T temper designates a thermal strengthening process followed by an aging treatment and/or mechanical work. Again, the digits indicate the specific processes involved. A comprehensive treatment of alloy systems and temper designations is presented in Refs. 3 and 4.

Principal alloys in the 2000, 5000, 6000, and 7000 aluminum systems were covered in this study. Alloys of the 2000 alloy system are heat treatable to high strength levels. At the higher strength levels of their heat treatable range, these alloys feature low resistance to fracture. At intermediate levels of strength the formability and machinability of these alloys make them desirable for machined parts, forgings, structural members in aircraft, etc.

The 5000 series alloys represent material which can be processed to yield strengths (YS) in the order of 30 to 40 ksi. These alloys have a high inherent resistance to fracture. The good corrosion resistance and welding characteristics of most of these alloys have led to their extensive use for a variety of structures in marine applications, as well as for containers, piping, etc. In general, the 6000 series alloys have properties similar to the 5000 series and are used in many of the same applications.

The 7000 series alloys are the ultrahigh-strength alloys favored by the aircraft industry. These alloys are heat treatable to YS levels of 70 to 80 ksi and in this condition, in 1-in. plate sizes, are generally of low fracture toughness.

The strengthening mechanism of most aluminum alloys is one of precipitation hardening or the dispersion of a system of fine intermetallic particles throughout the softer aluminum matrix. The microfracturing process in these alloys (in all except environmentally influenced fracture) is one of microvoid coalesence of the metal, where the brittle intermetallic or precipitate particles fracture in advance of a moving crack, creating microcracks in the matrix. The microcracks then enlarge in a ductile fashion. This fracture mode is illustrated by fractographs of fractured C_v specimens of 2219-T87 (Fig. 1). The increase in dimple size without a comparable increase in C_v energy illustrates both the limitations of the C_v test and the low intrinsic fracture toughness characteristic of high-strength aluminum alloys.

All materials used in the studies covered by this report represent rolled plate produced according to standard commercial practice. The nominal chemical composition limits are given in Table 1. Tensile and fracture toughness information are presented in Table 2.

FRACTURE TOUGHNESS TESTS

Fracture Mechanics Tests

Fracture mechanics tests characterize fracture toughness in terms of the value of the elastic stress field intensity K in the region ahead of the crack-tip plastic zone. The critical stress intensity level for crack extension (instability) is designated by the parameter K_{Ic}. The subscript I defines the condition of the opening mode (5) for which the applied stress is normal to the plane of the crack.

The K_{Ic} value must be determined under the condition of maximum possible mechanical constraint that can be applied to the metal at the crack tip. Such a condition is termed plane strain, and when it is attained, K_{Ic} represents the lowest value of fracture toughness and is said to be geometry independent. Plane strain is attained in K_{Ic} testing by imposing predetermined requirements on the width, length, thickness, and crack depth

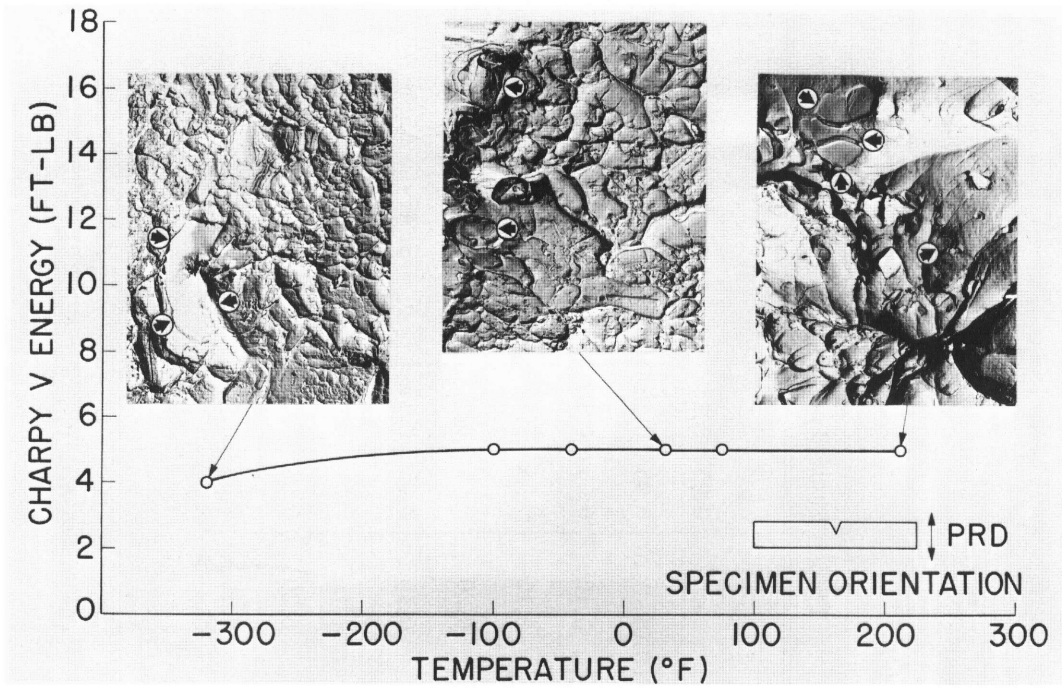

Fig. 1 - Fracturing mode of a high-strength aluminum alloy

of the fracture mechanics specimens to ensure that valid K_{Ic} values are obtained. Of these dimensions, thickness is most significant to valid K_{Ic} determinations, because it is the basic dimension from which the other dimensions required for maximum mechanical constraint are determined. For example, an increase in thickness is required with an increase in fracture toughness to simultaneously maintain flaw width and depth dimensions sufficient to maximize constraint conditions at the crack tip. Once a valid plane strain K_{Ic} value has been established, it is then possible to calculate critical flaw size-stress level relationships for various kinds of flaws in the material, based on equations derived by linear-elastic fracture mechanics. The calculations, therefore, presuppose that equivalent conditions of maximum constraint are involved. To ensure that the requirements for plane strain can be met, the thickness of the K_{Ic} specimen must satisfy the conditions

$$B \geq 2.5\,(K_{Ic}/\sigma_{ys})^2,$$

where

B = thickness (in.),

K_{Ic} = critical plane strain stress intensity factor (ksi $\sqrt{\text{in.}}$),

and

σ_{ys} = yield stress (ksi).

It is important to note that the ratio of $(K_{Ic}/\sigma_{ys})^2$ is proportional to the crack-tip plastic zone size. According to this ratio, a specific K_{Ic} value related to metal of increased yield strength results in a decrease in the plastic zone size, i.e., a decrease in fracture toughness. An increase in the K_{Ic} value for a given level of yield strength

Table 1
Chemical Composition Limits*

Alloy Designation	Composition (%)*										
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Each	Total	Remarks
2020	—	—	4.5	0.5	—	—	—	—	—	—	0.2 Cd, 1.1 Li
2024	0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	0.25	—	0.05	0.15	—
2219	0.20	0.30	5.8-6.8	0.20-0.40	0.02	—	0.10	0.02-0.10	0.05	0.15	0.05-0.15 V, 0.10-0.25 Zr
5083	0.40	0.40	0.10	0.3-1.0	4.0-4.9	0.05-0.25	0.25	0.15	0.05	0.15	—
5086	0.40	0.50	0.10	0.20-0.7	3.5-4.5	0.05-0.25	0.25	0.15	0.05	0.15	—
5456	0.40 Si + Fe		0.10	0.50-1.0	4.7-5.5	0.05-0.20	0.25	0.20	0.05	0.15	—
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.05	0.15	Si:45-65 Mg
X7005	—	—	—	—	1.4	0.13	4.6	—	—	—	0.14 Zr
7075	0.50	0.7	1.2-2.0	0.30	2.1-2.9	0.18-0.40	5.1-6.1	0.20	0.05	0.15	—
7079	0.30	0.40	0.40-0.8	0.10-0.30	2.9-3.7	0.10-0.25	3.8-4.8	0.10	0.05	0.15	—

Table 2
Properties of Aluminum Alloys

Alloy	YS (ksi)		UTS (ksi)		30°F C_v (ft-lb)		30°F DT (ft-lb)		K_{Ic} (ksi $\sqrt{in.}$)	
	RW	WR	RW	WR	RW	WR	RW	WR	RW	WR
1100F	9.8	-	13.0	-	58	-	-	-	-	-
2024-T4	48.1	48.3	72.4	71.9	10	7	490	279	47.4	31.0
2024-T351	40.5	43.9	59.5	65.8	-	-	377	206	-	-
2020-T651	-	76.3	-	80.4	-	-	79	79	-	-
2219-T87	57.9	55.2	72.0	72.0	5	5	207	207	33.3	30.1
2219-T851	59.3	58.4	73.4	74.3	5	5	422	248	37.7	37.1
6061-T651	41.7	40.0	45.7	47.0	11	8	1045	548	-	-
6061-T651	38.0	38.3	41.5	44.3	10	10	880	614	-	-
5083-0	19.1	19.4	45.4	45.1	30	23	1840	1530	-	-
5086-H112	26.3	24.2	43.6	43.0	35	22	2210	1480	-	-
5456-H321	37.8	34.0	54.1	55.0	15	8	1400	726	-	-
7005-T63	46.3	45.9	53.2	51.7	19	13	1400	770	-	-
7075-T6	78.5	77.8	90.0	88.2	5	4	110	102	33.1	24.0
7075-T6	-	74.6	-	83.9	-	-	123	61	-	-
7075-T7351	63.9	65.6	75.4	75.5	6	4	249	176	33.3	26.7
7079-T6	77.1	74.9	86.0	85.4	5	2	249	81	-	21.7
7106-T63	52.1	52.5	61.2	60.8	10	8	1085	419	-	41.7

corresponds to a rapid increase in the plastic zone size and the $(K_{Ic}/\sigma_{ys})^2$ ratio and, therefore, the B requirement for retention of the plane strain condition. Consequently, for materials of high fracture toughness the required specimen size becomes very large. For example, a material with a ratio of 2.0 requires a B (test thickness) value of at least 10 in.

If the thickness is less than the minimum B requirement, the mechanical constraint is then less than adequate for plane strain, even for a very deep crack, and the measurement of fracture toughness must be considered as relating to a plane stress, specimen geometry-dependent K_c value. Plane stress K_c conditions involve fractures of mixed-mode (flat plus slant) or full slant appearance. Mathematical relationships between the parameters K_c and K_{Ic} have been proposed for calculation of the K_{Ic} stress-intensity factor measured under K_c conditions and vice versa (6). These relationships are only approximations at the present state of development of fracture mechanics. For metals of relatively high fracture toughness (high ratio of K_{Ic}/σ_{ys}) the relationships provide a means for the calculation of approximate plane stress critical flaw sizes. Since the flaws for this stress state are very large, a premium is not placed on exactness of the calculations. Such calculations may be regarded as estimates that provide guidelines for general engineering interpretations involving relatively tough materials.

At the present stage of development, fracture mechanics tests do not lend themselves to routine testing. The cost of K_{Ic} testing is high, due to the requirement of close tolerances on specimen dimensions, stringent conditions for producing acceptable fatigue cracks, and other aspects of research laboratory equipment and procedures required in the conduct of the tests. Because of the limitations of fracture mechanics testing,

considerable benefit can be derived from a correlation of K_{Ic} values with the results of simple engineering tests that can be used for routine fracture toughness characterization. The engineering tests can be used across a full spectrum of fracture toughness levels ranging from plane strain to full plane stress. Within the limits of geometry factors that provide for valid K_{Ic} measurement, direct correlations between the tests should be possible. Beyond the limits for which valid K_{Ic} values can be obtained, extrapolation of the correlations may be made to provide approximations of the K_{Ic} value. For intermediate to high fracture toughness levels, the approximated K_{Ic} value is then used for calculating critical flaw size-stress levels for instability with the added consideration of the effects of plane stress.

Values of K are calculated from experimental determinations of crack-tip opening displacements obtained by means of a clip gage spanning the crack opening. Load-clip gage displacement plots provide the indication of a crack-tip opening instability by a drop in the load with increasing clip gage displacement. The nominal stress is calculated using appropriate equations. The critical stress-intensity factor for instability K_{Ic} is derived from fracture mechanics equations that relate K to crack depth and nominal stress. Crack instability occurs at a value of K_{Ic} which is unique to the material. Different combinations of crack depth and nominal stress can be used to obtain this value, provided plane strain conditions are satisfied.

The problem of conducting valid K_{Ic} tests and the interpretations for tests relating to tough materials is a complex subject which is covered in a simplified introductory manner in Ref. 1.

There are various fracture mechanics tests available for obtaining valid K_{Ic} data (7) provided the requirements for plane strain are met. The single-edge-notch (SEN) tensile specimen, Fig. 2, dimensioned for full thickness testing of 1-in.-thick plate was used for the investigations to be described. The specimen was side grooved on each side along the expected fracture path to a depth of 5% of the thickness to provide enhanced detectability of crack instability on the load-displacement curve. A 0.10-in. fatigue crack was formed at the bottom of a 1.5-in.-deep machined notch in conformance with the requirements of ASTM-E24 Committee's recommended practice for conducting K_{Ic} tests.

Load-displacement curves were plotted by an X-Y recorder from the output of a strain-gage-type load transducer on the tensile machine and a crack opening displacement clip gage placed in the notch opening of the specimen. The load at the lowest distinct deviation from linearity occurred at or very near to maximum load; this value was used for calculation. A single-iteration correction for the influence of the plastic zone on effective crack depth was included in the K_{Ic} calculation.

C_v Tests

The C_v test* has been recognized as lacking adequate discrimination capability for the full range of fracture toughness of aluminum alloys. In general, the C_v test is insensitive to changes in temperature, Fig. 3, and the energy range for the spectrum of aluminum alloys corresponds to low values compared to those recorded for steels and titanium alloys. The C_v test has serious limitations, even for metals of intrinsically high C_v energy. For example, for steels it must be indexed by other fracture toughness tests or by service experience for proper interpretation of results.

*Details of the C_v test are given in ASTM STD E23-66.

Notched Tensile Tests

For many years the principal method for fracture toughness evaluation of aluminum alloys has been based on tests of notched round tensile bars. The parameter of comparison is the ratio of the breaking strength of the notched bar to the tensile yield strength of the material, for a specified notch acuity. Increasing values of the ratios above 1.0 are considered to indicate increasing ability of the material for plastic deformation at the notch tip.

The specimen configuration used for comparison in this investigation was a 0.750-in.-diam bar notched to a 0.422-in.-diam test section. The root radius at the bottom of the sharp V notch was 0.001 in. maximum. The specimens were tested in tension at room temperature at a 0.002-in./in./min loading rate.

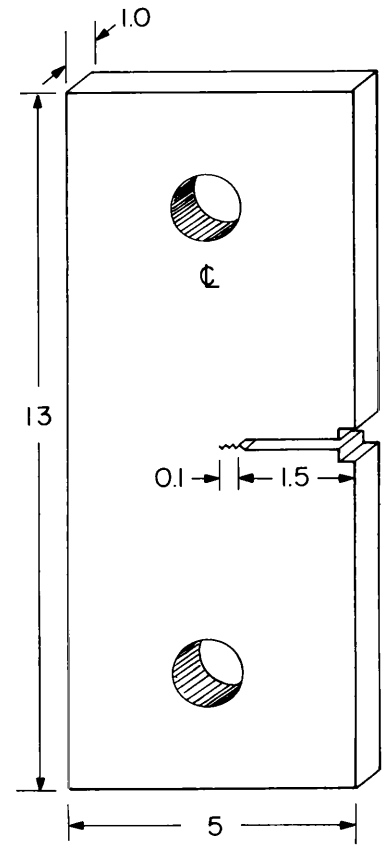

Fig. 2 - SEN tensile specimen used for fracture mechanics tests

DT Test

The DT test was developed to provide a practical laboratory procedure for measurement of the fracture toughness associated with the characteristic fracture propagation mode of the metal. A principal requirement for this purpose, which is a feature of the DT test, is the simulation of a sharp natural crack for the initiation of the fracture. This feature is obtained for the DT test by the simple expedient of introducing a brittle electron beam (EB) weld, thereby eliminating the complications of fatigue precracking. The energy required to fracture the specimen serves as an index of the size of the crack-tip plastic zone associated with the natural process of fracture propagation. The width-to-thickness geometry of the DT test is sufficient to establish conditions for the development of the natural fracture mode related to intrinsic toughness and thickness aspects. For relatively brittle materials, which fracture in the plane strain mode (flat fracture) with small plastic zones, low energy absorption is measured. With increasing toughness the plastic zone size increases, culminating in the development of a large plastic enclave preceding the fracture process. At high fracture energies, slant fracture (shear) is generally obtained. Mechanical constraint effects due to thickness, which influence the plastic zone size, may be evaluated directly by scaling the size of the DT specimen.

In effect, the DT test defines the fracture mode (plane strain, mixed-mode plane stress, or full plane stress) when conducted for the specific section size of interest. The effects of deviations from the specific size (DT tests of thickness less than plate thickness) may be interpreted from the intrinsic fracture toughness value and fracture mode that is observed. For example, a flat-break fracture which implies plane strain conditions would not be changed by increased thickness. Similarly, a full-slant plane stress fracture, associated with high energy absorption measured for a 1-in. DT test specimen, implies that an increase to sections of 2- to 3-in. thickness would not be expected to decrease the fracture toughness level significantly. Thus, the characterization of the thick-section fracture toughness as related to gross strain mechanical conditions would not change. For intermediate fracture toughness levels represented by mixed-mode

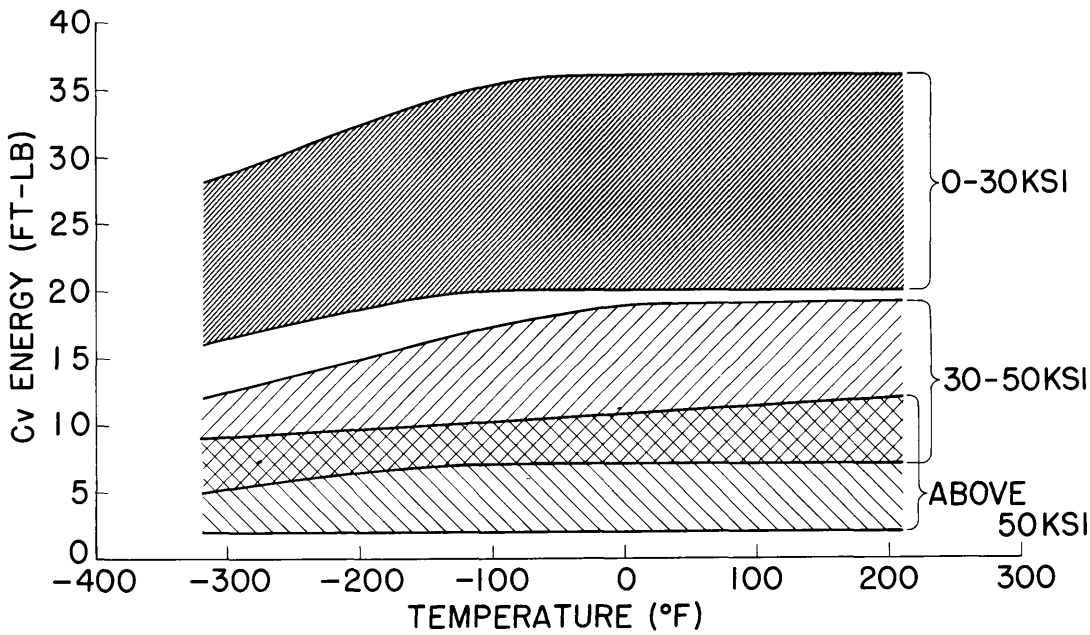

Fig. 3 - Summary of C_v features of aluminum alloys as a function of strength level

plane stress fractures, the effects of changes in section size require more detailed assessment for purposes of engineering interpretation. Studies of section size effects are being conducted to corroborate deductions that may be made from fracture mechanics calculations for the intermediate range of toughness.

Because the natural event of fracture which is measured by any fracture toughness test is energy, it should be expected that measurements of the energy to fracture in the DT test should be indexable accurately to fracture mechanics K_{Ic} tests for plane strain or near plane strain conditions. In the case of mixed-mode K_c fracture conditions, for which K_{Ic} correction calculations must be made for fracture mechanics tests because of inadequate thickness constraint, increased DT energy is obtained which corresponds to the K_c increase. For conditions of full-slant fracture, the much higher DT energy relates to full plane stress K_c conditions. This condition of high fracture toughness can be represented as an approximation of the K_{Ic} value derived by extrapolation of the correlation data. Subsequent K_c calculations derived from the approximated K_{Ic} value indicate that very large flaw sizes and plastic loads are required for fracture. The estimates appear to be reasonable as indicated by separate correlations of DT test fracture resistance to Explosion Tear Test (ETT) performance (8). In effect, the full plane stress K_c conditions (heavy shear borders or full-slant fracture) translate to flaw size and stress calculations of such a magnitude so as to be of no concern except for conditions of gross plastic overload and huge flaw sizes.

A schematic of the DT specimen for 1-in.-thick aluminum plate is shown in Fig. 4. An EB weld, embrittled by diffusing in phosphor bronze during the welding operation, is used to generate the desired deep, sharp crack. Impact loading with a calibrated falling or swinging weight (similar to a large C_v machine) is used to fracture the specimen and measure the energy required to fracture a specified area of plate material.

The brittle crack-starter weld of the DT specimen also provides a limit-severity test condition for strain-rate-sensitive materials. Strain-rate sensitivity effects are

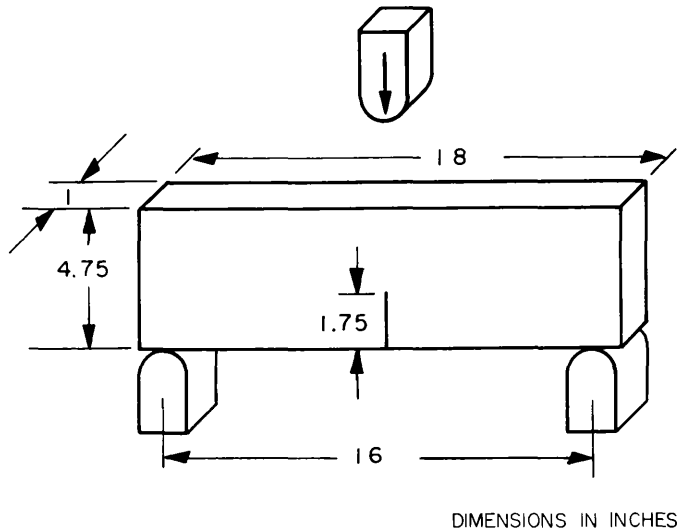

Fig. 4 - DT specimen for testing a 1-in.-thick plate of aluminum alloys

thus integrated into the DT energy value measured. If the material is not strain rate sensitive, the brittle weld is then equivalent to a deep fatigue crack.

The fracture surface characteristics of DT specimens for extremes in fracture toughness for aluminum alloys are shown in Fig. 5. The flat fracture, indicated on the left, corresponds to brittle (plane strain) behavior and low DT energy values. Very high levels of toughness correspond to conditions of plane stress for which high DT energy values and slant fracture, indicated on the right, are obtained.

CORRELATIONS OF FRACTURE TOUGHNESS TESTS

Correlations have been developed between the K_{Ic} and DT fracture toughness values using 1-in.-thick specimens. Additional correlations have been developed between the notched tensile, C_v, K_{Ic}, and DT tests.

The ASTM-E24 recommended practices for specimen preparation, testing, and analysis were followed closely in K_{Ic} tests of aluminum alloys. These requirements limited the available test material to the 2000 and 7000 series alloys for valid tests for the 1-in.-thick material.

Interpretations of DT and C_v data in previous studies (8) have depended on extensive indexing to the ETT. The ETT is a prototype structural element test designed to simulate elastic and/or plastic loading of a flawed panel of prime plate material. Explosive loading methods are employed to deform the 1- by 22- by 25-in. test panel into a cylindrical form with the primary stress being normal to a centrally located flaw. A 2-in.-long, through-thickness, embrittled EB weld, similar to the DT crack-starter weld, initiates a propagating crack into elastically or plastically loaded material, depending on fracture toughness. The indexing parameter of the ETT is the amount of surface plastic strain required to cause extensive fracture of the test piece. Thus, the ETT yields an indication of the material's tolerance for large flaws. The typical performance of low, intermediate, and high fracture toughness material is shown in Fig. 6. The fracture modes correspond, respectively, to plane strain (6a), mixed-mode plane stress (6b and 6c), and full plane stress (6d).

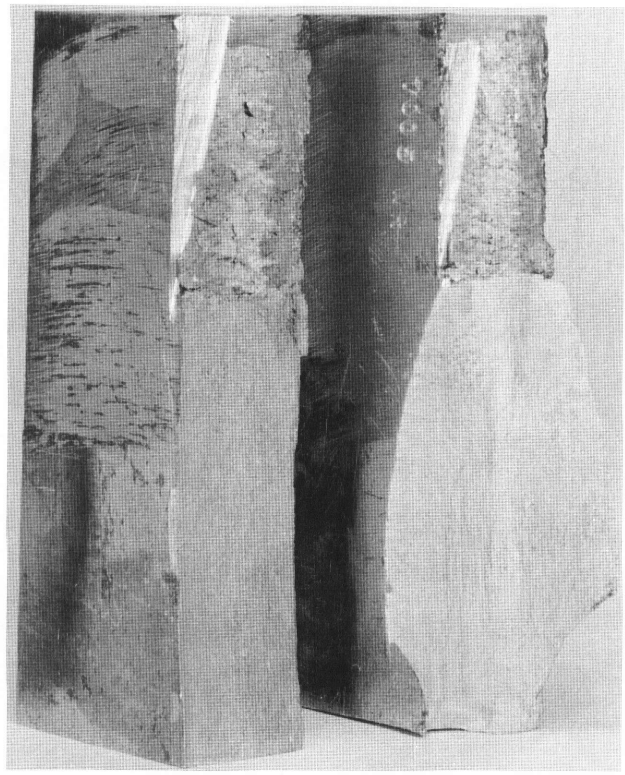

Fig. 5 - DT fracture appearance for low-fracture-touchness (left) and high-fracture-toughness (right) aluminum alloys

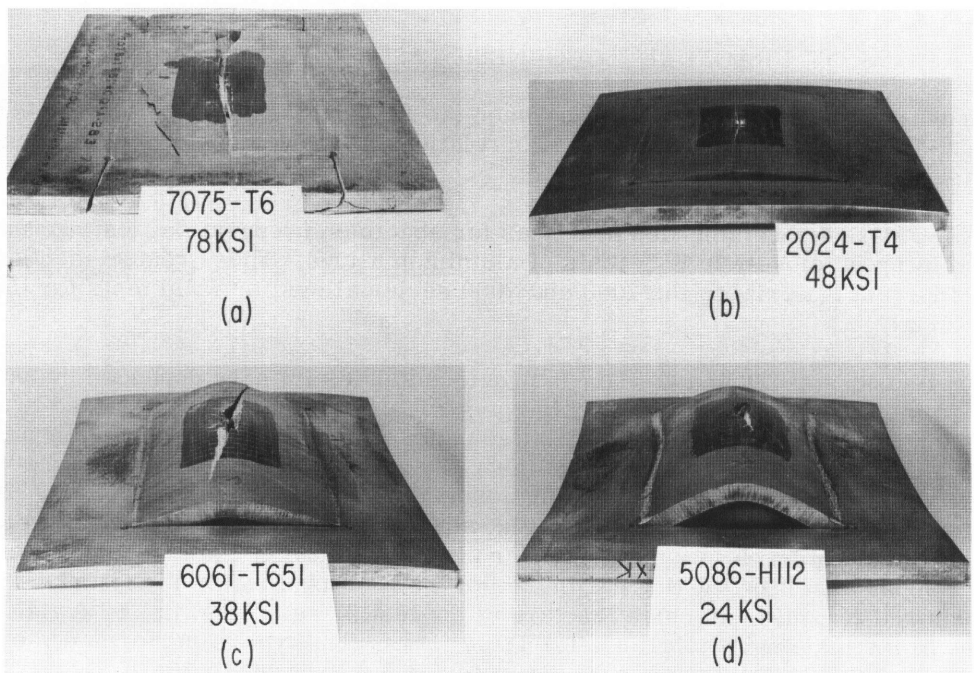

Fig. 6 - Range of fracture toughness levels as evidenced by ETT performance

An important point to note in interpreting ETT results is that aluminum alloys do not possess the high intrinsic energy absorption properties in fracture propagation that have been observed for high-quality steels and titanium alloys (8). Aluminum alloys require relatively low energy for crack extension in a ductile mode. This means that high resistance to "tearing" may not be attained for the case of plastic overload of a large region of a structure, simply by the selection of a material with the ability to plastically deform in the presence of a flaw. Certain commercial steels and titanium alloys feature similar properties. This property has been described previously as "low-energy shear."

The ETT-DT correlations reported previously (8) remain as the primary validation for fracture propagation resistance for materials of relatively high fracture toughness. The ETT data now serve additionally to verify the K_c calculations of large to huge flaw sizes required to fracture 1-in.-thick plates of high fracture toughness. In effect, the K_c calculations and the ETT observations are in agreement.

Correlation of DT and C_v Tests

The correlation between C_v and DT fracture energies is shown in Fig. 7. The plot indicates that the DT test is much more sensitive to fracture toughness differences than the C_v test, because it provides an "expanded" energy scale. The insensitivity of the C_v test over the full range of fracture toughness of aluminum alloys does not provide for the desired differentiations between alloys. For example, for two aluminum alloys measuring 7 to 8 ft-lb C_v energy, ETT results show a variation in behavior from almost "flat" fracture to fully ductile fracture requiring approximately 8% plastic strain for propagation. Obviously, this represents a major difference in fracture toughness. The corresponding DT energy for fracture of 279 and 548 ft-lb, respectively, clearly indicates this difference. The wide range in ETT fracture toughness performance, noted for a given value of C_v energy, documents that the C_v test is very limited in interpretation capability for aluminum alloys.

Correlation of Notched Tensile and DT Tests

A comparison of the notched tensile ratio with DT energy is illustrated in Fig. 8. Two sets of notched tensile data are shown; one is for machine notched ($k_t \geq 3.5$)* specimens, and the other is for similar specimens with the notches additionally sharpened by fatigue cracking. Increased constraint introduced by deeper and sharper flaws led to slightly lower ratios for the fatigue-cracked specimens. The correlation band indicates a general correspondence between the two tests; however, based on ETT results the DT test is indicated as being the most sensitive to changes in fracture toughness for aluminum alloys.

Correlation of K_{Ic} and DT Tests

A plot of K_{Ic} as a function of yield strength, Fig. 9, indicates a general inverse relationship between fracture toughness and yield strength. The K_{Ic}-Optimum Material Trend Line (OMTL) for the "weak" direction evolves due to the selection of the best materials (for the strength level) which define the DT-OMTL. Both tests show a rapid decrease of the upper limit of fracture toughness (best material) with increasing yield strength.

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*Elastic stress concentration factor k_t is the ratio of actual maximum stress to the nominal stress for a notched tensile bar. The value of K depends on the notch radius and the notch depth with respect to the bar diameter.

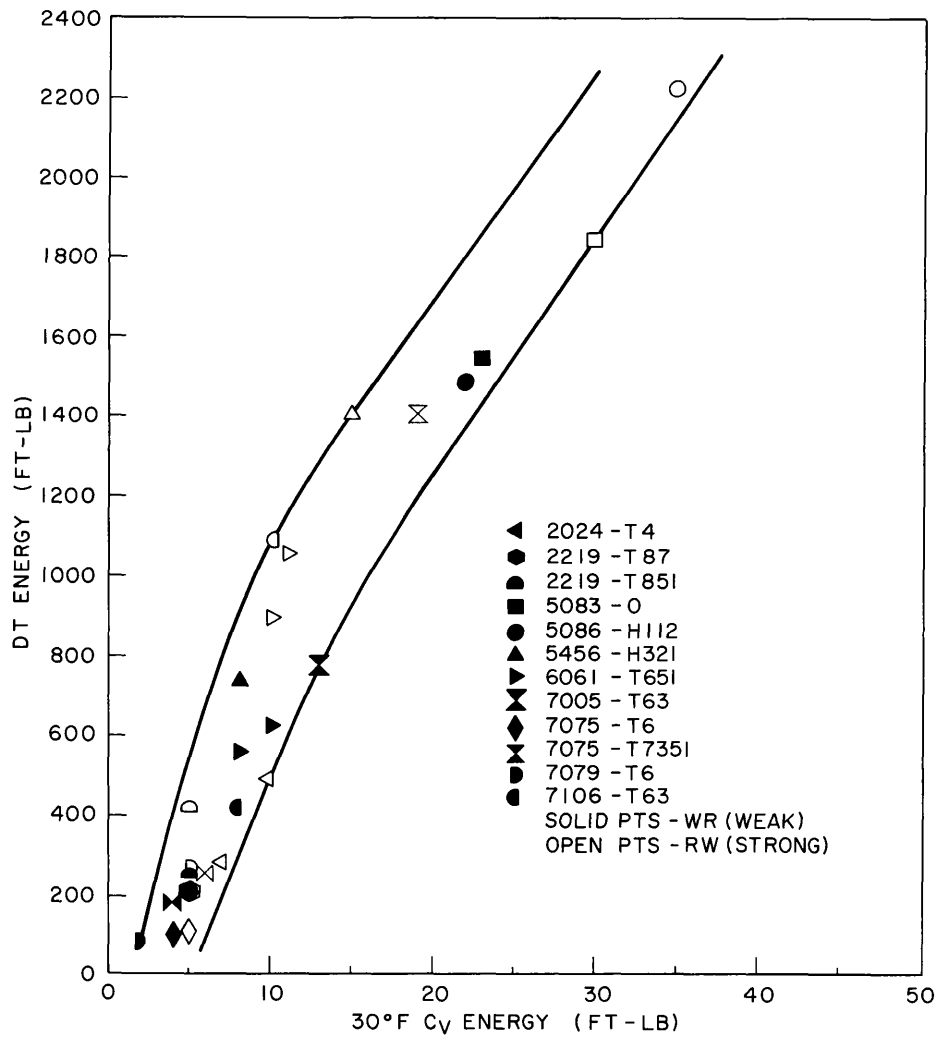

Fig. 7 - Correlation of DT and C_v energy criteria for aluminum alloys

The DT-K_{Ic} correlation shown in Fig. 10 illustrates that an increase in K_{Ic} values is associated with corresponding increases in DT energy values. However, the K_{Ic} values obtained are limited to less than 45 ksi $\sqrt{\text{in.}}$ for the 1-in.-thick plate tested. Higher K_{Ic} fracture toughness measurements could not be made, since the $(K_{Ic}/\sigma_{ys})^2$ ratio would be such that specimen thicknesses considerably in excess of 1-in. would be required for valid K_{Ic} determinations. As mentioned earlier, in material for which 1-in. thickness is not sufficient for valid K_{Ic} testing, the K_c-mixed-mode condition controls the fracture process. If the intrinsic metallurgical quality remains constant with increased thickness, the trend line in Fig. 10 can be extrapolated to give estimates of the K_{Ic}-DT relation based on 1-in.-thick DT specimens for materials of greater thickness. As data for thicker materials become available, these estimates will be refined as required.

The DT-K_{Ic} correlation of Fig. 10 is not linear over the entire range of fracture toughness; a different relation for brittle and tougher materials is apparent. This is to be expected since the influence of the inherent plasticity of the metal is greater in the DT test than the K_{Ic} test. The K_{Ic} test is based on the measurement of conditions

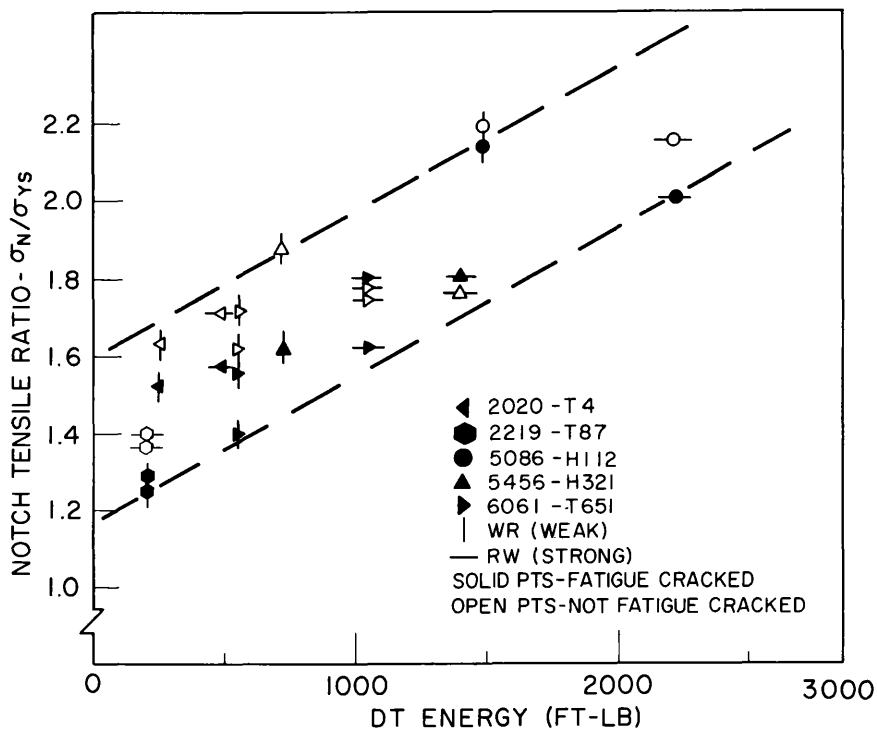

Fig. 8 - Comparison of notched tensile ratio with DT energy

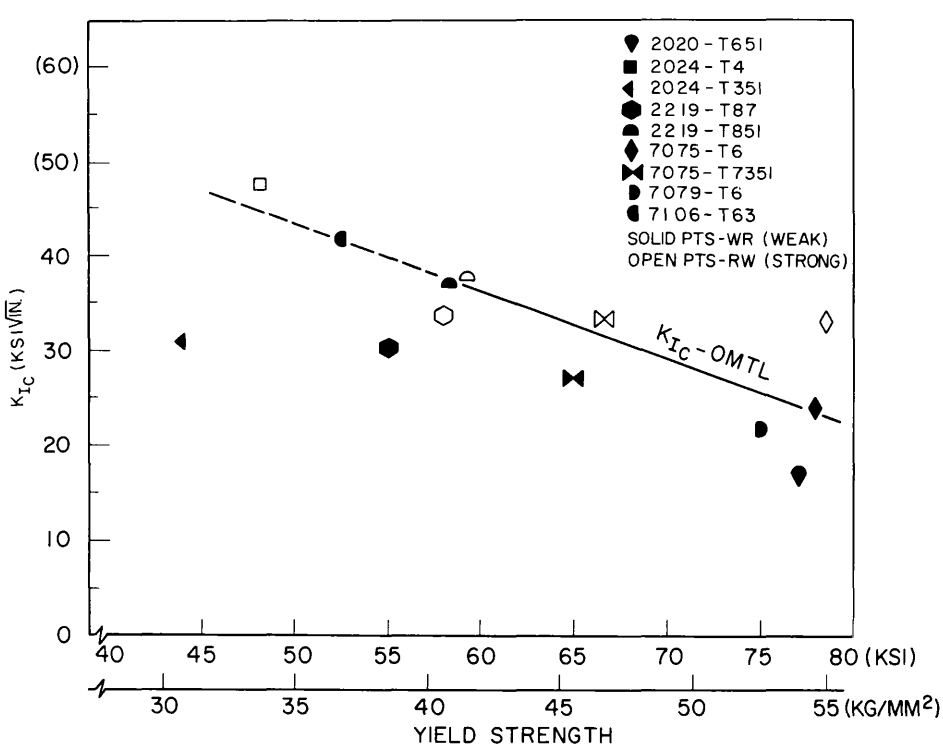

Fig. 9 - Inverse relation of yield strength and K_{Ic} fracture toughness for aluminum alloys. This relationship is similar to that demonstrated for steels and titanium alloys.

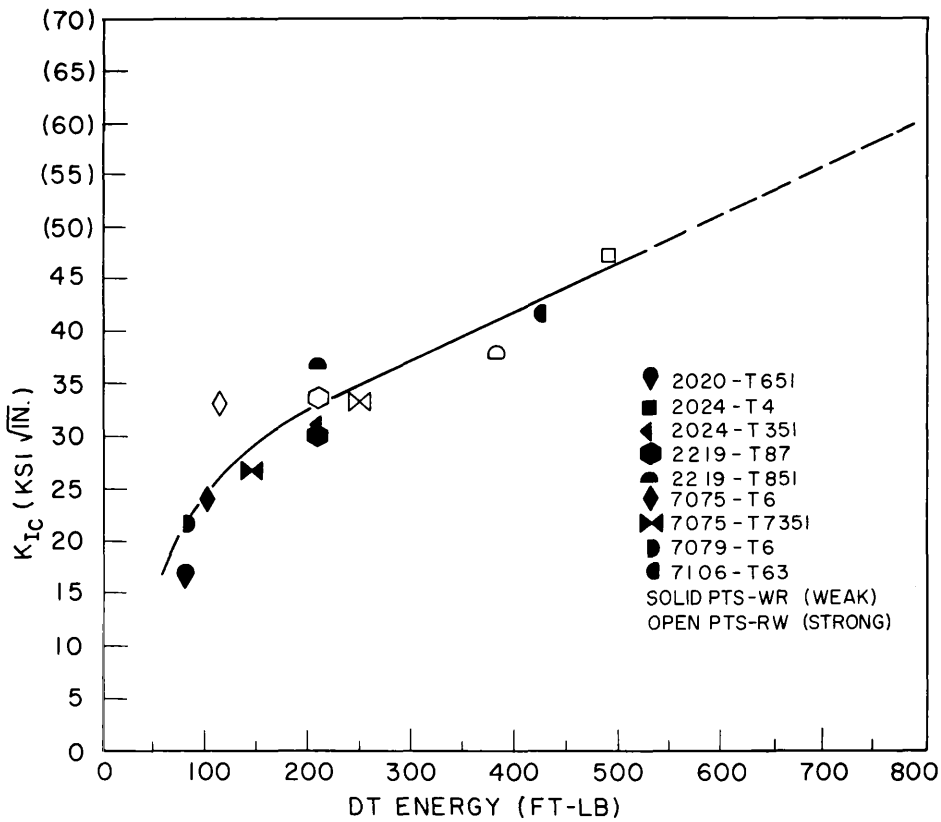

Fig. 10 - Correlation of K_{Ic} with DT energy

related to the first instability of a deep, sharp crack while the metal is fully constrained. Subsequent crack growth, crack-tip blunting, and accompanying plastic zone effects are not considered. The DT test records the entire event of fracture, including plasticity effects in the total process of crack extension. This causes the slope of the correlation curve to decrease as alloys of higher fracture toughness are considered. In effect, the DT test provides a more sensitive index of increasing fracture toughness as deviations from theoretical plane strain conditions are developed with increasing fracture toughness.

The strain energy parameter $\mathcal{G}_{Ic}$ is compared to DT energy in Fig. 11. Normalizing the DT data on the basis of area (in.-lb/in.^{2}) provides a direct comparison with the $\mathcal{G}_{Ic}$ value expressed in the same units. Discussions of the basic aspects of this correlation are beyond the scope of this report; however, it can be stated that the excellent correlation indicates that the same fracture aspects are measured by both test methods for reasonably valid K_{Ic} values. The basic aspect is the size of the plastic zones which determine energy absorption in the fracture process.

Correlation of K_{Ic} and C_v Tests

A plot of K_{Ic} vs C_v energy is shown in Fig. 12. A general trend of increasing C_v energy with increasing K_{Ic} values is indicated, though the C_v data are limited to very low values. Yield strength normalization procedures which improved a similar correlation for steels (1) had no effect on the aluminum data. This is another indication of the poor fracture toughness indexing possibilities of the C_v test for aluminum alloys.

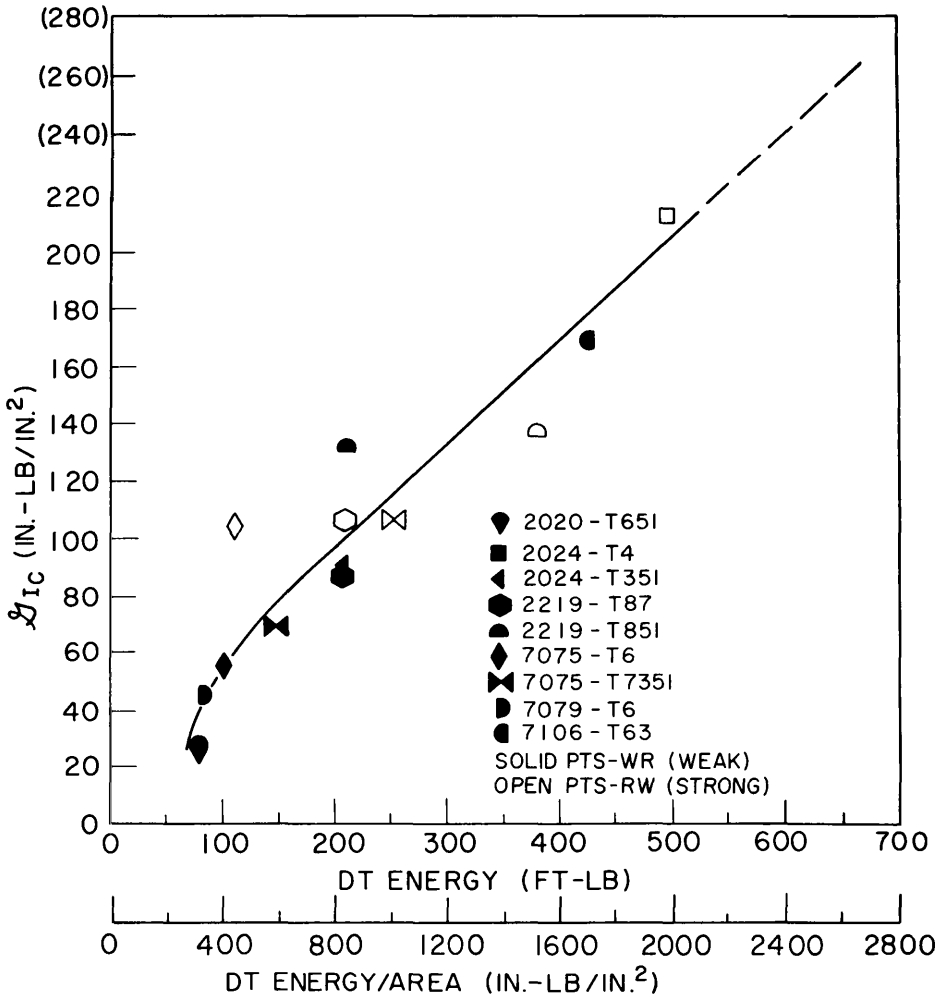

Fig. 11 - Comparison of a fracture mechanics parameter $\mathcal{G}_{Ic}$ with DT energy

INTERPRETATION OF CORRELATION RELATIONS

The aim of these investigations was the use of fracture mechanics analytical procedures for the characterization of fracture toughness of aluminum alloys in terms of critical flaw size and stress level requirements for fracture.

Correlation of engineering fracture toughness tests with K_{Ic} provides for expressing the fracture toughness of materials in terms of critical flaw size-stress level requirements for fracture. While the correlations are strictly valid at present only for fairly brittle materials, extrapolations to tougher materials can be shown to involve very large flaw sizes such that the approximations are sufficiently accurate for most engineering applications.

A two-step analytical procedure was recently evolved for steels (1) and high-strength titanium alloys (2) that provides for reducing the complex problem of interpretation of fracture toughness data to failure conditions into a simple, straightforward presentation.

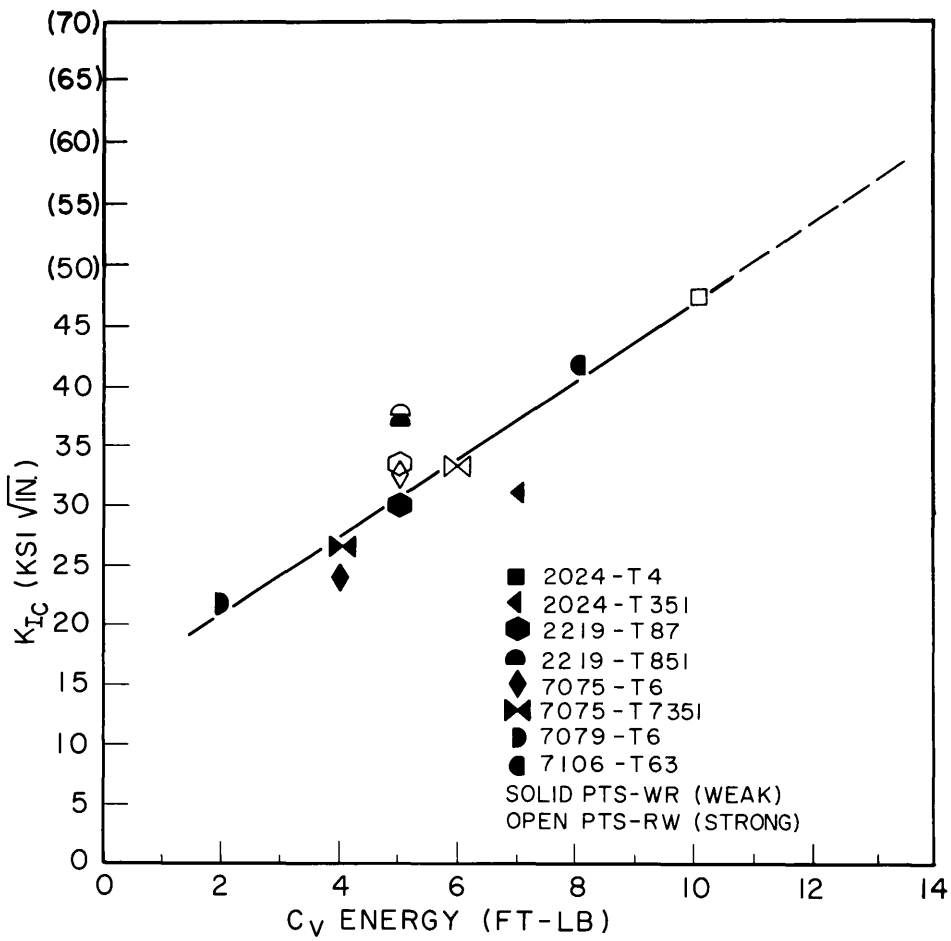

Fig. 12 - Correlation of K_{Ic} with C_v energy

This is examplified by the K_{Ic}/σ_{ys} Ratio Analysis Diagrams (RAD) evolved for the generic classes of steel, Fig. 13, and the α-β-type titanium alloys, Fig. 14. Some important aspects of these diagrams are:

1. The fracture toughness scales are indexed to DT, K_{Ic}, and C_v parameters according to the correlations.

2. The "strength transition" is clearly shown by the OMTL.

3. The K_{Ic}/σ_{ys} ratio lines define low (I), intermediate (II), and high (III) levels of fracture touchness characteristics in terms of characteristic flaw size-stress combinations. These relationships (order of flaw size and order of critical stress) are easily remembered and therefore provide rapid assessment with a degree of accuracy sufficient for most engineering applications.

4. The zonal locations of specific alloy families in reference to the OMTL and to the K_{Ic}/σ_{ys} ratio line zones are an evident feature of the diagrams.

5. New data points can be indexed to the diagrams from any of the fracture toughness scales, making the relative quality of the material immediately apparent.

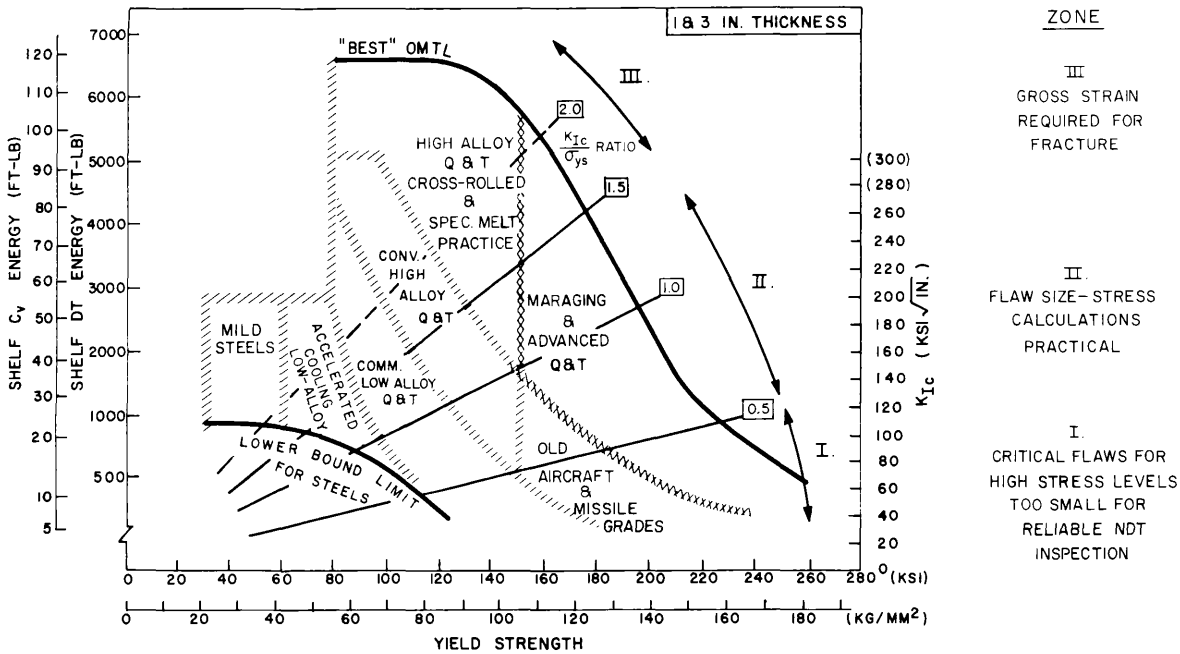

Fig. 13 - RAD for high-strength steels—from Ref. 1

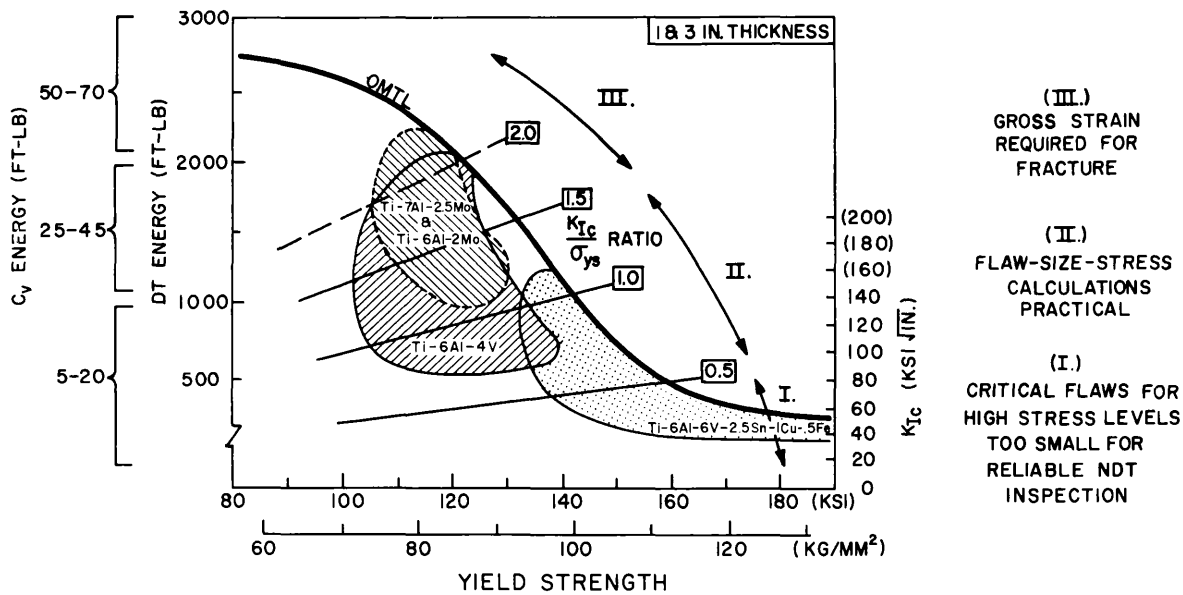

Fig. 14 - RAD for high-strength α - β titanium alloys—from Ref. 2

The procedure that was used to arrive at the RAD for steels and for high-strength titanium alloys will be explained in detail for the case of aluminum alloys in the following sections.

Fracture Toughness OMTL Diagram for Aluminum Alloys

The fracture toughness OMTL diagram for 1-in.-thick aluminum plate is shown in Fig. 15. The OMTL curve represents the fracture toughness properties for any level of yield strength, as defined by the DT test, for the alloys tested to date. Because of the wide variations in anisotropy of alloys, a separation of the data on the basis of fracture direction is required. Thus, the OMTL is based on the best "weak" fracture direction properties, since it would be the controlling fracture direction in most engineering cases. The same treatment was applied for the case of steels and titanium alloys — the data of Figs. 13 and 14 relate to "weak" direction properties. In cases of specific engineering interest in the strong direction, the DT value so obtained can be plotted and interpreted as for any other value.

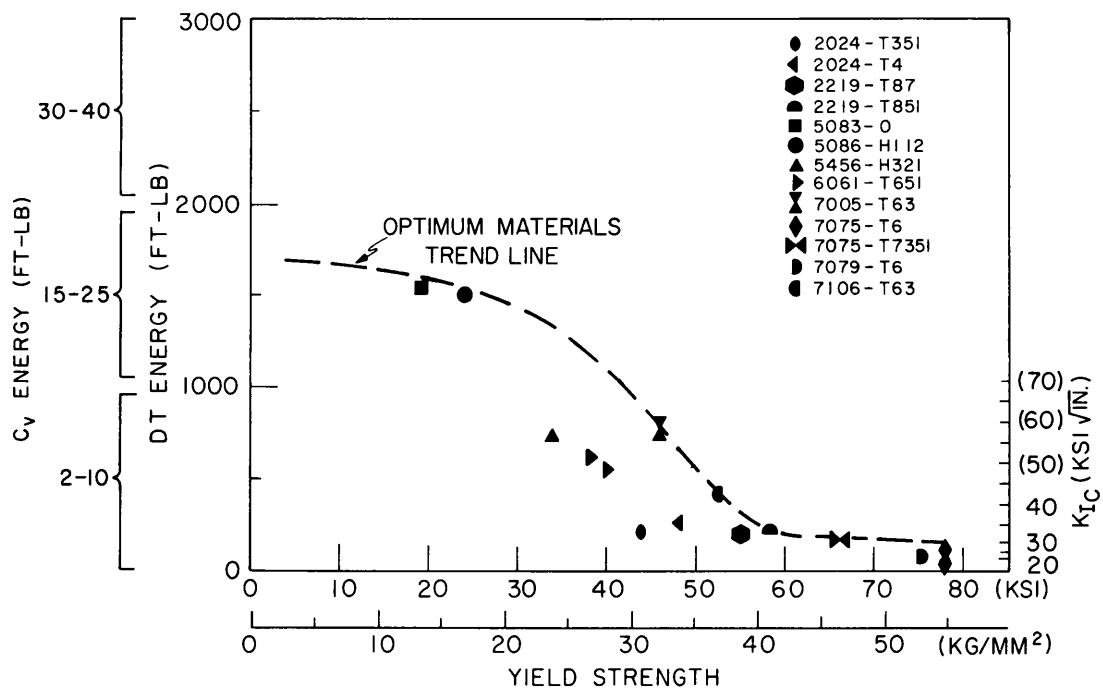

Fig. 15 - OMTL Diagram for aluminum alloys. The diagram presents relationships to C_v, DT, and K_{Ic} scales.

The K_{Ic} and C_v scales are positioned according to the correlation plots with DT energy. Values of K_{Ic} in parenthesis above 45 ksi $\sqrt{\text{in.}}$ are extrapolations from the K_{Ic}-DT correlation plot. Data can be entered on the diagram from any of these scales provided the yield strength of the material is known.

The rapid change in fracture toughness indicated by the OMTL strength transition is clearly evident from the general behavior of aluminum alloys in the ETT, Fig. 6. In effect, the series represents the "effect" of following the OMTL curve from low to high values of DT energy.

Flaw Size Analysis Diagrams

Typical Flaw Size Analysis Diagrams referenced to an OMTL zonal diagram are shown in Fig. 16, for a 1-to-10 (depth-to-length) semi-infinite flaw and for yield stress loading; Fig. 17 relates to the case of one-half yield stress loading. The critical flaw depths for short, stubby flaws of 1-to-2 (depth-to-length) can be estimated by multiplying the indicated values by a factor of 2.5. Although limited, all the DT fracture toughness data for 1-in. plate are zoned according to weak-direction properties for different generic families of aluminum alloys studied. This grouping of the DT data defines zones of fracture toughness characteristics for each generic family. The zonal locations indicated for each family cover the yield strength and fracture toughness range experienced to date for the alloys investigated. For any given alloy, variations of strength and toughness within a zone reflect differences in chemistry, processing, and heat treatment. The shape and size of the zones are expected to change as DT data are obtained for a wider variety of alloys for each family.

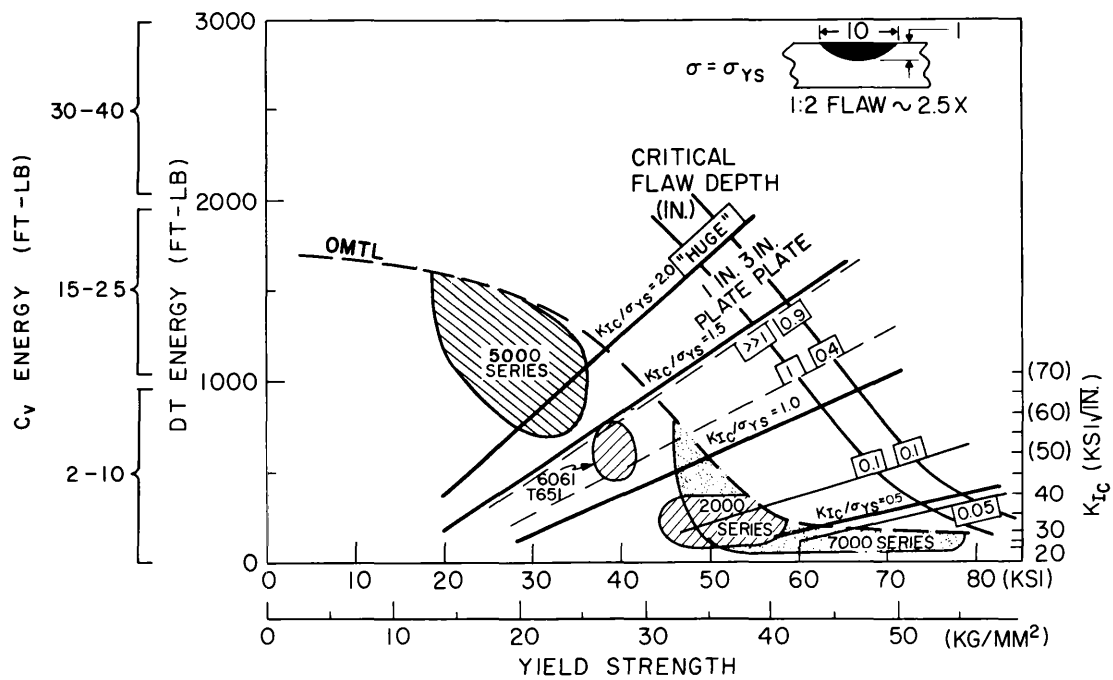

Fig. 16 - Flaw Size Analysis Diagram which presents calculations of critical flaw sizes for yield level loading

The diagrams feature critical iso-flaw depth lines calculated for both 1- and 3-in.-thick plate considering K_{Ic} or K_c conditions as appropriate. The lines are positioned on the diagram from calculations derived from the K_{Ic} scale. The critical flaw depth-stress level calculations are considered to be reasonably accurate for K_{Ic} values up to 45 ksi $\sqrt{\text{in.}}$ for 1- to 3-in.-thick plate. This follows because plane strain or near plane strain conditions dominate.

Above K_{Ic} values of 45 ksi $\sqrt{\text{in.}}$, the calculations have been adjusted to account for the increased effects of mixed-mode and full plane stress K_c conditions. The formal relationships for K_{Ic}-to-K_c calculations are recognized to represent approximations; however, high accuracy is not required for the critical flaw sizes indicated in this region of

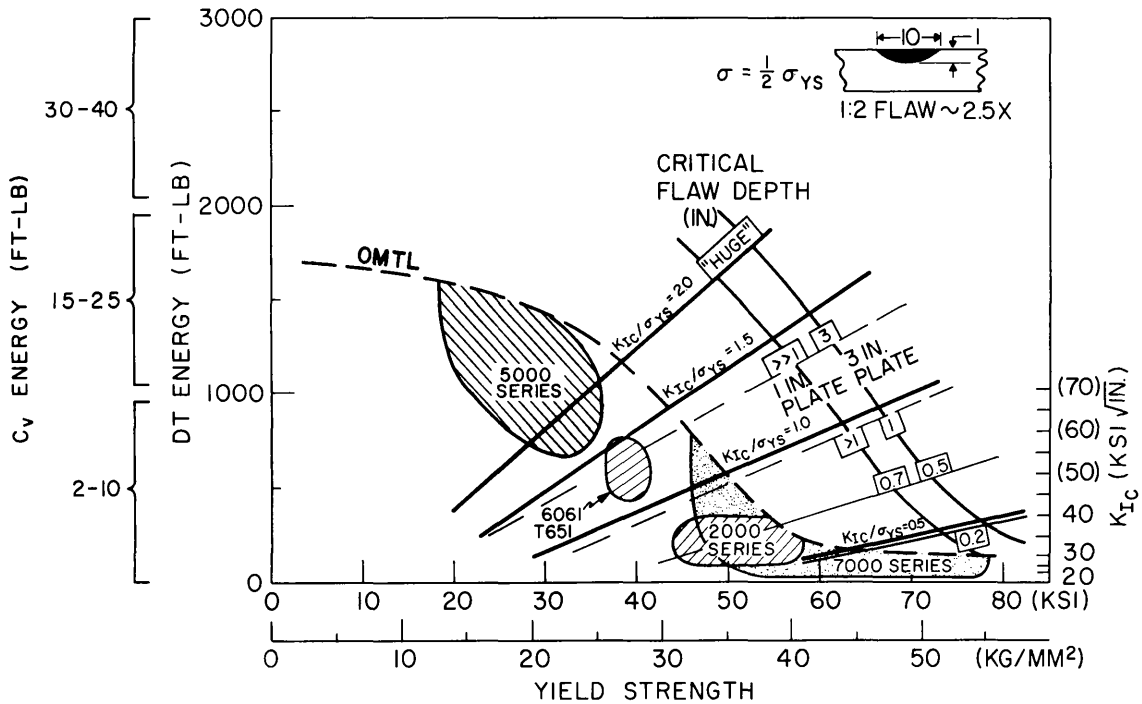

Fig. 17 - Flaw Size Analysis Diagram which presents calculations for stress levels corresponding to 0.5 of yield level loading

relatively high fracture toughness, since "huge" flaws with lengths and depths considerably in excess of section thickness are indicated.

By following the OMTL curve from low to high strength, a sharp drop in critical flaw size may be noted in the region of 30- to 50-ksi yield strength. Material below 30-ksi yield strength is characterized by very high plane stress fracture toughness and corresponding huge flaw sizes associated with plastic overload requirements for fracture. For materials of 50-ksi or higher yield strength, brittle fracture may occur from minute flaws in the order of tenths or hundredths of inches depending on stress level as well as specific fracture toughness level. From these comparisons, it is obvious that in the range of 30- to 50-ksi yield strength, there is a major premium to be gained by using the very best materials available.

It was mentioned in an earlier section that the plastic zone size is proportional to the ratio $(K_{Ic}/\sigma_{ys})^2$. Thus, the iso-flaw depth diagrams depict a system of critical flaw depth lines which relate to the ratio $(K_{Ic}/\sigma_{ys})^2$. The simple form of the ratio, K_{Ic}/σ_{ys}, also serves to provide equivalent indexing of this information and therefore can be used as a simplified engineering procedure for assessment of stress level-flaw size relationships for failure. For example, the flaw size diagrams are zoned by K_{Ic}/σ_{ys} ratio lines of 0.5, 1.0, 1.5, and 2.0. These ratio lines define five zones of rapidly changing fracture toughness and critical flaw sizes. The K_{Ic}/σ_{ys} ratio lines can be used in this fashion because the ratio is the basic parameter in the equations used for calculating flaw size and for defining fracture toughness.

By substituting the ratio lines for the iso-flaw depth lines, a simplified engineering analysis of fracture toughness of 1- to 3-in.-thick plates can be made:

1. Above a K_{Ic}/σ_{ys} ratio of 2 — Nominal stresses in excess of yield and crack lengths and depths many times the plate thickness, i.e. "huge," are required for fracture. This follows because full plane stress conditions would apply even for 3-in. thickness.

2. Ratios between 1.5 and 2 — Nominal stresses above yield and through-thickness flaws, with lengths and depths well in excess of the plate thickness, are required for the initiation of fracture in 1-in.-thick material. Fracture propagation would be expected in the plane stress, slant mode, Flaws in the order of an inch to several inches in depth, and lengths in excess of plate thickness, are required for fracture of 3-in.-thick plate. Mixed-mode plane stress conditions will prevail for the 3-in. plate thicknesses.

3. Ratios between 1 and 1.5 — Stresses in excess of yield and through-thickness flaws, with length in excess of the plate thickness, are required for fracture propagation in the mixed plane stress mode for 1-in. plate.

4. Ratios between 0.5 to 1 — Critical flaw depths in the order of tenths of inches are sufficient to cause plane strain fracture at relatively high levels of elastic stress for both 1- and 3-in. thickness.

5. Below 0.5 ratio — Relatively low elastic stresses and minute flaws (critical flaw depth in order of hundredths of inches) are sufficient to initiate and propagate plane strain fractures for 1-in. and greater thicknesses.

A further simplification can be made, which is applicable to 1- to 3-in. sections for most engineering purposes:

$K_{Ic}/\sigma_{ys} > 1.5$ - no need to calculate flaw sizes—these are very large and are associated with plastic loading.

$K_{Ic}/\sigma_{ys} < 1.5$, but > 0.5 - use Flaw Size Analysis Diagrams for the best definition of approximate critical flaw size and stress.

$K_{Ic}/\sigma_{ys} < 0.5$ - critical flaw sizes are very small and may be below reliable detectability limits.

RATIO ANALYSIS DIAGRAM

The first edition* K_{Ic}/σ_{ys} RAD for aluminum is presented in Fig. 18 with the K_{Ic}/σ_{ys} ratio lines referenced to the OMTL zonal diagram. In general, aluminum alloys of interest for structural applications have yield strengths in the range of 20 to about 80 ksi. To cover this strength range with the ratio lines, a linear scale of K_{Ic} was used for values below 30 ksi $\sqrt{\text{in.}}$ This represents an expansion of the K_{Ic} scale used in the Flaw Size Analysis Diagrams. Each alloy family is indexed according to the significance of K_{Ic}/σ_{ys} ratio lines in terms of the critical flaw size-stress relationships. For example, the DT zonal location of the 5000 series alloys with respect to the ratio lines indicates very high fracture toughness capabilities for these alloys below 40-ksi yield strength. Large to huge flaws and general plastic yielding are required for fracture. The 5000 series alloys define the OMTL up to about 35-ksi yield strength. Due to the metallurgical nature of these alloys, yield strengths much above 45 ksi would be difficult to obtain in thick sections and then only with low levels of fracture toughness.

*Additional studies are underway to characterize the zonal location of other typical aluminum alloys in cooperation with the aluminum industry. These studies should not change the basic concepts of this report; the results will be a more detailed coverage of the aluminum alloy systems.

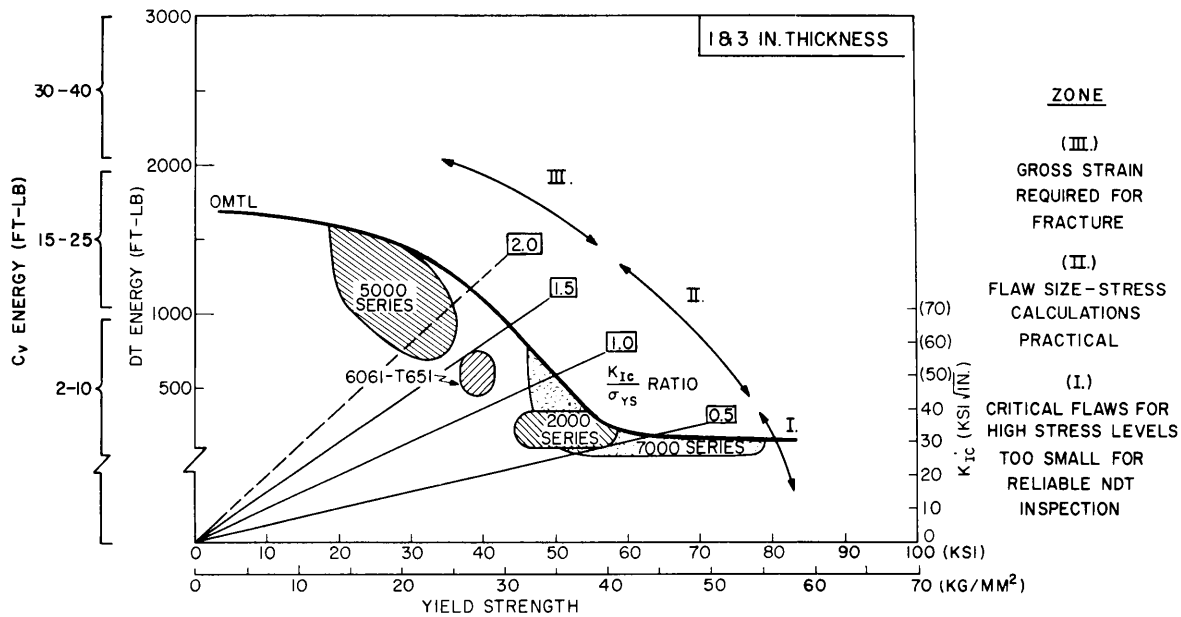

Fig. 18 - RAD for aluminum alloys

Alloys in the 6000 series can be expected to span the yield strength range of about 20 to 65 ksi (4) depending on chemistry and tempering treatment. The 6061 alloy in the T651 temper is the only one of this family for which DT data are available. The alloy has a yield strength around 40 ksi for this temper condition and a level of fracture toughness below that of the OMTL but still in the region where flaws in the order of inches and gross strain are required for fracture for 1-in.-thick sections.

The 2000 series alloys are designed for the general yield strength ranges of 40 to 65 ksi and from RAD definitions would be expected to be brittle at the higher end of this range. The 2000 series alloys investigated for this report define a DT zonal region corresponding to small flaws (tenths of inches) and high elastic stress requirements for crack initiation.

In general, only alloys in the 7000 series are used above 65-ksi yield strength. These alloys are the high-strength aircraft alloys, such as 7075, and are relatively brittle even for thicknesses less than 1 in. The special-purpose 7005 and 7106 alloys are designed for use at lower strength levels and define the lower strength portion of the DT zonal region. In this region of rapid OMTL transition, intermediate levels of toughness for these special-purpose alloys are obtainable provided close control of chemistry and processing practice is exercised.

SUMMARY

The spectrum of commercial aluminum alloys concerns a wide range of fracture toughness. The high-strength alloys are relatively brittle and as such may be characterized by formal procedures of linear elastic fracture mechanics. The low-strength alloys feature high fracture toughness which results in blunting and deformation of cracks — in effect, the problem of failure cannot be expressed as fracture in a conventional sense. The failure processes then involve large amounts of plastic deformation and ductile tearing. Alloys of intermediate strength may be expected to behave in a ductile or semibrittle

mode depending on specific flaw size-stress conditions. These features are not unique to the aluminum alloy system and have been defined similarly for steels and titanium alloys.

Recognition of these facts clearly implies a separation of fracture toughness features into regions, the characterization of which is related to mechanical conditions best expressed as linear elastic, elastic plastic, and gross strain. In terms of fracture mechanics terminology, these regimes are identified, respectively, as plane strain K_{Ic}, mixed-mode plane stress K_c, and full plane stress K_c (slant fracture). Since strictly valid fracture mechanics definitions at the present stage of development apply only for the K_{Ic} plane strain case (brittle alloys), alternate procedures must be found to fully characterize the fracture toughness of alloy systems. The only procedure which retains a reasonable analytical promise for definition of critical flaw sizes and stress levels involves the use of a test specimen configuration which defines the characteristic fracture mode of the material and the associated energy requirements for fracture. Such a test clearly indicates if the fracture process is controlled by K_{Ic}, K_c (plane-stress mixed-mode), or gross strain parameters. The energy index provides for correlation to K_{Ic} values and for extrapolation of these relationships to cover the K_c regime. The gross strain (slant fracture) regime is "self characterizing," i.e., plasticity rather than fracture dominates.

The Dynamic Tear (DT) test provides for the desired full spectrum definition of fracture toughness. All aluminum alloys may be characterized by the use of this test, and the decrease in fracture toughness with increase in yield strength (strength transition) is clarified. Yield strength diagrams are presented which are indexed commonly by DT, K_{Ic}, and C_v scales. The relationships between these scales were evolved by detailed cross correlations of these parameters. The C_v scale relationship is inadequate for most engineering purposes, and relationships presented primarily document this fact. The strictly valid and extrapolated portions of the K_{Ic} scale serve a most important purpose of providing flaw size-stress definitions for failure. These are expressed in terms of K_{Ic}/σ_{ys} ratio lines, which relate directly to the flaw size calculations.

Much of the debate concerning the interpretability of extrapolated K_{Ic} values (in effect K_c conditions) is reduced to insignificance from an engineering point of view, because the critical flaw sizes and stresses involved for this regime are extreme. Knowledge that the necessary flaw sizes are many times the plate thickness and the related stresses are above yield suffices.

With this philosophy, Ratio Analysis Diagrams (RAD) are evolved which provide the following important engineering displays in an integrated fashion:

1. All fracture toughness test scales are indexed to the same diagram.

2. An Optimum Material Trend Line (OMTL) is indicated which defines the decrease in fracture toughness as a function of increasing strength level for the best material of specific strength levels. An alternate definition of this trend line is "the leading edge of the technology" for the alloy families involved.

3. K_{Ic}/σ_{ys} ratio lines are superimposed on the diagram to define in a simple way the approximate values of critical flaw size-stress conditions for fracture.

4. The K_{Ic}/σ_{ys} ratio lines also define three broad regimes (zones) relating specifically to plane strain K_{Ic}, plane stress K_c, and gross strain conditions for fracture.

5. All available data for the various aluminum alloy systems may be entered in the diagram. Zoning the data points defines the general fracture toughness characteristics for each generic alloy family.

The clarifications which emerge from these integrations of fracture tests, interpretations of the analytical significance of the tests, and specific metal quality aspects should serve the common needs of design engineers and alloy development metallurgists.

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13. ABSTRACT

Interpretations of fracture toughness characteristics as measured by various test procedures are presented for structural aluminum alloys. Quantitative definitions of the significance of engineering fracture toughness tests are provided by extension of analytical procedures evolved from fracture mechanics theory. The procedural simplicity of the engineering tests coupled with the analytical capabilities of fracture mechanics theory provides for a significant advancement in fracture-safe design procedures for aluminum alloys covering the full range of yield strength.

The interpretative procedures are evolved from correlations of K_{Ic} with the Dynamic Tear (DT) and Charpy V-notch (C_v) test. An Optimum Material Trend Line (OMTL) diagram is developed which summarizes all the DT fracture toughness data and is additionally indexed according to the K_{Ic} and C_v correlation plots.

Iso-flaw depth lines based on flaw size-stress level calculations for fracture of 1- and 3-in.-thick sections are then placed in overlay on the OMTL diagram. The K_{Ic}/σ_{ys} ratio lines are indexed to the iso-flaw depth lines, and a K_{Ic}/σ_{ys} Ratio Analysis Diagram (RAD) emerges. The RAD provides for simplified, general engineering interpretation of flaw size-stress conditions for fracture. The general fracture toughness characteristics of different aluminum alloy families are simply defined by zones encompassing all the fracture toughness data and their position relative to the K_{Ic}/σ_{ys} ratio lines.

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Aluminum alloys						
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Plane strain (K_{Ic})						
Plane stress (K_c)						
Charpy-V notch test						
Fracture mechanics						

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