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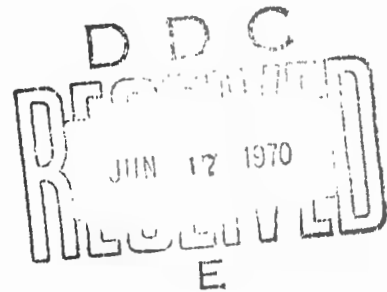
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Fracture Toughness of Structural Metals

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ABSTRACT

The traditional engineering approach to failure-safe design has been the use of conservative values for the mechanical parameters involved. The level of conservatism can now be more precisely selected, since the development of fracture mechanics has provided a theoretical stress analysis for the cracked-body case. A fine-scale definition of the relationship between critical flaw sizes and elastic stress levels can now be established by calculation. The quantitiveness of fracture mechanics has recently been extended for general engineering use by the provision of graphical correlations between stress-intensity values from fracture mechanics tests and fracture energy values obtained from Charpy V-notch and Dynamic Tear tests. Fine-scale definition of critical flaw sizes can now be determined from results of these engineering-type fracture tests when fracture instability can occur at elastic stress levels.

An extension of the quantitative analysis for critical flaw sizes into the regime of general engineering design, where a safe amount of plastic strain must precede fracture, is the objective of current research. Theoretical solutions to the nonlinear plastic state are complicated by other material characteristics such as transitions in microfracture modes and strain rate effects. Meanwhile, engineering developments for defining conditions leading to fracture under plastic strain conditions are based upon a tear energy concept using analysis diagrams which feature inputs of temperature and section size parameters for mixed-mode fracture conditions. The engineering analysis diagrams are sufficiently flexible to allow upgrading their quantitiveness as the theoretical treatment of plastic instability evolves.

PROBLEM STATUS

This report summarizes the trends in the engineering aspects of fracture technology as it is being developed in the Strength of Metals Branch of the Metallurgy Division. Work is continuing on the major aspects of the problem.

AUTHORIZATION

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FRACTURE TOUGHNESS OF STRUCTURAL METALS

INTRODUCTION

The traditional engineering approach to failure-safe design has been the use of conservative nominal stresses, and complex structures have been designed from simplified guides or models based on the theory of elasticity. Allowable stress levels for specific materials are based on tensile properties determined from smooth-body specimens, and with this approach, very few structural failures have occurred because of the empiricism of the tensile test. Too many failures have occurred, however, because the engineering design analysis did not consider fracture resistivity. Even with the development of linear-elastic fracture mechanics, communication between the metallurgist, the fracture mechanician, and the design engineer remains minimal because of the gap between the three disciplines.

The quantitiveness of fracture mechanics has been largely unavailable to the practicing engineer for analysis of fracture resistivity even though the merit of quantitiveness is generally recognized. One important reason that adoption of performance criteria based upon stress-intensity values has been limited is the unfavorable economics of plane-strain fracture testing. The rigor of "valid" plane-strain test procedures including the thickness requirements is a deterrent to a broader use of ASTM test methods. The difficulty in applying the mathematics of the stress-vs-flaw-size relationships to real structures is an additional obstacle. A significant achievement has been accomplished recently which will help to overcome these obstacles by providing graphical correlations between stress-intensity values and energy values obtained from practical fracture tests, the Charpy V-notch (C_v), and the Dynamic Tear (DT) tests. With these correlations, the results of engineering-type tests can be translated into charts of critical flaw size for guidance in engineering design (1-3). This achievement will encourage the use of performance criteria for fracture resistivity in general engineering design considerations.

Ideal materials for a linear-elastic fracture mechanics analysis are materials with fracture resistivity sufficiently low to permit unstable fracture initiation under plane strain conditions and elastic stress levels. For materials which are marginal in this respect, elastic fracture mechanics relationships can be extrapolated into the elastic-plastic region to provide useful information. However, the engineering significance of small but measurable crack movement to the structural performance of very thick sections in marginal materials requires additional consideration of property gradient effects. For materials with high fracture resistance, extension of the quantitative analysis provided by fracture mechanics into the net section plastic region is still in the research stage of development.

The general fracture resistivity characteristics of a structural metal are the results of interactions between critical metallurgical features and the mechanics of various loading systems. Fortunately, the conventional structural grades of steel have certain metallurgical features which simplify the engineering analysis of the fracture resistivity characteristics of these basic structural materials. The most important metallurgical features are those controlling the sharp transition in fracture resistance which occurs in a narrow range of temperature, the temperature transition. An understanding of the metallurgical aspects of the temperature transition is paramount to an

understanding of the effects of superimposed mechanical conditions. The metallurgical nature of titanium and aluminum alloys preclude the formation of a temperature transition, and the characterization of fracture resistivity of these alloys is primarily concerned with the mechanical aspects which impede plastic flow. Because certain metallurgical features give rise to unique fracture behavior, generalized fracture-safe design procedures correspondingly take advantage of these natural characteristics of structural metals.

This report considers the trends in the engineering aspects of fracture technology and emphasizes the metallurgical and mechanical features which result in rapid rises or transitions in fracture resistivity. These transitions are triggered when conditions depart from those associated with the restricted regime of ideal elastic plane strain fracture, and they define the link between elastic and fully plastic fracture behavior. Test methods for measuring fracture toughness through transition regions must have a capability of measuring over a broad range, and the DT test was developed and used for this purpose (2, 4). Analysis of the rapidly rising fracture resistance in transition regions is provided by diagrams which include the Fracture Analysis Diagram (FAD) and the Ratio Analysis Diagram (RAD). The concepts for providing analyses for the fracture toughness of structural metals have been available for several years, and the aims of this report are to present the engineering approach for coupling the quantitative-ness of fracture mechanics theory and to refine the interpretation of the empirical results of practical fracture toughness tests.

MECHANICAL ASPECTS OF FRACTURE RESISTIVITY

This section is a brief review of general principles related to the mechanical aspects of fracture. Detailed discussions of concepts and mathematical relationships can be found in the literature (5-7).

Mechanical constraint (triaxial stress) is generated by cracks and sharp notches plus thick sections. Constraint is the mechanical factor which tends to decrease the ability of structural metals to flow plastically by concentrating stress. The stress-concentration effects provided by a crack readily elevate the stress at the crack tip to yield strength levels, and a plastic zone is formed. This basic principle is illustrated in Fig. 1, where it is obvious that the larger the crack-tip plastic zone (increased notch ductility), the greater the resistance to fracture.

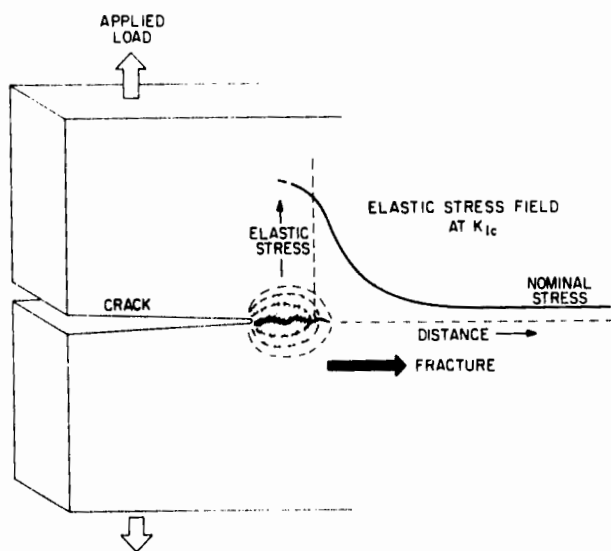


Fig. 1 - Plastic zone and stress field at a crack tip for fracture at elastic stress levels

To clarify the terminology used in this report, the fracture resistivity of a specific material concerns the general relationship between the size and strain energy of the plastic zone for crack extension under the full range of mechanical conditions (plane strain to plane stress). Fracture toughness is a specific value for fracture resistivity referred to a fixed set of mechanical conditions, such as the result obtained in a specific fracture test. A normalized fracture toughness value, such as the K_{Ic}/σ_{ys} ratio, is termed here fracture resistance. For most points in these discussions, the terms fracture toughness and fracture resistance are synonymous.

Since mechanical conditions change with structural design and flaw geometries, there is no unique plastic zone size or unique fracture toughness value for a specific material. A minimum plastic zone size occurs under conditions of maximum mechanical constraint (plane strain), and this minimum size has been related to the plane-strain, stress-intensity factor and the yield strength in the following equation:

$$r_y = \frac{1}{6\pi} (K_{Ic}/\sigma_{ys})^2.$$

Although this is an empirical definition of the size of the plastic zone, it does serve to indicate the relative influence of the plastic zone on the stress-intensity factor and the type of fracture instability that is apt to occur as a function of section thickness. For valid measurement of a K_{Ic} value, the plastic zone must be less than 1/20 of the section thickness.

Only a small crack extension is required for the measurement of plane-strain, stress-intensity values, and this may correspond to a limited extension of the crack front in the central region of a thick section. Further movement of the crack may result in a significant increase in fracture resistance, and until the natural shape of the crack front is attained, the fracture resistance associated with structural integrity is not fully established. Therefore, the measurement of a fracture toughness value from the initial movement of an imposed straight crack front in a test specimen can correspond to a variety of instabilities as far as the full section is concerned under service conditions.

Three general types of fracture instabilities are illustrated by the schematic load-displacement curves in Fig. 2. Type one is the sharp instability which occurs within the linear region of a load-vs-displacement relationship. Type one instability corresponds to a sharp, plane-strain (K_{Ic}) type of fracture where the initial crack movement signifies complete fracture of the section. This type of behavior can occur at low elastic stress levels for very brittle materials or at any elastic stress level up to approximately 80% of the 0.2% offset yield strength value. When the fracture resistivity is sufficiently high to require yield-level stress for the initial popin crack extension and the section is greater than 3-in. thick, additional consideration should be given to the propagation resistance of the fracture across the full metal section because of the effect of mechanical constraint gradients in thick sections.

Type two instability is the case where popin occurs after a small but significant deviation from linearity in the load-displacement relationship. This type of instability causes a sharp drop in load, but it is followed by a recovery in load, indicating popin arrest. A rising load is required then for continued crack-front movement.

In the type two case, some slow crack movement or through-thickness yielding which may involve only a restricted central region usually occurs prior to the first instability. This is a transition or a mixed-mode fracture where the center portion fractures in a plane-strain manner, but the surface material fractures in shear after ductility is exhausted, which usually requires a significant amount of plastic straining. At the start of a transition, plane strain conditions are breaking down, and fracture resistance is very sensitive to small changes in mechanical or metallurgical conditions. A small

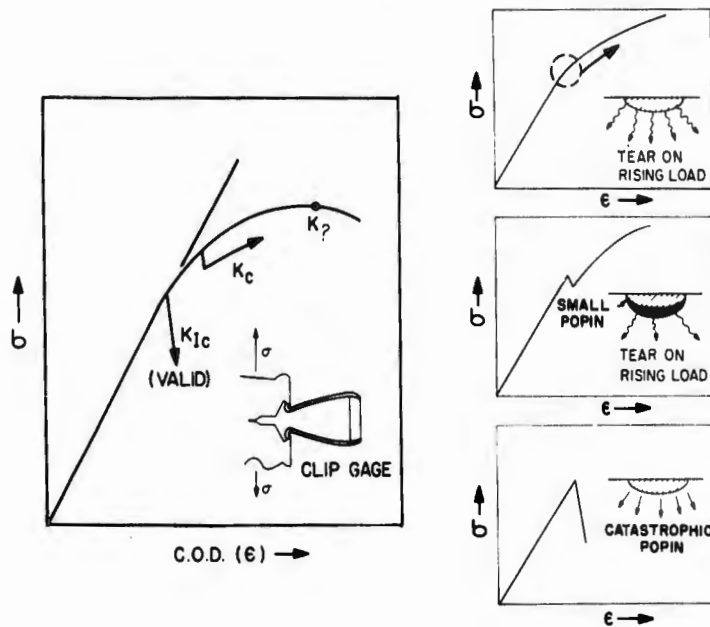


Fig. 2 - Load-displacement relationships for three levels of fracture resistance: (lower) fast instability type fracture at elastic stress levels and plane-strain stress state; (center) mixed-mode or transition-type fracture with arrest of initial popin crack and rising load required for terminal fracture; (top) fracture propagates after extensive plastic strain and plastic overload condition in the net section

decrease in constraint or increase in metal ductility will result in a rapid rise in resistance to fracture. Relationships of flaw size and stress level, based on fracture mechanics equations, can be extrapolated into this region, but there is no unique fracture-toughness value to serve as an indexible K_c , γ_c , or crack-opening-stretch (COS) value for a specific material because the section thickness and the compliance of the loading system have a great effect on the amount of crack extension that occurs from the initial popin.

The upper curve in Fig. 2 illustrates a load-vs-displacement curve for type three instability, which represents the case for a fully plastic fracture. Terminal fracture occurs after gross plastic strain has reduced the net section sufficiently to force an instability condition. Necking occurs when the net section is reducing at a pace faster than that at which the metal is being strengthened from strain hardening. The crack-extension rate is dependent upon the rate at which the load can supply the energy that is being absorbed by the large plastic enclave associated with fully plastic behavior, and consequently crack-extension rates of plastic fractures are much slower than those for cracks propagated by elastic strain energy release. The effect of flaw size on fracture potential in sections with this high level of fracture resistance is to reduce the net section until the remaining ligament is overloaded to a plastic instability condition.

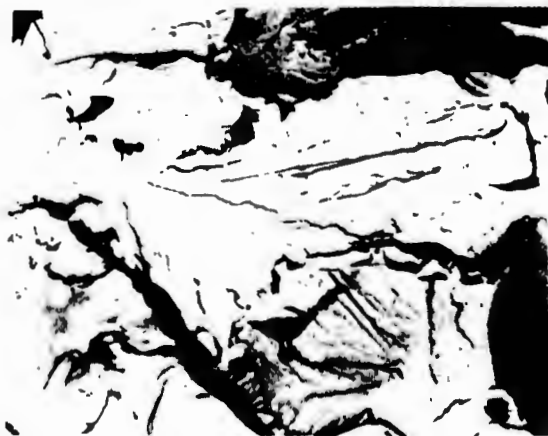
MICROFRACTURE MODE AND FRACTURE RESISTIVITY

One of the overriding metallurgical aspects of fracture resistivity is the mechanism of metal separation. The stress and strain patterns in the plastic zone account for the energy absorbed per unit of crack-tip stretch, but the microfracture mode controls the

amount of stretch that occurs prior to fracture. Since the operative microfracture modes are related to the basic microstructure, impurities, and processing conditions, brief discussions of this aspect are considered in the following sections for the more important structural metals.

Carbon and Low-Alloy Steels

Conventional structural and pressure-vessel steels, which represent the major tonnage of materials for all engineering applications, have a low alloy content and therefore low hardenability. In general, they have pearlitic microstructures after the usual air cooling from high temperatures, following a forming operation or a normalizing heat treatment. Two very contrasting microfracture modes are possible in these materials, cleavage and microvoid coalescence. Examples of these two extremes in metal separation are illustrated by the microfractographs shown in Fig. 3. These microfracture modes are readily distinguishable even without magnification because the flat facets of cleavage fracture provide a high reflectivity and bright appearance, whereas the dimpled surface from microvoid coalescence provides an absorptive surface and dull appearance.



CLEAVAGE



DUCTILE DIMPLE

Fig. 3 - Electron microscope fractographs illustrating the two microfracture modes of carbon and low-alloy steels with pearlitic microstructures: (left) cleavage, a brittle mode; (right) microvoid coalescence, a ductile mode. Approximately 4000X.

Cleavage fracture occurs when a critical level of stress is reached, and this fracture mechanism approaches a true tensile or opening mode type of separation (4, 5). Any condition that results in an increase in yield stress, such as decreasing temperature, increasing triaxiality, and increasing strain rate, will favor cleavage fracture. Although some strain hardening may be required to initiate cleavage fracture, once started, cleavage fractures propagate at high rates of speed because very little plasticity or energy is associated with the propagation of this type of fracture, and elastic strain energy can drive the crack.

When mechanical and thermal conditions in conventional pearlitic steels are such that through-section yielding occurs and cleavage fracture stress can no longer be attained even with high strain rates and strain hardening, fracture occurs by microvoid coalescence. The amount of plasticity that precedes total separation when this ductile

fracture mode is operative is controlled by the ductility of the grains and the number of voids or nonmetallic inclusions. The ductility of the metal grains controls the strain at which instability and separation occur, whereas the nonmetallics provide void sites that decrease the size of the stretching microligaments and tend to concentrate the strain. Although the ductility of grains can vary, fracture resistance corresponding to crack extension by microvoid coalescence is always at a high level in these materials, since fracture can occur only after a plastic instability condition has been reached in the net section.

The two microfracture modes operative in conventional structural steels provide for two extreme levels of fracture resistivity. Fractures can readily be initiated at elastic stress levels when cleavage fracture is the predominant microfracture mode (more than 80% of the section), and a high level of resistivity is the result when fracture occurs predominantly by microvoid coalescence. Mixed-mode fractures between these two extremes lie in a gray area where no simple relationship for fracture toughness can be stated for a specific material. In this region the interaction of the thickness parameter with temperature is of primary importance.

Since temperature has a strong effect on yield strength, it also has a strong effect on the transition from one microfracture mode to the other. For this reason, the transition region from plane strain to plastic fracture is logically related to temperature, and therefore it is termed the temperature transition. Detailed information concerning the interaction between temperature and section thickness for sections in A533 steel up to 12 in. thick are presented in Refs. 4 and 8. The development of performance criteria for fracture resistance based upon the temperature transition is discussed in a later section.

High-Strength Steels

When steels are designed metallurgically to feature a high yield strength, a quench and temper (Q&T) or a quench and age (Q&A) heat treatment is required. Characterization of fracture resistivity for these materials is more than a simple involvement with a transition between two extremes in microfracture mode occurring at ambient temperatures. Complex alloying and accelerated cooling can result in a variety of microstructures with contrasting ductilities and segregations of hard, nonductile particles other than nonmetallic inclusions. These metallurgical features tend to complicate a generalized fracture-safe design guide covering all high-strength metals, especially for welded structures where reheating in the heat-affected zones may produce brittle fracture paths.

Two additional microfracture modes can occur in the high-strength steels: grain boundary separation and quasi-cleavage (Fig. 4). These two microfracture modes, while brittle in nature, are not all bad because normally they correspond to a fracture resistivity above that associated with the pure cleavage of pearlitic steels. Unfortunately, when modest levels of fracture toughness are coupled with high yield strengths, the resulting fracture resistance may not be above plane-strain fracture conditions. Mixed-mode fracture is usually the case for Q&T steels with quasi-cleavage or grain-boundary separation operative in the central regions and a significant amount of surface material separating by microvoid coalescence.

Section thickness has a two-way influence on the fracture resistivity of Q&T high-strength steels because the most favorable metallurgical microstructure for fracture resistance requires a high cooling rate. Increasing section thickness and limited hardenability can lead to a fracture-toughness gradient from surface to center in addition to increasing the mechanical constraint. Mechanical constraint is the principal parameter controlling the transition from plane-strain conditions at ambient temperatures, since most Q&T steels have a temperature transition below 30° F if the steel has been properly alloyed, processed, and heat treated.

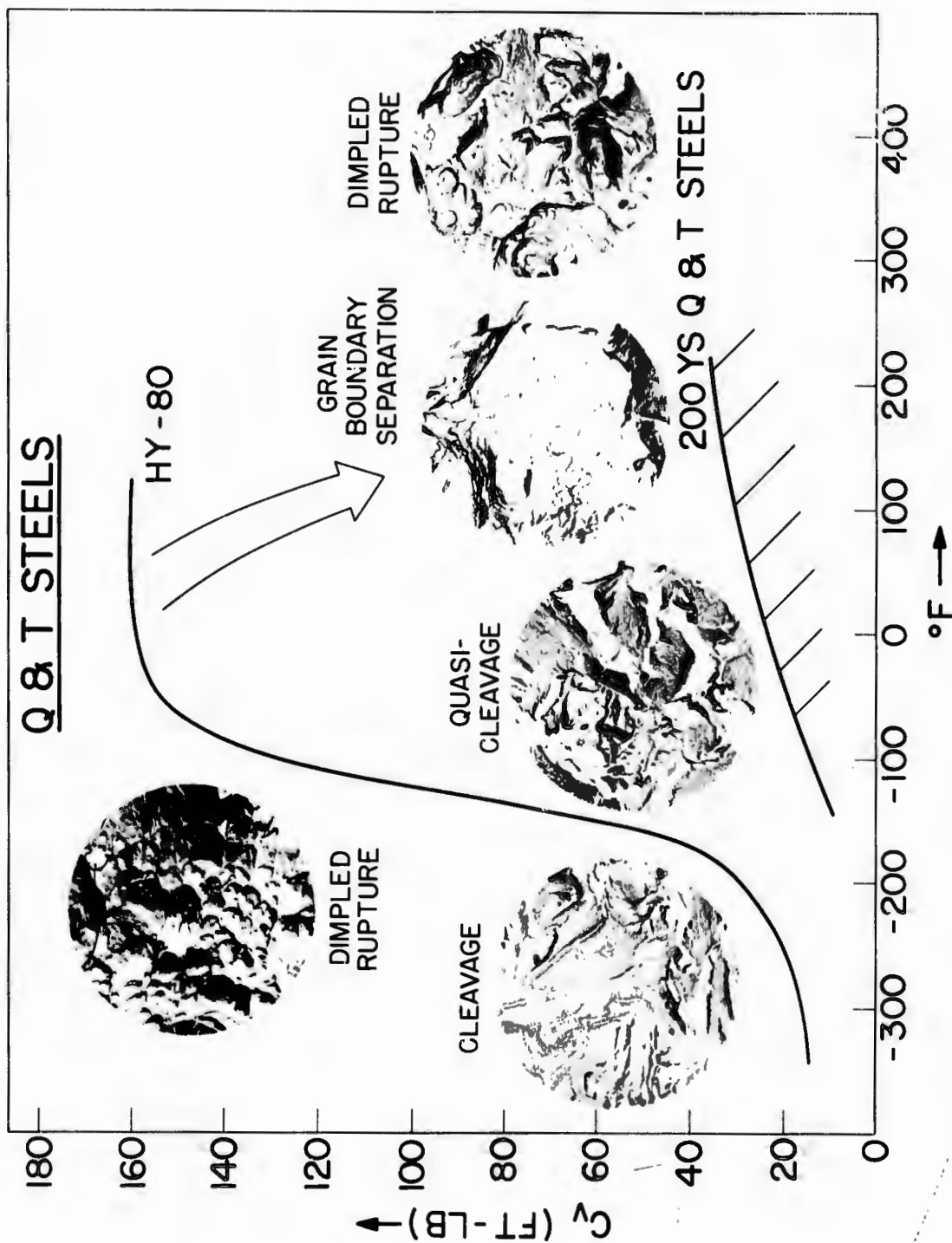


Fig. 4 - Microfracture mechanisms of high-strength steels in relation to C_v curves. Approximately 4000X.

Fracture toughness must increase in proportion to yield strength to maintain the same level of fracture resistance. As the metallurgical techniques for increasing yield strength block the formation of dislocations and thereby limit ductility, the natural trend is a decrease in fracture resistance with increasing yield strength. If a specific thickness is considered, say 1 in., and the effect of yield strength on fracture toughness is examined, a sharp decrease in fracture resistance is observed over a very narrow range of yield strengths (2,3). For premium materials, this strength transition occurs between 180 and 210ksi (9). Use of the RAD to provide analyses for the various mechanical and metallurgical interactions affecting materials in the strength transition range will be discussed in a later section.

Nonferrous Metals

Only titanium and aluminum alloys are considered here, but in general, fracture in nonferrous metals does not propagate by a cleavage microfracture mechanism. Separation can occur by quasi-cleavage, but this brittle microfracture mode is normally induced by environmental conditions with a slow extension of the crack front (subcritical crack growth). The most common microfracture mode associated with the terminal fracture of nonferrous metal sections is microvoid coalescence, but this does not always provide for a high level of fracture resistance as was the case for the conventional structural steels. Plane-strain types of fracture with fast propagation rates can occur in high-strength nonferrous metals even though the microfracture mode is a ductile, microvoid coalescence type.

Unlike the metallographic features of high-strength steels, the microstructure of high-strength nonferrous alloys may contain, by design, large particles of phases which are hard and essentially brittle. This metallurgical feature is found in some high-strength aluminum alloys where a highly ductile matrix tends to compensate for large quantities of hard and brittle phases. The soft matrix acts as a crack blunter and local crack arrestor, but high levels of fracture resistance cannot be achieved with a large number of hard, brittle particles even though they are coherent with the matrix. Fortunately, cleanliness is not as great a problem for nonferrous alloys as it is for steel because a protective atmosphere is required during melting to counteract their high reactivity to atmospheric gases. Except for mechanical entrapment, there are no deoxidation problems, but the melting point of tramp elements may be low, which encourages grain boundary and film types of segregation.

The property gradient from surface to center locations in Q&T steel products is not a problem for nonferrous alloys because most metallurgical reactions for strengthening nonferrous metals are diffusion controlled, and the hardening reactions are therefore slower than the crystallographic reactions in quenched steels. Slower metallurgical reactions and higher thermal conductivity in aluminum alloys help to limit any formation of deleterious microstructures because of an insufficient cooling rate. However, grain and phase refinement is a more difficult problem for the nonferrous alloys than for the steels, and many recent improvements in fracture resistivity are based upon thermo-mechanical processes which provide fine-grained microstructures.

PERFORMANCE CRITERIA FOR FRACTURE RESISTIVITY

The ultimate goal for engineering fracture research is a complete integration of the mechanical and metallurgical aspects of fracture into a single analytical model. The achievement of this goal is in the distant future, especially for fractures involving net-section plastic strains, but meanwhile practical engineering test methods and quantitative analyses of test results in the more critical ranges of fracture resistance have been

developed. These engineering approaches are based on the dominant parameters affecting the fracture resistivity of various alloy systems. For example, the development of performance criteria for conventional carbon and low-alloy steels concerns the temperature transition; the development of performance criteria for high-strength steels takes into account the temperature transition, but the key feature is the strength transition; and development of performance criteria for nonferrous alloys concerns only the strength transition.

Procedures for developing performance criteria for design applications involve the translation of empirical test results into data more directly related to structural terminology. This translation is provided by analysis diagrams which display mechanical behavior throughout the transition regions. The diagram approach permits development of the interrelationships between various metallurgical and mechanical parameters, which can be used also for alloy and process development as well as fracture-safe design concepts. Much of the terminology of the analysis diagrams, especially the Fracture Analysis Diagram, is already commonplace, and the general acceptance of the Ratio Analysis Diagram is rapidly expanding as high-strength materials come into more general use. In the following sections, attention is focused on the recent coupling of fracture-mechanics theory to test procedures and to the transition analysis diagrams. For detailed discussions of fracture-safe design procedures and material characterizations, the reader is referred to various selected references.

TEST METHODS FOR MEASURING FRACTURE RESISTANCE

NDT (Nil-Ductility-Transition) Test

The level of fracture resistance at the NDT temperature has been defined by the mechanical conditions specified in the test method, ASTM E208. A picture of the equipment and a series of specimens tested in increments of 10° F are shown in Fig. 5 to illustrate the test method and the transition in performance that is obtained at the NDT temperature. Below the NDT temperature, fracture resistance is so low (nil ductility) that plane-strain fractures can be initiated from small flaws and dynamic-yield stress levels. Local dynamic strain rates can be caused by either rapid loading or static loading plus small popins from brittle weld regions such as arc strikes. Using the average flaw size that is obtained from the brittle weld bead crack starter and a bending load in a DWT specimen, the level of fracture resistance at the NDT temperature has recently been shown to correspond to a $K_{Id}/\sigma_{ys} = 0.5$ (Ref. 8). This definition in fracture-mechanics terminology permits the determination of an NDT temperature using other test methods which provide measurement of fracture resistivity in terms of the dynamic plane-strain stress-intensity factor, K_{Id} . The level of fracture resistivity corresponding to a K_{Id}/σ_{ys} ratio of 0.5 translates into a requirement for a minimum section of 5/8 in. to achieve adequate constraint for a plane-strain fracture. In other words, use of a specimen less than 5/8-in. thick, such as the C_v specimen, to establish a fracture-toughness value corresponding to the NDT temperature, involves an elastic-plastic fracture condition rather than a plane-strain elastic fracture condition.

DT (Dynamic Tear) Test

The Dynamic Tear test method measures the intrinsic resistance to the propagation of fracture as a function of section thickness. Two specimen designs, 5/8 in. and 1 in. thick, are shown in Fig. 6. Most of the fracture resistivity studies at NRL on high-strength metals have utilized the 1-in.-thick specimen, and a standard method for conducting the 1-in. DT test has been prepared (10). The development of an ASTM standard method for conducting the DT test is currently being considered by a subcommittee of ASTM E-24.

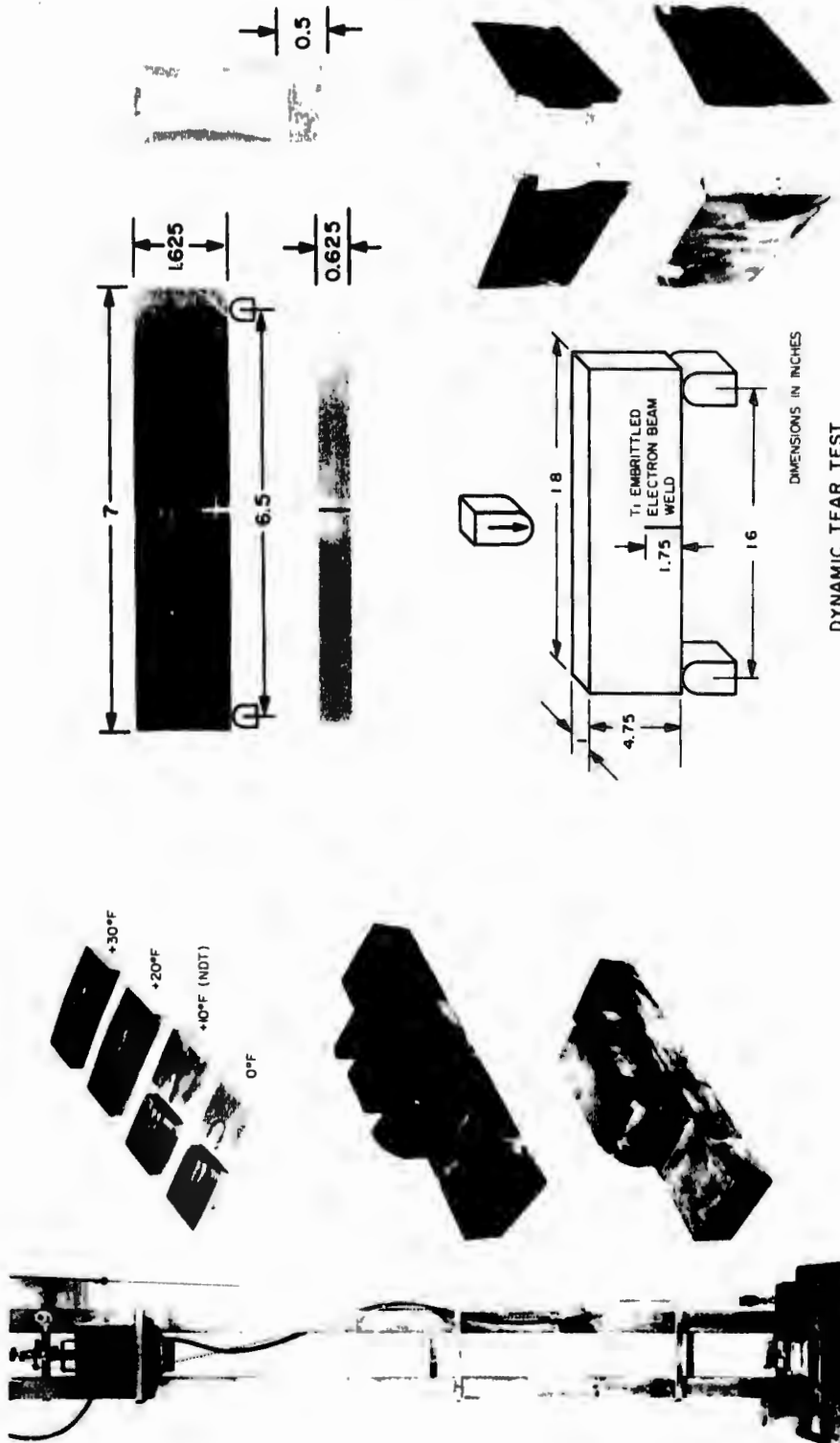


Fig. 5 - Drop-Weight-Test (DWT) equipment and DWT series illustrating the sharp increase in dynamic fracture toughness above the NDT temperature

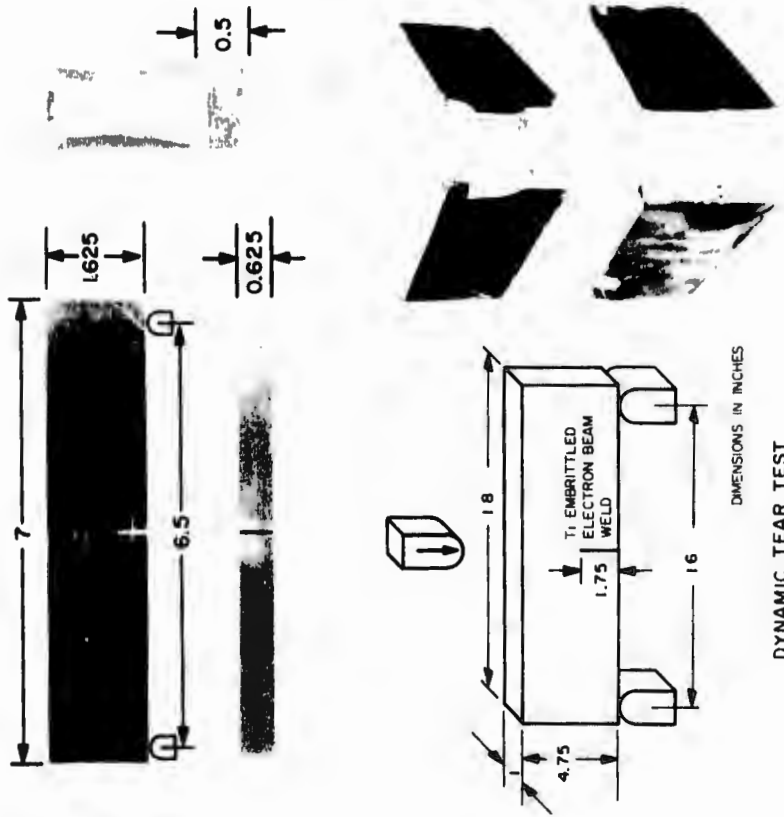


Fig. 6 - Features of 5/8-in. and 1-in. DT test specimens. The 5/8-in. DT specimen (top) features a machine slit with a knife-edge-sharpened notch tip. The 1-in. DT specimen (bottom) features a brittle electron beam weld, which is also used for the 5/8-in. DT, as desired. The broken halves of the 1-in. DT specimens illustrate brittle and ductile type fractures.

The DT test method has been extended to include specimens up to 12 in. thick and weighing 4580 lb. This experimental program has closed the ultimate link between linear-elastic fracture mechanics and the transition in fracture resistance with temperature. The limit conditions for holding a plane-strain stress state in conventional structural steels at high temperatures, and thereby postpone and possibly eliminate the transition in fracture resistivity with temperature, has until recently been a matter of speculation. Use of very thick sections in A533 steel for the construction of reactor pressure vessels prompted the AEC to procure several plates of 12-in.-thick materials for the purposes of establishing the validity of a significant temperature transition and a Fracture Analysis Diagram for thick section material. The major portion of this program has been completed, and the existence of a limit transition temperature range (LTTR) has been proven. It was found that the maximum shift of the midpoint in the temperature transition is to a 60 to 80° F (33 to 45°C) higher temperature. Thus, the temperature which relates to the dynamic plane-strain limit for this steel can be deduced simply by conducting 5/8-in. DT tests and then adding the temperature increment to indicate the midpoint (FTE) temperature (2,3). The Fracture Analysis Diagram for specific cases involving a variety of section thicknesses can be derived for most engineering purposes for materials with a high level of fracture resistivity in plastic fractures or upper shelf conditions.

DT-NDT

The breakaway from plane strain conditions at the NDT temperature is readily apparent in the dynamic tear energy-vs-temperature relationship as illustrated in Fig. 7. As fracture resistance overcomes the constraint of a deep notch, fracture toughness rises until a maximum value is achieved. Using a 5/8-in. DT specimen and measuring the DT energy, a direct correspondence in the mechanical behavior of steel in this section size and in the NDT specimen is observed. This correspondence in behavior has been observed for the broad range of pearlitic steels where sharp, unambiguous NDT temperatures are readily obtained with the standard test method. The fracture-mechanics analysis of this behavior ties in with engineering experience including the observation of shear lips approximately 1/16-in. deep at the NDT temperature and a rapid rise in lateral contraction or through-thickness yielding for sections approximately 1 in. thick at temperatures slightly above NDT. The increase in surface shear is indicative of through-thickness yielding and loss of plane strain constraint with corresponding rapid rise in fracture resistivity.

C_v -NDT

The LTTR for conventional structural steels is sufficiently steep in the $K_{I_d}/\sigma_{ys} = 0.5$ range (NDT conditions), so that the relationships for Charpy V and 5/8-in. and 1-in. DT energy as a function of temperature have a close correspondence. It is not surprising that the C_v index of 10 ft-lb corresponded to fracture initiation conditions from small arc strikes in the ship plate steels of World War II. This level of energy corresponded to the toe of the transition curve for Charpy V energy as illustrated in Fig. 8. The study of World War II ship steel fractures also provided another index of 20 ft-lb for fracture propagation. Within this narrow temperature range corresponding to a change in the C_v energy from 10 to 20 ft-lb, a sharp rise in fracture resistance occurred.

Unfortunately, the same C_v energy index of 10 ft-lb does not correspond to the NDT level of fracture resistance for the broad range of conventional steels because of the variation in the sensitivity of each steel to the shallow notch and the limited constraint of a 10-mm section. A unique index for the C_v energy value for each steel is therefore required to correspond to NDT temperature conditions. A C_v energy value may be used

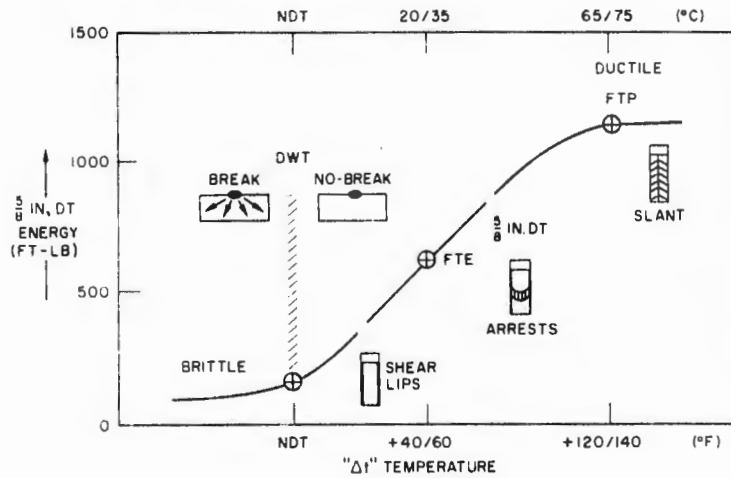


Fig. 7 - The correspondence between results of the DWT-NDT test and the DT test. The fracture resistance level of steel at its NDT temperature is equivalent to a $K_{Id} \sigma_{ys} = 0.5$ ratio (9) which is the limit of the plane-strain measuring capability of a 5/8-in. DT specimen. The rise in fracture energy and change in fracture appearance of the specimens at the NDT temperature document the transition from plane strain (elastic) to high-ductility plane stress (plastic) fracture for a steel which develops high-shelf-level fracture toughness.

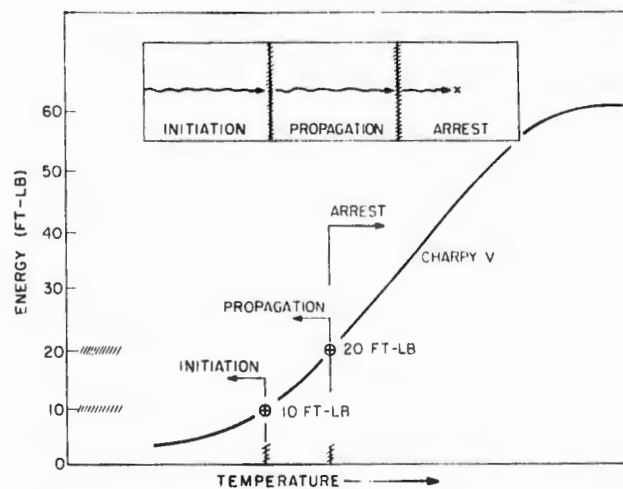


Fig. 8 - Summary of C_v energy values of ship fracture initiation, propagation, and arrest plates at the failure temperatures

as a performance criterion for specification purposes when the C_v index occurs within the transition region of the C_v energy-temperature curve. However, caution must be exercised when C_v criteria are extended to steels with metallurgical features resulting from Q&T or Q&A heat treatments because for some of these steels the entire C_v energy-temperature relationship is displaced to lower temperatures in the amount of 120° F (1,2).

C_v-DT

The C_v test can also be used to provide an index of plastic fracture resistance. A comparison of upper-shelf-level C_v values to DT energy values is shown in Fig. 9, where a direct correspondence in energy values is noted. The correlation band is sufficiently broad, however, so that Charpy V energy values must be used with caution as performance criteria because the geometrical limitations of the C_v specimen become more critical with many of the higher strength steels and all of the nonferrous alloys (1).

The general availability of the C_v test equipment and familiarity with the test method is an advantage in using a C_v performance criteria for fracture resistance. However, when materials are highly segregated, such as in welds, and when materials have fracture resistivity characteristics that do not feature a significant effect of temperature at a fracture-resistance level corresponding to a K_{I_d}/σ_{ys} ratio of 0.3 to 0.6, performance criteria can be more precisely based on dynamic tear energy values obtained with a 5/8-in. or 1-in. DT test. The DT test not only features a precise value for constraint, but it also samples a larger amount of material for evaluation.

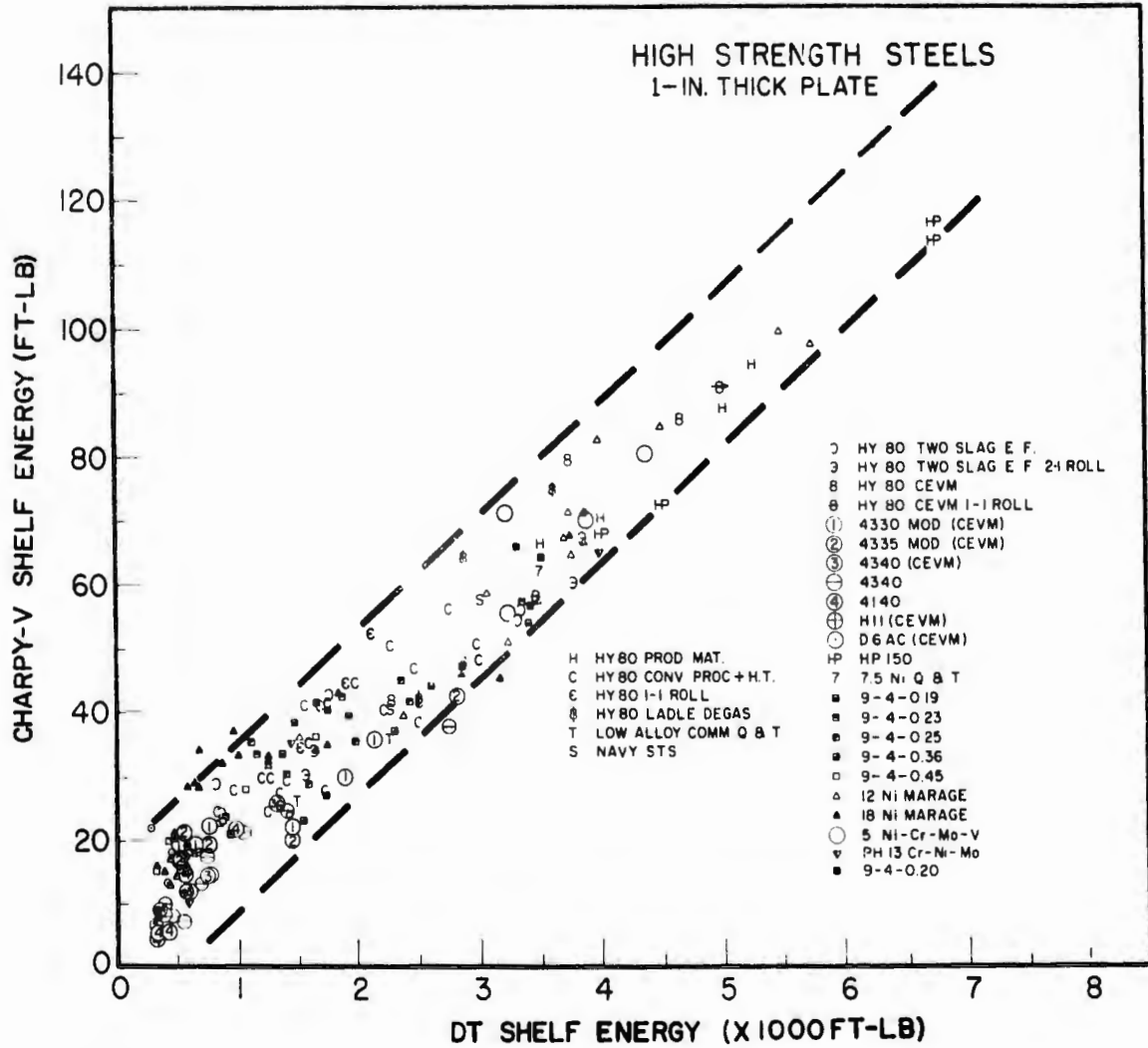


Fig. 9 - Correlation of C_v shelf energy with DT shelf energy

DT- K_{Ic}

Since the Dynamic Tear test provides a measure for the natural propagation resistance of fracture, it is not surprising that a close correlation exists between the plane-strain stress-intensity factor of fracture mechanics and dynamic-tear energy. The correlation between K_{Ic} and DT energy for a variety of high-strength steels is presented in Fig. 10, where the limit for valid K_{Ic} measurement with 1-in.-thick specimens is indicated. The close correlation between the fracture toughness values measured with the DT test and valid K_{Ic} tests provided the first coupling between an engineering type of test and a linear-elastic fracture mechanics parameter. As a result of this achievement, DT energy values could be translated into K_{Ic} values making available a fracture-mechanics analysis where conditions for plane-strain fracture pertain. Use of the analytical capability of fracture mechanics is readily accomplished with the assistance of flaw size diagrams (as shown in Fig. 11) which display graphically the relationships between critical flaw sizes and stress levels. The K_{Ic}/σ_{ys} ratio normalizes the fracture toughness value K_{Ic} to yield strength, and this ratio is indicative of a specific level of fracture resistance which corresponds to equal mechanical performance in all structural metals.

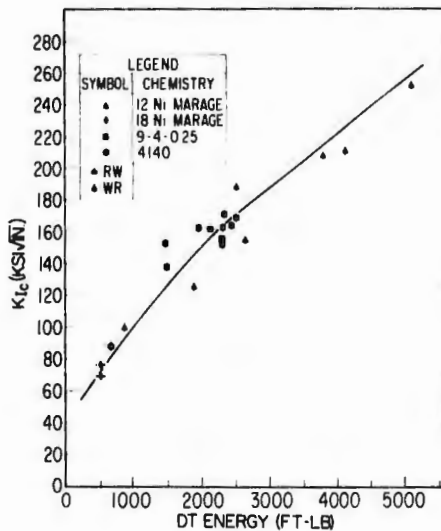


Fig. 10 - Correlation of K_{Ic} and DT test values for steel

ANALYSIS DIAGRAMS AND PERFORMANCE CRITERIA

The Fracture Analysis Diagram for Carbon and Low-Alloy Steels

The original Fracture Analysis Diagram (FAD), Fig. 12, was intended to provide a mechanical analysis for the temperature transition that occurred in the fracture resistance of carbon steels in sections ranging from 5/8 to approximately 3 in. thick. As previously stated, the FAD procedure for fracture-safe design has been extended recently to include sections up to 12 in. thick. This achievement proved the existence of a limit condition for plane-strain fracture and thereby established the concept of the limit transition temperature range (LTTR). The LTTR is a metallurgical barrier to plane-strain fracture in the conventional structural steels. Detailed discussions concerning the development and use of the FAD for selecting performance criteria and for fracture-safe design are provided in Refs. 2 and 8.

$$K_{IC} = \frac{1.1}{\sqrt{Q}} \sigma \sqrt{\pi a}$$

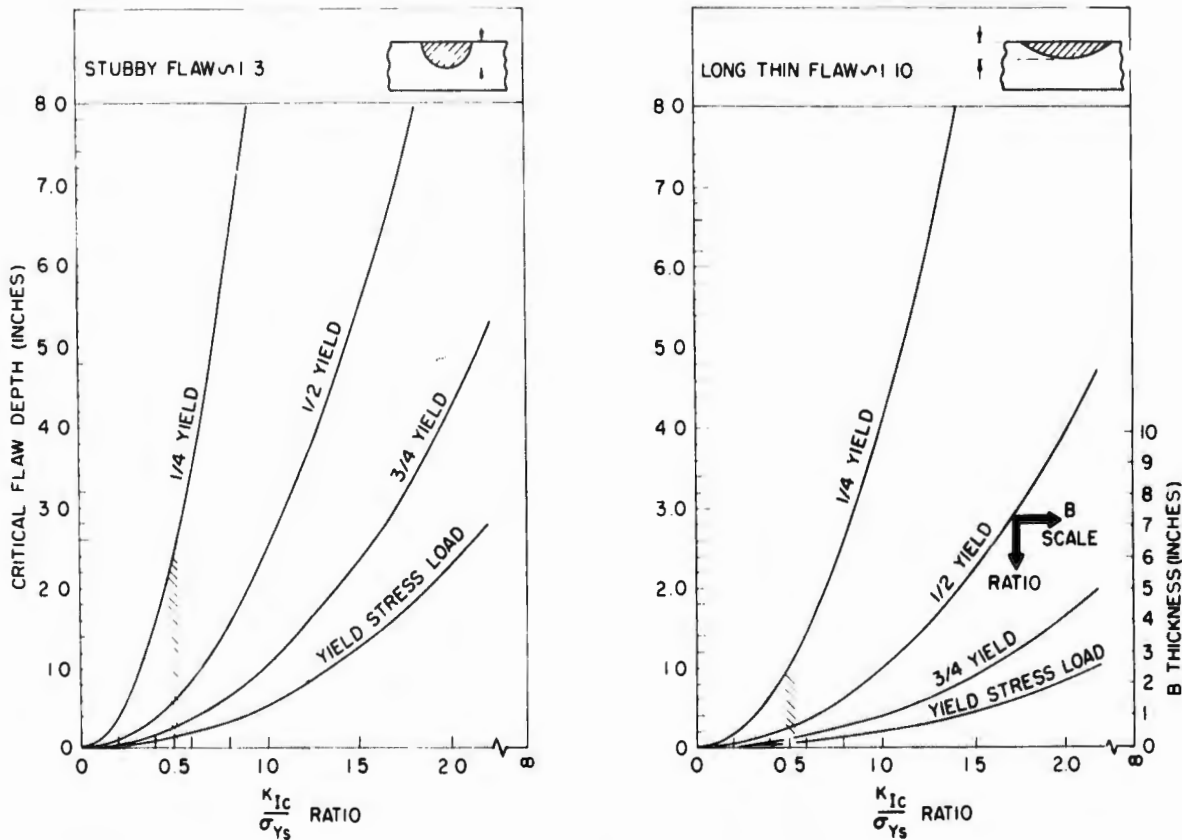


Fig. 11 - Relationships between critical flaw size and stress as a function of K_{IC}/σ_{ys} ratio. The relationships are calculated from a fracture-mechanics analysis for a surface flaw and plane-strain stress state. Section size requirement for a plane-strain fracture is indicated by the B scale in the right-hand plot.

The mechanical conditions for brittle fracture initiation are indexed in the FAD to the NDT temperature. The diagram indicates that at this critical temperature and below, carbon and low-alloy steels have sufficiently low fracture resistivity so that unstable fracture may be initiated from small flaws, less than 1/2 in. long, under local dynamic loading to yield stress levels. The tradeoff for increase in critical flaw size with lower stress levels is indicated on the FAD. Although the flaw sizes indicated in the original diagram were established from the analysis of a large quantity of service failures, the original flaw size-vs-stress level relationship has been verified by fracture mechanics calculations (3). As temperature increases above the NDT, fracture resistivity rapidly rises, and at NDT +60, the fracture transition elastic (FTE) temperature, fractures can no longer be initiated at nominal elastic stress levels regardless of flaw size. This extensive mechanical analysis applies to any conventional structural steel.

Using the fracture mechanics definition for a plane-strain stress state, $\beta = (K_{IC}/\sigma_{ys})^2/B = 0.4$, where B = thickness, the breakaway points on the LTTR can be calculated for various section thicknesses. The breakaway points from plane strain conditions related to the LTTR of the HSST A533 steel are shown in Fig. 13. The baseline

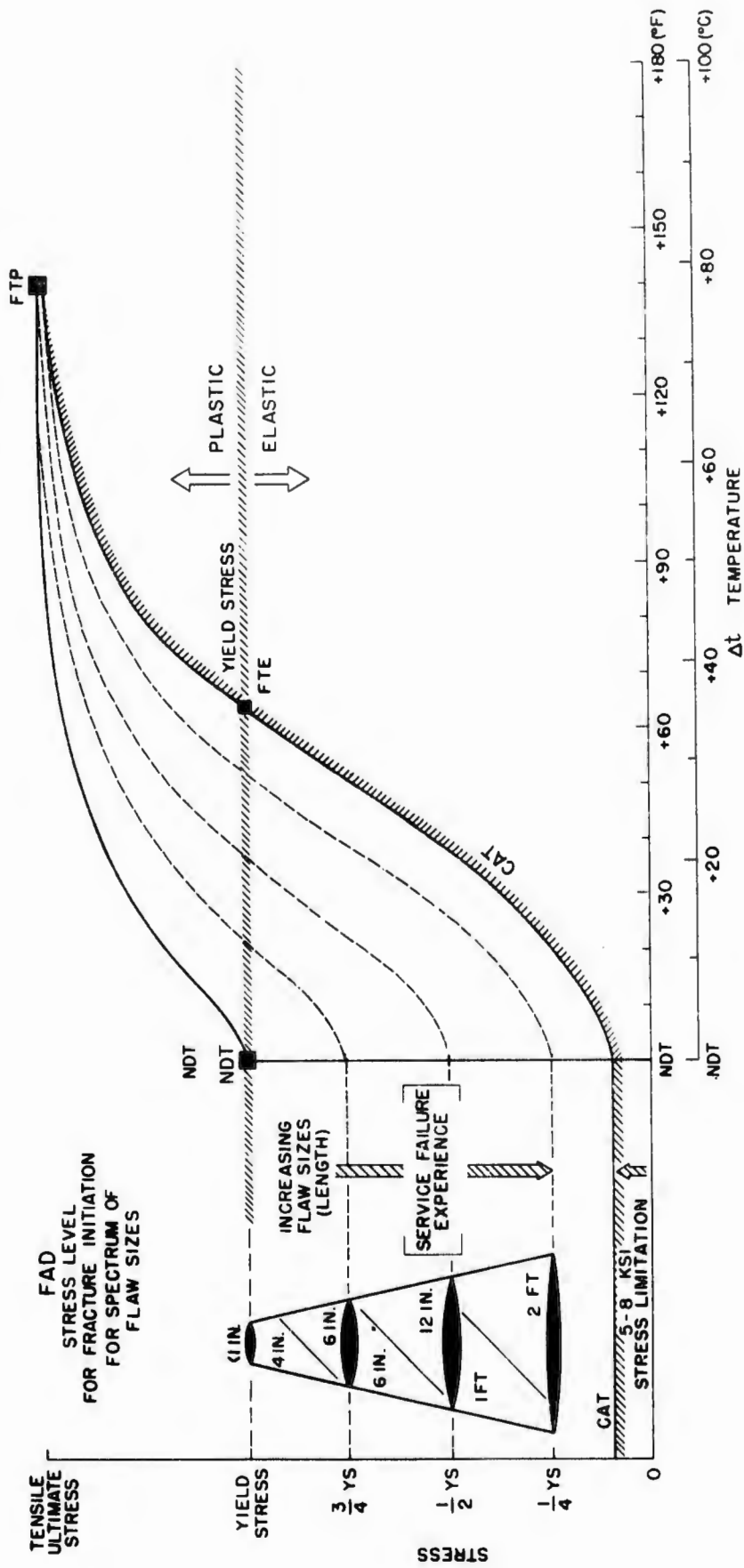


Fig. 12 - Generalized Fracture Analysis Diagram (FAD)

fracture resistivity for the material is indicated by the LTTR and labeled as the true K_{Ic} fracture relationship which is the baseline fracture-resistivity characteristic for that steel (8). Fracture toughness characteristics of specific section thicknesses have their own temperature transitions, and several selected relationships are shown in Fig. 13 to indicate the rapid rise in fracture resistance as plane strain conditions break down. The start of the temperature transition is the region of low fracture resistance, and fracture mechanics theory can be used for the finer definition of structural performance in this critical region. The translation of extrapolated K_{Ic}/σ_{ys} ratios in terms of critical flaw sizes can be made from the flaw size diagrams in Fig. 11. Although this procedure probably results in conservative values, defining fracture conditions quantitatively beyond the extrapolated curves in Fig. 13 is not justifiable, since significant amounts of net-section plastic strain then precedes fracture. Plastic strain criteria for this high level of fracture resistance are currently in the research stage of development. It should be pointed out, however, that at this level of fracture resistance, fine-scale definition of flaw sizes is no longer needed to retain a high level of structural integrity.

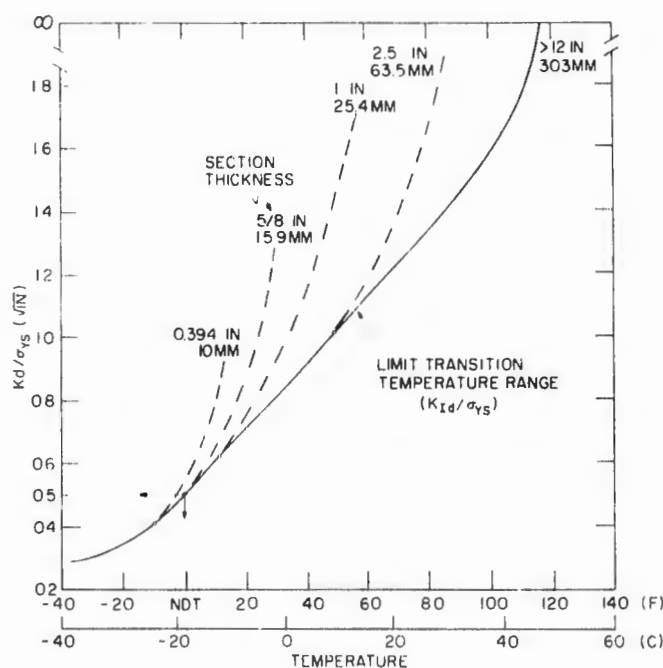


Fig. 13 - The use of fracture mechanics relationships for the fine-scale analysis of fracture resistance at the start of the temperature transition for selected section thicknesses. The Limit Transition Temperature Range shown is the metallurgical limit for plane strain fracture in A533 steel (4).

Ratio Analysis Diagram for High-Strength Steels

The Ratio Analysis Diagrams (RADs) have been under development since 1962, and the concept is intended to provide an interpretation of the relationship between fracture resistivity and yield strength level for a broad range of high-strength metals. The current, generalized RAD for steels is presented in Fig. 14, where the regions for

various types of steels are indicated. The upper bound of fracture resistivity over the full range of yield strength is called the Technological Limit Line because it indicates the current state-of-the-art production of premium materials. The sharp transition in fracture resistivity with an increase in yield strength as shown by the various types of steel is termed a strength transition. Although the position of the strength transition on the basic RAD was established with 1-in.-thick materials, the fracture resistivity of other thicknesses can be deduced from the 1-in. DT data. The K_{Ic} / σ_{ys} ratio lines on the diagram indicate equivalence in mechanical performance, and translation of performance in terms of critical flaw size-vs-stress level relationships can be obtained graphically from these diagrams, as previously described, using Fig. 11.

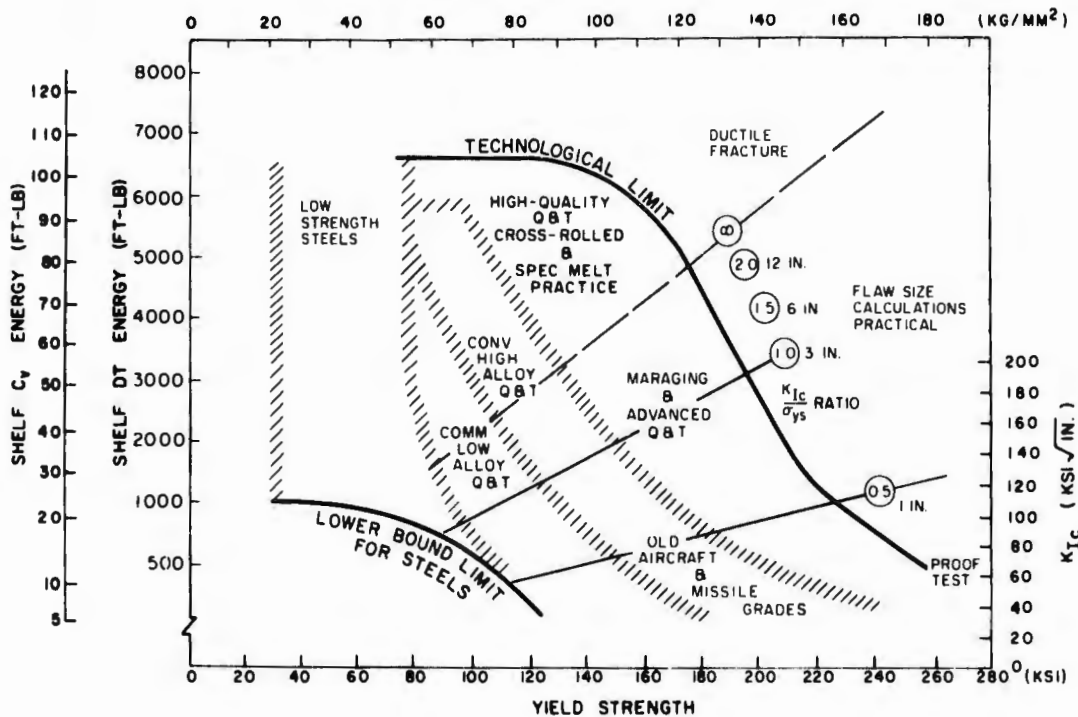


Fig. 14 - Metallurgical zoning of the RAD which defines the strength transition for various generic alloy steel types (2)

Valid relationships for the linear-elastic fracture mechanics portion of the analysis provided by the RAD is maintained up to a ratio of approximately 1.0, which corresponds to a thickness requirement of 2-1/2 in. for a valid plane-strain stress state. When sections thicker than 3 in. are analyzed, additional consideration must be given to metallurgical gradients. The true assessment of resistivity is an integrated value for the total section, since only a small center portion may be involved in plane-strain fracture. Surface flaws may never initiate an instability fracture in thick sections involving high K_{Ic} values because of the drag of the crack border, which is under plane stress conditions at surface locations. For this reason, ratio lines above 1.0 are condensed, and RAD positions above the line labeled infinity (∞) are considered to represent no potential for fracture instability at elastic stress levels. Therefore, when the DT energy value for a material lies above the infinity ratio line, projections for critical flaw sizes can no longer be made using linear-elastic fracture mechanics relationships since net-section yielding will always precede fracture even for thick section material.

For general use of the RAD analysis, mechanical performance can be classified into three categories. Below the ratio of 0.5, all materials are very brittle and critical flaw sizes are sufficiently small to preclude reliable detection by nondestructive inspection methods. Structures with thick sections in materials with this low level of fracture resistance must be proof tested to prove the absence of oversize flaws. For materials which lie between the ratio of 0.5 and infinity, consideration must be taken of the thickness of the section. If the section thickness is adequate for plane-strain instability fracture, then fracture-mechanics relationships may be used to determine the maximum flaw size that can be tolerated. If plane strain conditions do not pertain, performance criteria can be based on flaw sizes estimated from extrapolated K_{Ic}/σ_{ys} ratios using the procedure described previously for the temperature transition. For materials which lie above the ratio line, labeled infinity, flaw size is considered only as a reduction in net section, since structural failure can occur only by plastic instability.

Knowing what conditions may be encountered in service, we can readily use the analytical power of the RAD to optimize tradeoffs with respect to yield strength, quality, inspection standards, and design refinement. For general engineering design, the real value of the fracture-mechanics input to this type of analysis is the precise definition of the boundary conditions for potential fracture at elastic stress levels.

An example of the use of the RAD to provide an analysis for the interaction between metal quality, as affected by melting practice, mechanical performance, and yield strength level, is taken from a recent study of steels in the strength transition region (9). A summary of strength transitions as a function of melting practice for four new materials is presented in Fig. 15, where the strength transition occurs in the yield-strength range of 180 to 210 ksi for 1-in. material. The following four steels were included in this study: 18Ni-8Co-3Mo, 12Ni-5Cr-3Mo, 9Ni-4Co-0.2C, and 18Ni-8Co-2Cr-1Mo-0.1C.

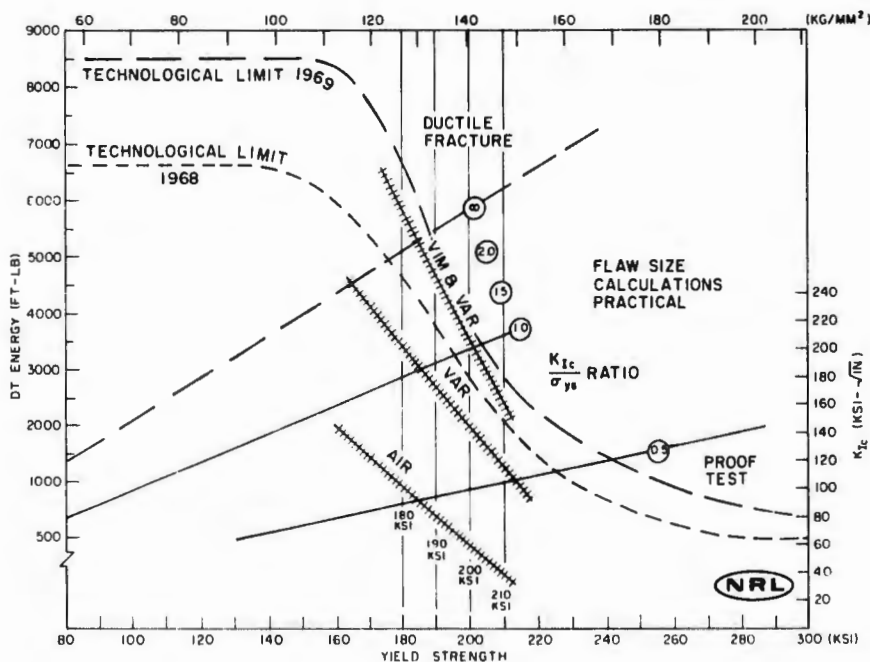


Fig. 15 - Metallurgical zoning of the RAD which defines the effects of specific melting practices. These include air melting under slags (AIR), vacuum-induction melting (VIM), and vacuum-arc remelting (VAR). A combination of these is indicated by the VIM-VAR notation (9).

From the RAD position of air-melted steel, it is readily apparent that any air-melted material in the 180- to 210-ksi yield-strength range would not be suitable for high-performance structures, even for designs and fabrication quality which would limit tensile stresses to the elastic range; i.e., no plastic hinges and no 3X stress concentrations permitted. On the other hand, it is noted that a great improvement in performance is achieved by a double vacuum-melting process (vacuum-induction melting of base materials and vacuum-arc remelting) which places all materials with up to 200 ksi yield strength above the ratio 1.0 line.

One of the most significant aspects of the fracture resistivity of steels is the steepness of the slope of the Technological Limit Line within a very narrow range of yield strengths (180 to 210 ksi). Quantitative information concerning the relationship metal quality and yield strength on fracture resistance for this critical range of materials is readily provided by the RAD analysis. The advantage of selecting a lower yield-strength level and a higher relative design stress to provide a high level of fracture safety can easily be seen from the slope of the strength transition curves. An important forecast can be made also on the basis of the RAD in Fig. 15, namely that improving the metal quality tends to steepen the strength transition, and for steels with yield-strength levels beyond the current strength transition above 220 ksi, only low fracture-resistance levels below $K_{Ic} / \sigma_{ys} = 0.5$ ratios are obtained. It is apparent that new innovations in metallurgical design such as macrocomposites, rather than additional refinement of homogeneous alloys, may be the approach to high fracture resistivity in the ultrahigh-strength steels.

Ratio Analysis Diagram for Titanium Alloys

The metallurgy of titanium alloys affecting fracture resistance concerns primarily two aspects: (a) the matrix microstructure, alpha (HCP), alpha beta and beta (BCC); and (b) the oxygen content. Oxygen content is perhaps the most critical aspect, since it is frequently an intentional alloying element for increasing yield strength, but it has been shown to have a degrading effect on fracture resistivity (11).

The generalized RAD for titanium alloys is shown in Fig. 16 where the large zonal regions of the three types of alloys illustrate that a broad range of quality is possible at any specific yield strength. Alpha alloys are limited to a yield-strength level of 120 ksi, and materials with an alpha matrix can be procured with fracture resistivity levels sufficiently high to preclude the plane strain type of fracture over their entire strength range.

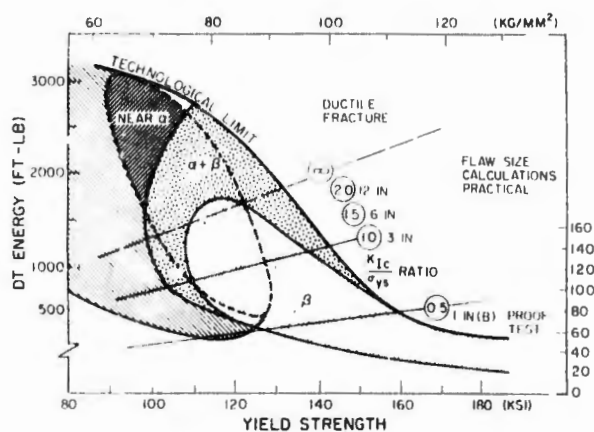


Fig. 16 - Metallurgical zoning of the RAD for the three generic classes of titanium alloys (11)

Beta alloys are ultrahigh-strength materials, and most beta alloys have yield strength levels above 120 ksi. Fracture resistivity levels are correspondingly low with RAD positions below the ratio, $K_{Ic} / \sigma_{ys} = 1.0$ line. The fracture resistance of these alloys is frequently degraded when they are welded, and fortunately the development of improved, weldable alloys of the beta type may be expected in the near future.

Metallurgically, the development of alpha-beta alloys is aimed at optimizing the fracture resistance of the alpha system with the high yield strength of the beta system. The alpha-beta alloys cover the critical strength transition range of yield strengths. Close control of processing, heat treatment, and oxygen content is required to maintain a fracture resistivity above the $K_{Ic} / \sigma_{ys} = 1.0$ line.

No C_v index scale appears on the titanium RAD because the C_v specimen does not provide a sensitive index to the fracture resistance compared to that provided by the DT test or the K_{Ic} test. Interpretation of C_v energy is difficult, and since the DT test provides a more discriminating index to the fracture resistivity of these materials, performance criteria for fracture resistivity have been based upon a DT energy value for critical structural applications involving thick sections.

Ratio Analysis Diagram for Aluminum Alloys

The RAD for structural aluminum alloys is not as fully developed as that for steels and titanium alloys, but sufficient data have been generated to provide a general view of the zonal regions of high-strength alloys (12). The numerical classification for aluminum alloys separates them metallurgically and also provides a separation with respect to yield strength, Fig. 17. Although the absolute fracture-toughness values (energy absorbed) for aluminum alloys are low with respect to those for steels and titanium alloys, there is a pronounced strength transition from plastic fracture to plane-strain elastic fracture, as there is for the high-strength steels and titanium alloys.

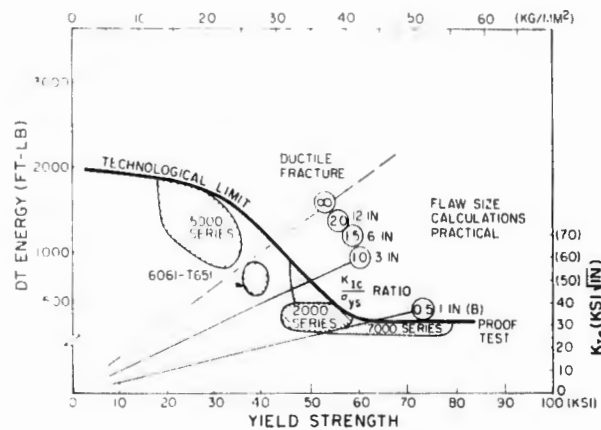


Fig. 17 - Metallurgical zoning of the RAD for various series of aluminum alloys (12)

The aluminum alloy system is metallurgically different than that for the steels and titanium alloys in that there is less variation in fracture resistivity for a specific generic alloy. Also the only alloys in the strength transition range are the 6000 series alloys, and all others are either above the $K_{Ic} / \sigma_{ys} = 1.0$ ratio line or below the 1.0 ratio line. Aluminum alloys with yield strength levels above 60 ksi are in the 7000 series, and all

thick-section (> 0.6-in.) material at this strength level lies below the brittle boundary of $K_{Ic} / \sigma_{ys} = 0.5$.

No C_v scale appears on the aluminum RAD shown in Fig. 17 because C_v energy values are difficult to interpret, and the full range extends only from 5 to 25 ft-lb. C_v energy has been criticized as being too insensitive to changes in the structural performance of aluminum alloys, and therefore further development of the DT energy characterization of aluminum alloys is being encouraged by the Metal Properties Council.

Since the DT test provides a more precise index to the analytical procedures of fracture mechanics, this new information will provide rapid assessment of structural performance with a degree of accuracy sufficient for most engineering applications without resorting to an expensive fracture mechanics test for material acceptance criteria.

SUMMARY

The traditional engineering approach to failure-safe design using low nominal stresses is rapidly becoming obsolete with the development of more rational design procedures and fracture technology. Most conventional engineering structures will retain unrefined details where plastic strain will be encountered, and the only recourse to achieving a high level of structural integrity is an adequate level of resistance to fracture. Fracture technology has made many significant advancements in recent years, and a major milestone was reached when the traditional engineering approaches, including the temperature transition concept, were coupled to the analytical capability of linear-elastic fracture mechanics.

A prerequisite to an understanding of the engineering approach to fracture safety is recognition of characteristic metallurgical features of the various alloys around which models for defining fracture resistivity are developed. The principal metallurgical aspects of fracture resistivity are microfracture mode, quality, and the tradeoff of ductility for increased yield strength.

Fracture-safe design models with the conventional pressure-vessel and structural steels are based on the transition in the microfracture mode from cleavage to a ductile fracture within a narrow temperature range. The overall model is called the Fracture Analysis Diagram (FAD) which displays the relationship between the critical mechanical factors (stress, flaw size, and section thickness) within the temperature transition region. If one is forced, for economical reasons, to use conventional steels in the temperature range where plane-strain fracture at elastic stress levels is a possibility, fine-scale definition of critical flaw sizes can be obtained with a supplementary diagram which presents flaw size-vs-stress relationships as a function of K_{Ic} / σ_{ys} ratios.

Fracture toughness indexes to the FAD and RAD analyses are obtained with either the DWT-NDT, the DT, or the C_v test. The C_v test serves as a secondary test to the DWT-NDT and the DT tests. With the development of relationships between the results of engineering fracture tests and fracture mechanics stress-intensity parameters K_{Ic} and K_{Id} , it is not necessary to conduct valid fracture mechanics tests to make practical utilization of the quantitiveness of fracture mechanics theory.

Fracture-safe design models for high-strength steels and nonferrous alloys are based upon the requirement for increasing fracture toughness with increasing yield strength. The model for providing an analysis for fracture resistivity of these materials is called the RAD, which provides an interpretation of fracture resistance sufficiently accurate for most engineering uses. Inputs to the RAD are DT energy, C_v energy, and yield strength. The general level of performance can be readily determined with the

regional position on the diagram from the proximity to critical K_{Ic} / σ_{ys} ratio lines. Fine-scale definition of critical flaw size-vs-stress relationships can be obtained from flaw size diagrams which are based on fracture mechanics equations, as described above. If the use of a material with a K_{Ic} / σ_{ys} ratio less than 0.5 is required because of strength-to-weight restrictions and if the section thickness exceeds 5/8 in., conducting valid fracture mechanics tests is recommended together with proof testing as a final inspection procedure for flaws. For materials with a fracture resistivity significantly outside of that for unstable fracture at elastic stresses, precise definition of critical flaw sizes is unnecessary. Flaws in structures of materials with high levels of fracture resistivity serve only to decrease net sections to the point where plastic instability occurs.

CONCLUSIONS

On the basis of the information presented in this interpretive report, the following conclusions are stated concerning the status of the engineering approach to fracture-safe design using fracture-toughness values as performance criteria.

1. The coupling between engineering fracture tests (C_v and DT) for measurement of fracture resistance and linear-elastic fracture mechanics theory has been achieved.
2. Interpretive diagram systems (FAD and RAD) have been developed which couple the fracture toughness values from engineering fracture tests to the analytical capability of fracture mechanics.
3. The DT test has the capability for measuring a broad range of fracture toughness extending from the low energy region pertaining to elastic fractures to the high-energy region pertaining to fully plastic fracture.
4. Difficulties in the interpretation of C_v energy values within the transition region (plane strain to plane stress) for high-strength steels and nonferrous structural alloys may limit the use of C_v energy as a performance criteria for certain materials.

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<p>The traditional engineering approach to failure-safe design has been the use of conservative values for the mechanical parameters involved. The level of conservatism can now be more precisely selected, since the development of fracture mechanics has provided a theoretical stress analysis for the cracked-body case. A fine-scale definition of the relationship between critical flaw sizes and elastic stress levels can now be established by calculation. The quantitiveness of fracture mechanics has recently been extended for general engineering use by the provision of graphical correlations between stress-intensity values from fracture mechanics tests and fracture energy values obtained from Charpy V-notch and Dynamic Tear tests. Fine-scale definition of critical flaw sizes can now be determined from results of these engineering-type fracture tests when fracture instability can occur at elastic stress levels.</p> <p>An extension of the quantitative analysis for critical flaw sizes into the regime of general engineering design, where a safe amount of plastic strain must precede fracture, is the objective of current research. Theoretical solutions to the nonlinear plastic state are complicated by other material characteristics such as transitions in microfracture modes and strain rate effects. Meanwhile, engineering develop-</p>			

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ments for defining conditions leading to fracture under plastic strain conditions are based upon a tear energy concept using analysis diagrams which feature inputs of temperature and section size parameters for mixed-mode fracture conditions. The engineering analysis diagrams are sufficiently flexible to allow upgrading their quantitiveness as the theoretical treatment of plastic instability evolves.