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Dynamic Tear Energy—A Practical Performance Criterion for Fracture Resistance

E. A. Lange and F. J. Loss

Strength of Metals Branch
Metallurgy Division

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NAVAL RESEARCH LABORATORY
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ABSTRACT

The Dynamic Tear (DT) method of testing for fracture toughness was developed to overcome the limitations of the Charpy V (C_v) test and to provide information of engineering design significance. Key features of the DT test are described, including specimen design, impact test machines, and methods of energy measurement. A relationship exists between the DT energy and the fracture mechanics stress-intensity factor K_{Ic} which allows the translation of these energy values into design parameters, such as critical flaw size and stress level, by means of suitable charts.

The current need for the use of the DT test in the development and selection of high-strength structural metals has become evident through examples of conditions to which the C_v test has been shown to be inadequate. For example, when fracture toughness criteria defined by the C_v and DT tests are compared for a high-strength titanium alloy, a 180-ksi yield strength steel, a 140-ksi yield strength steel weld metal, and a Q & T 2-1/4% Cr - 1% Mo steel of 90-ksi yield strength, the C_v test is shown to provide information in variance to that from the DT, DWT-NDT, and Robertson tests. Therefore, it is concluded that the DT test method has desirable features for general industrial use which provide broad-scope characterization of the fracture resistance of steels, titanium alloys, and aluminum alloys.

PROBLEM STATUS

This report completes one phase of the problem; work on other phases is continuing.

AUTHORIZATION

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DYNAMIC TEAR ENERGY — A PRACTICAL PERFORMANCE CRITERION FOR FRACTURE RESISTANCE

INTRODUCTION

Economic competition, weight premiums, and availability of materials with high yield strength are accelerating the trend for use of higher nominal stresses in the design of conventional structures. As nominal stresses increase, the probability for catastrophic failures increases, because small crack instabilities are less likely to be arrested due to the higher strain energy release rate associated with the higher stress levels. Safe operation of structures at high stresses requires an accurate definition of the fracture resistance of materials to ensure that an adequate reserve is maintained in material performance to balance the effects of design refinement, fabrication quality, and reliability of inspection. Although there is a need for improvement in all factors affecting structural integrity and some interchange is possible, there is no safe substitute for accurate definition of the fracture toughness of the material, except by the use of uneconomically low stress levels.

One of the complicating aspects in defining the fracture toughness of metals is that fracture resistance depends highly on the mechanical conditions involved, especially those conditions related to constraint and strain rate. Fractures can occur at stress levels below yield stress or above yield stress depending on flaw size, section thickness, and strain rate. In addition, the performance of most of the conventional steels depends highly on temperature because of a sharp transition in fracture toughness in a relatively narrow temperature range. For these materials, low temperatures and thick sections promote separation by a cleavage mode which results in low resistance to fracture. High temperatures tend to increase fracture toughness; above the transition temperature range, separation can only occur by a ductile mode even for the case of maximum mechanical constraint associated with very thick sections (1). Since these basic characteristics of structural steels have become more generally recognized, the need to improve current methods for measuring fracture toughness has become increasingly evident to the working committees of the various technical societies, such as the ASTM and the ASME.

Fortunately for many conventional steels representing the majority of steel production on a tonnage basis, Charpy (C_v) energy levels can be correlated to structural performance for specific materials. These correlations are based either on an adequate number of unfortunate service experiences, as was the case for ship steels, or on comparisons with results from more definitive fracture tests, such as the drop-weight and nil-ductility-transition temperature (NDT) test (2). Even with this assistance the C_v test remains a narrow-scope test, and modifications, such as sharpening the notch or adding side grooves to increase lateral constraint, can only extend its measuring capability to a limited degree. The C_v specimen is too geometrically limited to evolve into a fracture toughness test of broad application.

The Dynamic Tear (DT) test was developed to overcome the limitations of the C_v test and to provide information of engineering design significance. With improved specimen design the range of measurement under plane strain conditions was increased and measurement of the resistance to propagation of fracture was improved. The objective was to provide practical test specimens for measuring the intrinsic resistance to the propagation of fracture. The test method is applicable to all structural metals irrespective of fracture toughness or yield strength; i.e., it is a test method with broad-scope

capability. The basic philosophy of the DT test specimen design and loading procedures is the provision of "limit severity" conditions simulating the worst mechanical condition that can be expected to occur in a structure. These conditions include high strain rate and a sharp, highly constrained crack. The test provides a sensitive measure of fracture resistance for both low and high levels that accurately relates to structural performance.

The DT test is in an advanced state of development; and characterizations of the fracture toughness of steels, titanium alloys, and aluminum alloys have been summarized recently (3-5). The objectives of this report are to describe the DT test methods and to illustrate the pressing need for general industrial use and standardization of the DT test procedures.

THE DYNAMIC TEAR TEST

DT Test Specimens

Dimensions and weights of various specimens which have been used for steel are listed in Table 1, and a detailed description for conducting the 1-in. DT test is provided in Ref. 6. A broad range of section thicknesses, 5/8 to 12 in., has been investigated to provide an analysis for size effect, since specimens of thicknesses greater than 1 in. are not practical for general engineering use. Most attention in the past several years has been given to the 1-in. and 5/8-in. DT specimens and to the development of correlations with thicker section performance.

Table 1
Dimensions and Weights of Various Steel Specimens Used in the DT Test

Specimen Designation	Thickness, B		Depth, W		Length, L		Span Between Supports, S		Brittle Weld or Notch Depth, a		Weight	
	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	Lb	Kg
5/8 in. DT*	0.625	1.6	1.62	4.1	7	18	6.5	16.5	0.5	1.3	2	0.9
1 in.	1	2.5	4.75	12.0	18	46	16	40.6	1.75	4.4	24	10
2 in.	2	5.0	8	20.3	28	71	26	66.0	3	7.6	127	57
3 in.	3	7.6	8	20.3	28	71	26	66.0	3	7.6	190	86
6 in.	6	15.2	12	30.5	62	158	58	147.3	3	7.6	1220	554
12 in.	12	30.5	15	38.1	90	228	84	213.3	3	7.6	4580	2080

*Also deep machined notch having tip sharpened by pressed knife edge.

The 5/8- and 1-in. DT specimens represent a full-thickness test for many cases and a close approximation for others. The significance of results from a subthickness test is obtained by correlation, which has been investigated in detail for a steel with a high upper shelf fracture in thicknesses up to 12 in. For very brittle material where linear elastic fracture mechanics is applicable, direct correlations of DT energy have been made to static stress-intensity factors, K_{Ic} (3). For materials with an intermediate level of fracture resistance, the "grey area," full correlations are not complete. However, the

DT test and correlative procedures appear to be the best overall approach to this intermediate, elastic-plastic region of fracture resistance.

Since the 1-in. DT specimen requires more metal than is sometimes available in research studies or is practical for routine testing, attention has been given recently to the development of smaller specimens of 5/8-in. thickness. The 5/8-in. DT specimen has been found to provide the same characterization ability as the 1-in. DT specimen for many materials. In addition, the 5/8-in. DT specimen may be alternatively prepared with a machined notch instead of the electron beam (EB) crack starter, as shown in Fig. 1. It can be shown that DT energy values from the 5/8-in.-thick specimen are readily transformed into 1-in. DT energy values by use of simple proportionality factors (7).

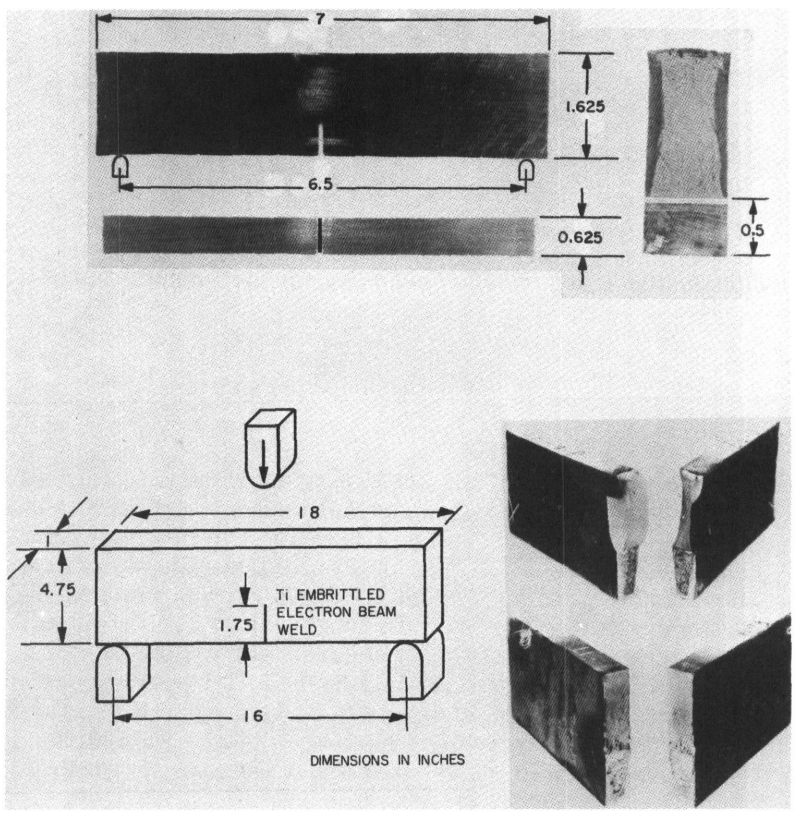

Fig. 1 - Specimens for the DT method of impact testing: 5/8-in. DT specimen (top) and 1-in. DT specimen (bottom)

Studies concerning the correlation between subsize test results and full-thickness performance are continuing, and preliminary results indicate that energy density in ft-lb/in.^{2}, is a very promising parameter for providing broad extrapolation of upper shelf DT energy values. The effect of increasing thickness in energy density for several steels in sections from 0.2 to 12 in. is shown in Fig. 2. For materials featuring transitions in fracture toughness involving changes in microfracture mode with temperature, additional consideration of the temperature parameter is required. The effect of section size on the temperature transition aspect of fracture is discussed in detail in Ref. 1.

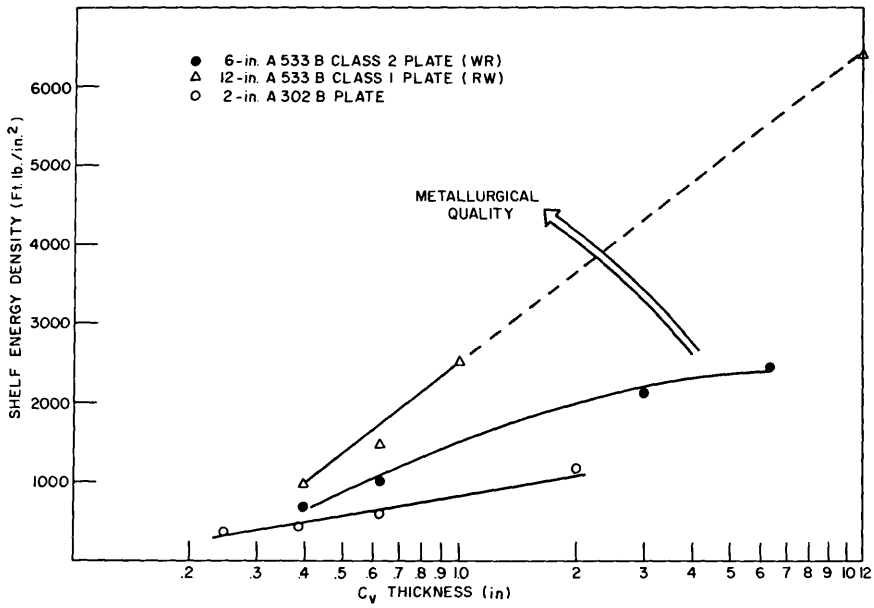

Fig. 2 - Relation of upper shelf DT energy density to specimen thickness for A302B and A533B steels, indicating that broad translation of test results is possible for ductile microfracture modes

DT Impact Machines

One of the desirable features of impact testing machines is their simplicity of operation. The pendulum-type machine is notable in this respect, and single pendulum machines are generally used. When required, a machine can be designed with two opposed pendulums matched for centers of percussion to eliminate the shock transmitted to the base mounting. The double pendulum machine shown in Fig. 3 has a 2000-ft-lb capacity, which is adequate for evaluating the fracture toughness of all metals using the 5/8-in. DT specimen. A capacity of 10,000 ft-lb is adequate for evaluating the fracture toughness of all metals, with few exceptions, using the 1-in. DT specimen. Specimens larger than 1-in. thick require impact machines with very high capacities, and for large DT specimens, vertical drop-weight machines have been used. An 800,000-ft-lb machine, which is used to fracture 12-in.-thick DT test specimens, is shown in Fig. 4.

DT Energy Measurement

DT energy can be determined readily with pendulum machines by computing the potential energy associated with the initial and final pendulum positions. A simple digital readout system can also be added as an accessory item for a pendulum machine. Vertical displacement of the pendulum is directly proportional to the output of a sine-cosine potentiometer mounted on the axis of rotation, and the output can be calibrated to indicate energy directly using a digital voltmeter. A schematic drawing of a digital readout system for a pendulum machine is shown in Fig. 5. Calibration of the direct reading system is a simple procedure after the capacity of the machine is established using the method described for the Charpy machine (8). With a shunt across the sine-cosine potentiometer, input voltage is adjusted to provide a reading on the digital voltmeter equal to the maximum capacity of the machine. The accuracy of all other readings on the digital

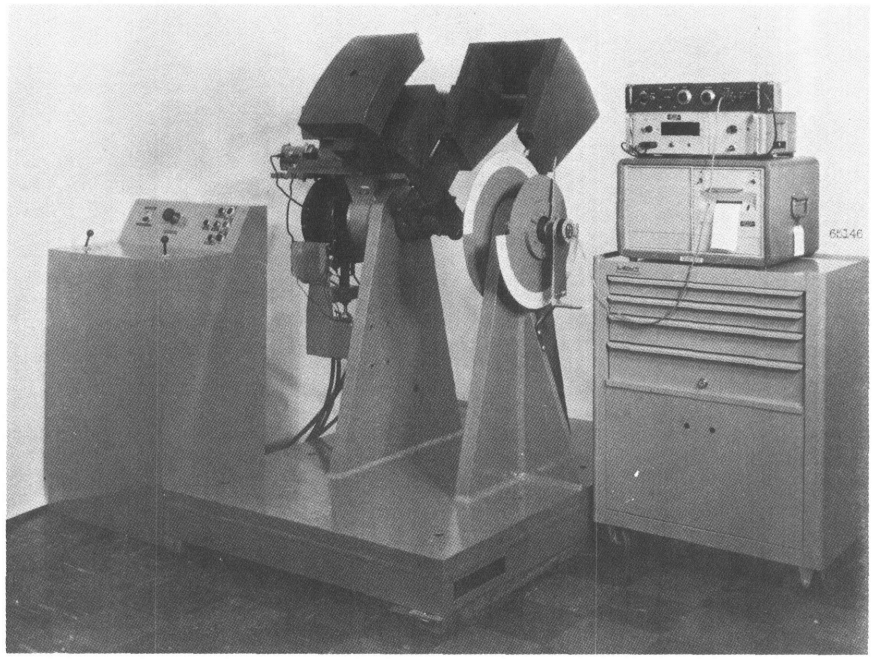

Fig. 3 - A double-pendulum, DT impact machine of 2000 ft-lb capacity used to fracture the 5/8-in. DT specimen. No shock is transmitted to the mount with this design.

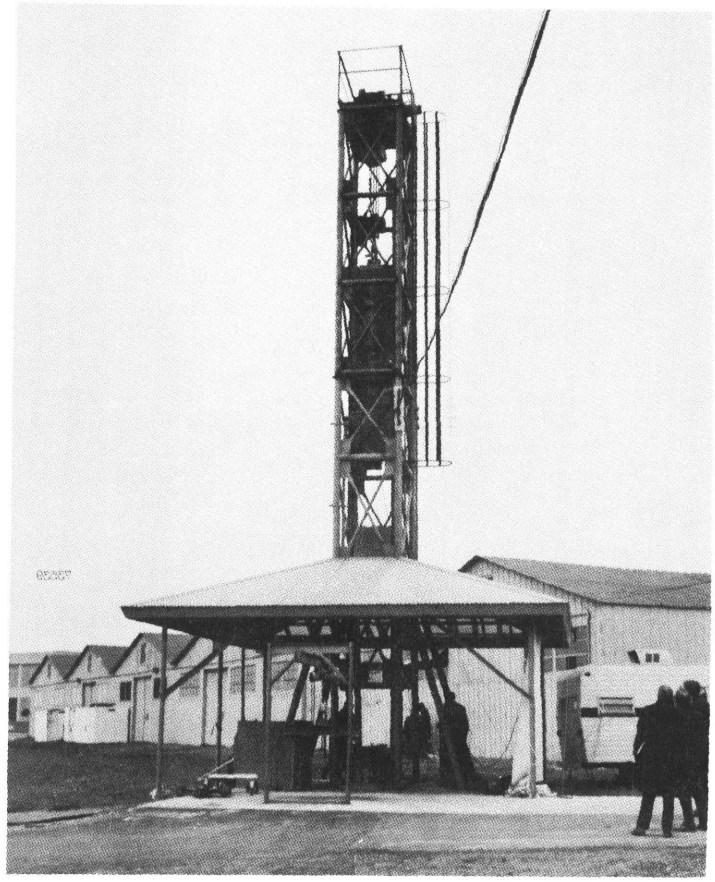

Fig. 4 - An 800,000 ft-lb drop-weight machine for testing 12-in.-thick DT specimens

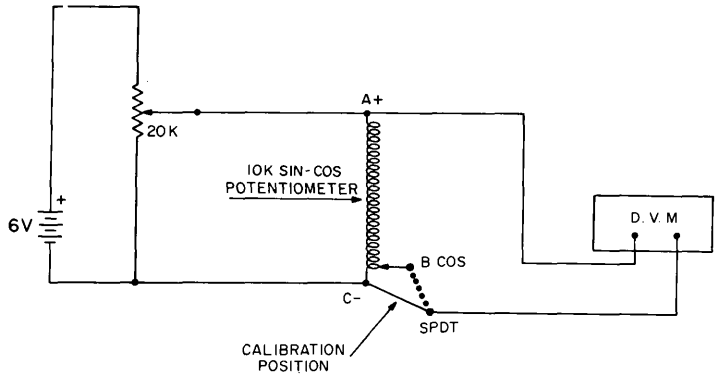

Fig. 5 - Circuit for digital readout system for pendulum-type DT test machines

voltmeter is in direct proportion to the accuracy of the radial potentiometer and the digital voltmeter, normally better than 0.5% of full scale.

DT energy from a vertical drop-weight machine can be obtained by either an instrumented hammer, a device for tracking the velocity of the weight, or a calibrated absorption device for measuring the residual energy of the weight after specimen fracture. DT energy measured by an instrumented hammer requires the stricken end to be reduced in cross section and to act as a short column. Strain gages are mounted at the midpoint of the column, providing an electrical output proportional to the load. The column should preferably be square in cross section with a minimum height equal to three times the width. The strain gages are connected in a conventional bridge circuit, and the bridge output is recorded by photographing an oscilloscope trace of the strain gage output. Because of the speed and vibrational aspects on the hammer force, a broadband oscilloscope with 100 to 300 kc band pass is required for accurate definition of the force-time record.

Calibration of the instrumented hammer is conducted statically in a conventional testing machine. DT energy is then computed as the change in kinetic energy of the hammer using

$$\Delta E = \frac{mV_0^2}{2} - \frac{m}{2}\left(V_0 - \frac{I}{m}\right)^2 ,$$

which reduces to

$$\Delta E = I\left[V_0 - \frac{I}{2m}\right],$$

where

ΔE = absorbed energy (ft-lb),

V_0 = impact velocity (ft/sec)

m = mass of hammer (lb/sec^2-ft), and

I = impulse from area under force-time oscilloscope trace (lb-sec).

A simple mechanical device that has been used to provide a measure of residual energy of the hammer in a vertical machine after the DT specimen has been broken is an anvil with soft lead bricks. The design of this device is shown in Fig. 6 for a testing machine of 20,000-ft-lb capacity. The soft lead bricks are cast to size and are nominally 2 by 4 by 8 in. Calibration of the lead bricks is obtained by measuring deformation as a function of drop height. Two lead bricks can absorb up to 20,000 ft-lb with adequate sensitivity and reproducibility. The calibration curve shown in Fig. 7 illustrates the accuracy of obtaining DT energy with this simple device.

Correlation Between DT Energy and Fracture Mechanics Parameters

Since all measurements of fracture resistance are manifestations of the size of the plastic zone associated with the crack, it is not surprising that direct correspondence can be found between test specimens featuring deep, sharp cracks. For example, the relationship between the fracture mechanics stress-intensity factor K_{Ic} and the DT energy measured with a 1-in. specimen is shown in Fig. 8 for a variety of steels. Through this correlation and the use of fracture mechanics analyses, it is possible to translate the DT energy to critical crack size-stress level relationships by means of suitable charts. It should be pointed out, however, that valid ASTM K_{Ic} values correspond to relatively brittle behavior, i.e., elastic fracture conditions. For engineering purposes, however, the relationships can be extrapolated into the elastic-plastic region so that the DT energy may be related to estimated values of K_{Ic} (or K_c) for calculating critical flaw

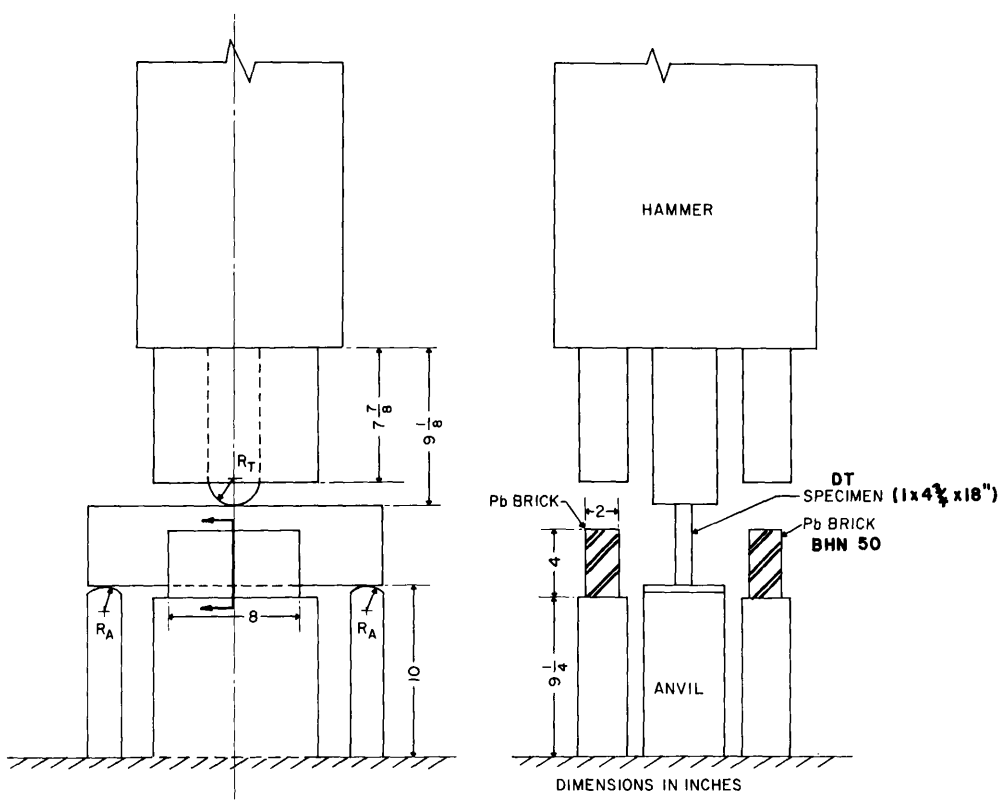

Fig. 6 - Device for measuring residual energy in vertical drop-weight machines. Soft lead bricks are positioned on anvils to absorb residual energy.

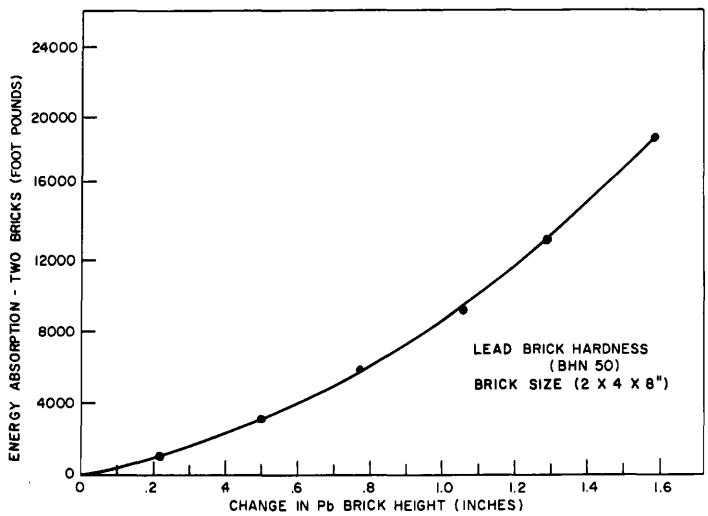

Fig. 7 - Calibration curve for lead brick residual energy measuring device illustrating the level of precision possible with this system

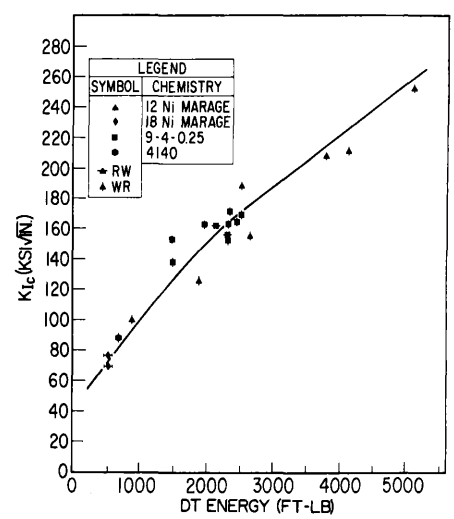

Fig. 8 - Relationship between the fracture mechanics stress-intensity factor K_{Ic} and the DT energy measured with a 1-in. specimen

sizes. Detailed discussion of how this is accomplished and graphical solutions based on fracture mechanics K_c to K_{Ic} transformation equations are presented in Refs. 3, 4, and 5 for steels, titanium alloys, and aluminum alloys, respectively.

When section size and fracture toughness level precludes the possibility of unstable fracture initiating at elastic stress levels or even after small plastic strains, one measure of resistance to fracture is the plastic strain associated with crack propagation. The Explosion Tear Test (ETT) has been used to provide this information, and three classifications of performance are illustrated in Fig. 9 (3). The shattered plate illustrates the low level of fracture resistance pertaining to fractures at elastic stress levels; an intermediate level of fracture resistance is illustrated by the plate with 5% plastic strain; and the plate with a large bulge resulting from approximately 15% plastic strain preceding fracture illustrates a high level of fracture resistance.

For the case of fracture involving large plastic deformations, it must be remembered that precise calculations of the critical flaw size-stress level relationship are neither necessary nor feasible to perform. DT energy values can be correlated with performance in the ETT to give an indication of the plastic strain required for fracture. Since structures are not ordinarily subjected to these large strains, fracture is impossible except for the case of very large flaws (several feet), which can lead to localized geometric instabilities (such as bulging in pressure vessels) or buckling situations in beams for which no degree of fracture toughness can preclude failure by ductile tearing.

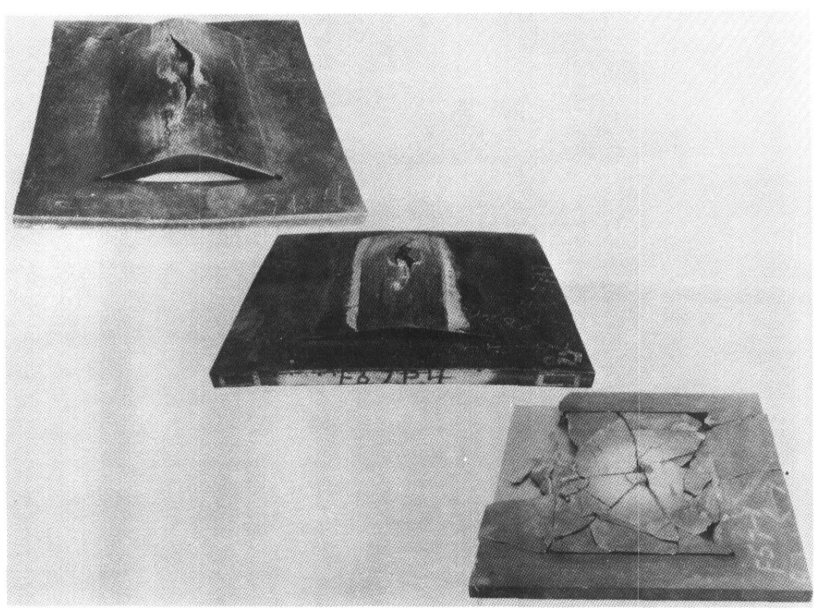

Fig. 9 - Examples of three classifications of fracture propagation resistance using the ETT. The shattered plate illustrates the low level of fracture resistance pertaining to fractures at elastic stress levels (bottom); an intermediate level of fracture resistance is illustrated by the plate with 5% plastic strain (center); and the plate with a large bulge resulting from approximately 15% plastic strain preceding fracture illustrates a high level of fracture resistance (top).

EXAMPLES OF CURRENT NEED FOR USE OF THE DT TEST

Several examples concerning practical problems of material characterization are described in this section to illustrate the need for the use and the scope of the DT test method.

Alloy Development

Research laboratories concerned with the development of new alloys require inexpensive mechanical test procedures to explore composition and processing variables within a reasonable budget. Although the standard C_v test is generally available and requires only a small amount of material, it cannot be depended on to provide fine-scale definition of the fracture characteristics of high-strength structural metals. To illustrate the unreliability of the results of the C_v test, a comparison is made in Fig. 10 of C_v energy and DT energy for several samples of a Ti-7Al-2Cb-1Ta alloy extruded at 1700°F and 1900°F. Note that the C_v energy values, obtained from the material in the adjacent DT specimens, do not correspond to either DT energy values or fracture appearance. For this alloy, the significant improvement in fracture toughness from an extrusion temperature below the β transus, 1700°F, would not have been deduced from the results of the C_v test. In fact, results from the C_v test indicate a slight advantage for the higher extrusion temperature, which is very misleading.

A second example which illustrates that the C_v test must be used with caution concerns an evaluation of the quality level of a high-strength steel as influenced by melting practices. All high-strength alloys require special vacuum melting to achieve a fracture toughness level commensurate with their high yield strength, and since vacuum melting is expensive, justification for various vacuum treatments is frequently an aim of research projects concerning material development. This objective was included in a study of the fracture characteristics of steels at the 180-ksi yield strength level, and one comparison was made with air-melted and vacuum-melted samples of an 18Ni maraging alloy having essentially the same base compositions and yield strengths. Fracture toughness determinations were made with both the C_v test and the 1-in. DT test with the following results:

18Ni Maraging Steel (180 ksi YS)	C_v Energy (ft-lb)	1-in. DT Energy (ft-lb)
Air melted	30	650
Vacuum melted	45	4500

C_v test results did not indicate that vacuum melting effected a significant improvement in fracture toughness; however, the 1-in. DT test results indicated that vacuum melting provided a very substantial improvement in fracture toughness. A 650-ft-lb DT energy for 180-ksi yield strength steel is indicative of a potential for brittle fracture initiating from very small flaws at elastic stress levels. The 4500-ft-lb energy level denotes extremely high toughness requiring flaws on the order of feet and plastic overloads to propagate fracture (3). It is apparent that the highly significant improvement in the structural performance of this material resulting from vacuum melting could not have been predicted on the basis of the results of the C_v test.

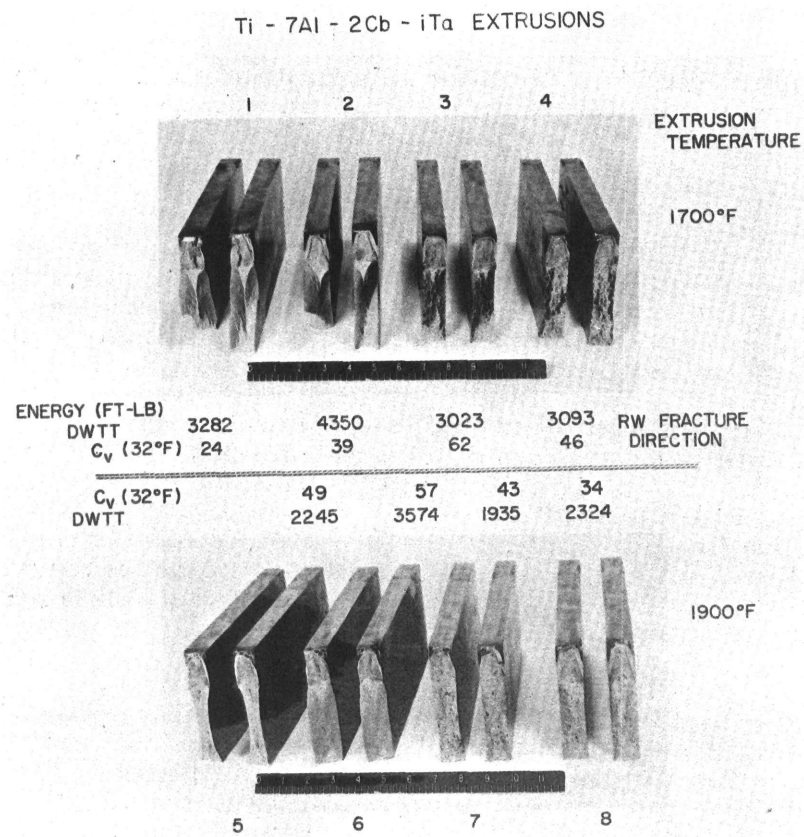

Fig. 10 - Comparison of Charpy V-notch energy values and DT resistance of extruded Ti-7Al-2Cb-1Ta alloy. Note the lack of correspondence between C_v energy values and performance in DT test. The average DT values show a significant improvement of the 1700°F extrusion temperature over the 1900°F temperature; this improvement is not reflected by the average C_v energies, which tend to show that the 1900°F extrusion temperature results in the same, or slightly improved, toughness.

Weld Metal Development

Although the structural performance of weldments depends on many factors, including weld metal quality, welding processes, and joint design, characterization of new weld metals requires accurate assessment of fracture toughness. The C_v test has been widely used to provide the fracture toughness of these heterogeneous materials, but recently problems have arisen with respect to the dependability of the C_v energy values.

The first problem encountered that provided a deterrent to the use of the C_v test for defining the fracture toughness of high-strength steel welds was scatter in the data, which made interpretation difficult. In addition, the C_v test indicated that only a shallow temperature transition (i.e., small energy increase with temperature) is characteristic for many high-strength steel weld metals. For example, a comparison of the results of the C_v test and the 1-in. DT test for a 1-in.-thick weld in a 5Ni steel at 140-ksi yield strength is shown in Fig. 11. The sharp temperature-transition characteristics of this

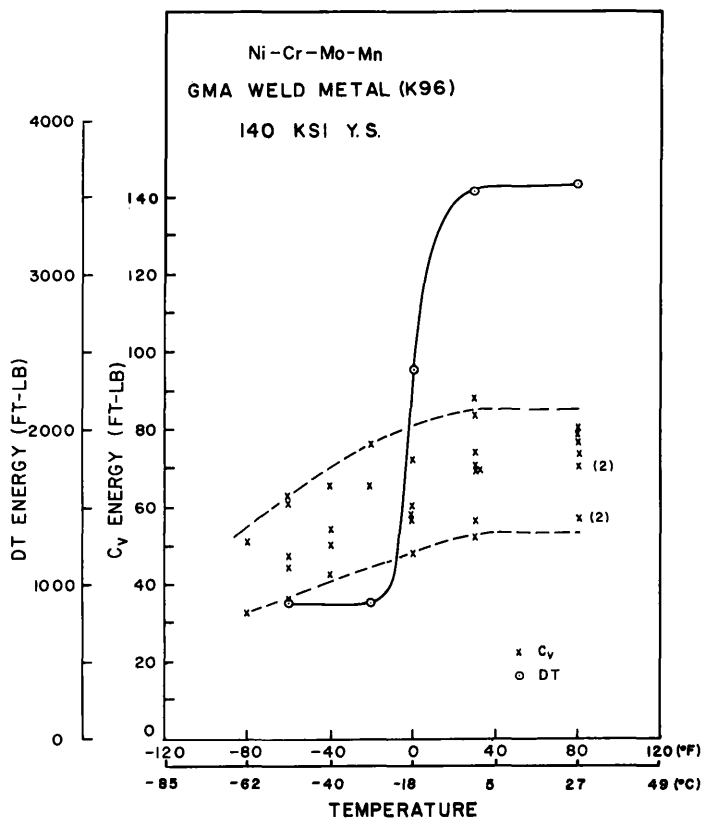

Fig. 11 - Comparison of the results of the C_v test and the 1-in. DT test for a 1-in.-thick weld in a 5Ni steel at 140-ksi yield strength. The C_v test does not indicate the sharp temperature-transition behavior of the weld metal as defined by the DT test.

material is indicated by the steep slope in the DT energy-temperature relationship, which is also reflected by a change in macrofracture mode from a flat type to a full slant type. This characteristic behavior would not have been suspected if the weld metal was judged only on the basis of the C_v test results. A sharp change in fracture energy did not occur in the C_v test, and no apparent change occurred in the fracture appearance of the C_v specimens with temperature. More scatter would be expected in the results of the C_v test, because the smaller specimens represent a more localized sample of the weldments. Since it is important for material selection and for fracture-safe design to precisely locate the temperature transition, it is apparent that the scatter in C_v energy values makes these tasks difficult and conservative values must be chosen for performance criteria. On the other hand, the temperature transition is precisely defined by DT energy, and a criterion for fracture resistance based on DT energy can assure reliable performance with respect to fracture resistance without jeopardizing good material because of a need for an excessively high minimum test value.

Temperature Transitions in Quenched and Tempered Steels

Difficulties associated with using the C_v test to define brittle-ductile transitions have been encountered for quenched and tempered steels of intermediate strength levels.

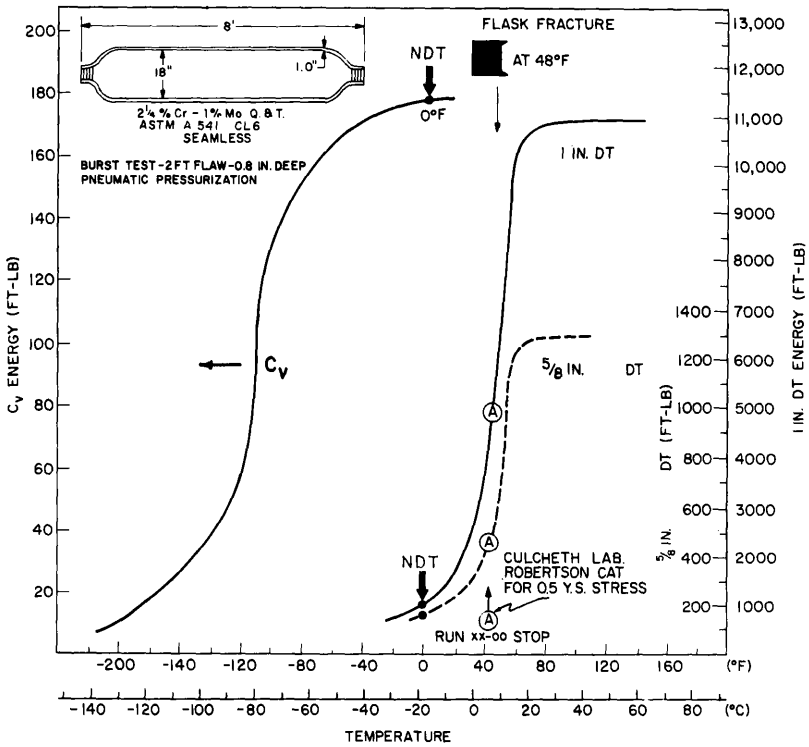

Fig. 12 - Comparison of Charpy V-notch, DT, drop-weight NDT, and Robertson crack arrest test results for A541 - Class 6 type steel at 84-ksi yield strength. Note that the C_v test indicates a very high level of toughness at the NDT temperature that, in reality, corresponds to brittle behavior as indicated by the DT and Robertson test results.

Results of C_v, 5/8-in. DT, and 1-in. DT tests are compared in Fig. 12 to the performance of a 2-1/4% Cr - 1% Mo steel in the DWT-NDT test, the Robertson crack arrest test, and a pneumatic burst test of an 18-in.-diameter pressure vessel. The transition region of the C_v energy curve is completely displaced below the transition regions of the DT energy curves for this material, and the upper shelf region of the C_v energy curve corresponds to the NDT temperature of 0°F. The burst temperature was 48°F, and the fracture in the pressure vessel propagated, in a mixed mode, 1/8-in. shear lips, which corresponded to the performance predicted for the material by the NDT test and the DT tests. However, the C_v test results would have predicted a full slant fracture mode. The Robertson crack arrest temperature was also approximately 48°F, which indicates that for a hard load, such as a hydraulic system, the fracture in the pressure vessel would have arrested after the forced initiation. The amount of bulging required to initiate fractures above the NDT temperature and in the transition region of the DT energy-temperature relationship requires further study for precise predictions, but the temperature at which resistance to fracture increases is in direct correspondence to the transition region of DT energy temperature relationship.

The lower portion of the DT transition region, the toe region, corresponds to a highly brittle condition involving fracture by a cleavage or quasi-cleavage microfracture mode with little or no shear lips. This low level of fracture resistance is also indicated by the NDT temperature, which invariantly indexes to the toe region of DT energy curves. Thick-section constraint and sharp defect conditions are not adequately simulated in the

C_v test to accurately locate the temperature transition of the fracture resistance for many quenched and tempered steels as well as the steel in the above example. In fact, indexing the C_v energy to provide performance criteria for fracture resistance of Q & T steels requires customized judgment for both temperature and energy values.

SUMMARY

The use of new materials and fabrication procedures frequently has resulted in the loss of a structure from catastrophic fracture. As the result of such experiences, stress levels in code designs are kept at low values to ensure safety from unstable, fast fracture, but more properly, fracture safety should be provided by the fracture toughness and consistent quality of the structural material. This situation can be remedied by making available a new and practical test method that provides an index of fracture toughness which can serve as a structural performance criterion.

The Dynamic Tear (DT) test is rapidly developing as a practical test method with broad-scope capabilities for characterizing resistance to fracture of structural metals. It has been under development for several years, and it has proven to be a very promising and universal method that applies equally to all metals. Material behavior in a DT specimen is indicative of behavior under limit severity crack tip conditions; thus the material performance is representative of "worst-case" conditions. The DT specimen circumvents the mechanical limitations of the Charpy specimen; in addition, DT energy values can be translated into apparent K_{Ic} values by correlation procedures. Therefore, when materials with limited levels of fracture resistance must be used because of other properties, usually high yield strength, critical flaw sizes can be calculated from the principles of fracture mechanics. The DT test also provides a definition of structural performance for materials which have high levels of fracture resistance and fractures which propagate under elastic-plastic or fully plastic conditions.

ACKNOWLEDGMENTS

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13. ABSTRACT

The Dynamic Tear (DT) method of testing for fracture toughness was developed to overcome the limitations of the Charpy V (C_v) test and to provide information of engineering design significance. Key features of the DT test are described, including specimen design, impact test machines, and methods of energy measurement. A relationship exists between the DT energy and the fracture mechanics stress-intensity factor K_{Ic} which allows the translation of these energy values into design parameters, such as critical flaw size and stress level, by means of suitable charts.

The current need for the use of the DT test in the development and selection of high-strength structural metals has become evident through examples of conditions to which the C_v test has been shown to be inadequate. For example, when fracture toughness criteria defined by the C_v and DT tests are compared for a high-strength titanium alloy, a 180-ksi yield strength steel, a 140-ksi yield strength steel weld metal, and a Q & T 2-1/4% Cr - 1% Mo steel of 90-ksi yield strength, the C_v test is shown to provide information in variance to that from the DT, DWT-NDT, and Robertson tests. Therefore, it is concluded that the DT test method has desirable features for general industrial use which provide broad-scope characterization of the fracture resistance of steels, titanium alloys, and aluminum alloys.

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