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Fracture-Toughness Tests for Titanium Alloy Plate and Forgings

R. W. HUBER AND R. J. GOODE

*Strength of Metals Branch
Metallurgy Division*

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The notch fracture-toughness characteristics of titanium alloy plate are being investigated to provide alloy selection design and specification criteria for the use of titanium alloys as hull materials for deep-diving submarines and for other structural applications.

Although the Navy's primary interest is in 120-ksi yield strength alpha or near-alpha titanium alloys, the entire spectrum of titanium alloys is under study. The results obtained from laboratory fracture-toughness tests, such as the Charpy V-notch test (C_v) and the newly developed NRL drop-weight tear test (DWTT), are correlated with explosion tear test (ETT) results. The explosion tear test is a simulated submarine-hull structural prototype test in which the metal is explosion loaded to establish its plastic deformation capability in the presence of a crack-like flaw.

Variations in notch fracture-toughness associated with alloy composition and interstitial level, processing, heat treatment, microstructure, and weld deposits were evaluated and assessed with the various fracture-toughness tests. The results of these studies show that it is possible to predict the expected structural performance of the titanium plate and forgings from the DWTT energy values through the correlation with the ETT. The relationships of the C_v test and the DWTT have been established for these materials. The relationships show that the sensitivity of the C_v test in measuring fracture-toughness differences is significantly less than that of the DWTT for the strength levels of interest.

Certain titanium alloy plates have exhibited a high level of fracture toughness in a prototype acceptance test and at a strength-to-density ratio equivalent to 200-220-ksi yield strength steels.

INTRODUCTION

For certain military applications it is important to develop information concerning the capability of structural materials to withstand plastic deformation overloads. Because crack-like flaws may be expected in real structures, it is essential to insure that overloads will not result in propagation of fractures from the cracks. This information is desired to serve not only for design guidance but also for the development of alloys, heat treatment, and the processing of materials which will have the maximum capabilities for fracture resistance for the strength level of interest.

For the present, linear elastic analysis based on fracture mechanics does not permit the development of information for the case of plastic overloads. However, it is possible to develop such guide lines by correlation of the performance of prototype structural elements with the results

of practical small-scale laboratory fracture tests, for example, the Charpy V-notch test.

There are other cogent reasons for investigating the significance of such laboratory tests. The Charpy V-notch is a widely used test, and a great deal of existing fracture-toughness information is related to this test. Therefore, it becomes important to develop an improved understanding of its significance. For alloy development and process studies of titanium, evaluation of the material may have to be accomplished with small specimens since the amounts of material will not permit tests involving large specimens.

Interest in titanium as a hull structural material has developed principally because of its high strength-to-weight ratio. Other considerations are its salt-water corrosion and erosion resistance, nonmagnetic properties, good fatigue endurance limits, good weldability, and the notch fracture-toughness characteristics of certain of its alloys. The reliability of military hull structures is dependent upon the fracture-toughness characteristics of the hull material. Unfortunately, most of the fracture-toughness information presently available for titanium alloys was obtained

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Note: This report was initially presented at the 1964 AIME Symposium on Fracture Toughness, October 20, 1964, Philadelphia, Pa.

from sheet material of relatively high interstitial levels (intentionally kept high for added strength), for aircraft and aerospace applications. It is well known that the fracture-toughness properties of titanium alloys are very sensitive to the oxygen, nitrogen, and carbon content, and for good fracture toughness in thick sections these elements must be kept at a low level, *e.g.*, 0.08 wt-% maximum for oxygen.

Two years ago a program was initiated in the Metallurgy Division of the U.S. Naval Research Laboratory to determine the notch fracture-toughness characteristics of titanium alloys in thick sections using the standard Charpy V (C_v) test and other new laboratory test methods. The significance of values obtained from these tests was evaluated by the use of a structural prototype element test which could be related directly to the service performance of these materials.

EXPERIMENTAL PROCEDURE

The spectrum of titanium alloys used to establish correlations between the laboratory tests and a structural prototype element test is listed in Table 1. The alloys were 1-in.-thick commercially produced plates of approximately 0.15 wt-% (minimum) and 0.08 wt-% oxygen, standard and low interstitial grade, respectively, as well as specially produced and processed 0.04 wt-% oxygen 125-lb laboratory heats. This variation in oxygen provided different combinations of strength and toughness. The alloys were tested in the annealed and heat-treated conditions to explore other combinations of strength and toughness. The dependence of toughness on specimen orientation was also investigated. These tests included the RW and WR orientations (1), *i.e.*, the directions which are longitudinal and transverse to the principal direction of rolling, respectively.

Room temperature tensile properties of the alloys were obtained using 0.313-in.-diam specimens tested at a strain rate of 0.002 in./in./min. The C_v specimens were tested over a temperature range of -320°F to $+212^{\circ}\text{F}$ using a machine calibrated according to ASTM specifications.

The other fracture-toughness tests used were the drop-weight tear test (DWTT) and explosive tear test (ETT). The DWTT is a small-scale

TABLE 1
Titanium Alloys Studied in the Charpy V-Notch, Drop-Weight Tear, and Explosion Tear Tests

ALPHA ALLOYS:	Unalloyed Titanium Ti-5Al-2.5Sn
NEAR-ALPHA ALLOYS:	Ti-7Al-2Cb-1Ta Ti-8Al-2Cb-1Ta Ti-6Al-4Zr-1V Ti-6Al-4Sn-1V Ti-6.5Al-5Zr-1V Ti-6Al-2Sn-1Mo-1V Ti-6Al-4Zr-2Mo
ALPHA AND BETA ALLOYS:	Ti-6Al-4V Ti-8Al-1Mo-1V Ti-6Al-2Mo Ti-7Al-2Mo Ti-7Al-2.5Mo Ti-7Al-3Mo Ti-7Al-3.5Mo Ti-7Al-4Mo Ti-6Al-6V-2.5Sn
BETA ALLOYS:	Ti-13V-11Cr-3Al

laboratory test which provides a measurement of the full-thickness fracture toughness of plate materials. The name was derived from the original use of a falling weight method of load application and is depicted in Fig. 1. The specimen size is 17 in. $\times$ 5 in. $\times$ 1 in., and a brittle crack-starter weld is employed on the tension loading edge of the specimen to provide a sharp, natural crack which impinges into the material of interest. The test section is 3.5 in.². A bracketing technique requiring three or more specimens was used to determine the fracture energy. An acceptable test using this method requires establishing a 250-500 ft-lb difference between incomplete and complete fracture. In order to economize on test material, a 5000 ft-lb pendulum-type impactor, shown in Fig. 2, was constructed to obtain a fracture-toughness measurement with one test specimen.

The ETT is a new method of full-thickness, fracture-toughness evaluation that can be classified

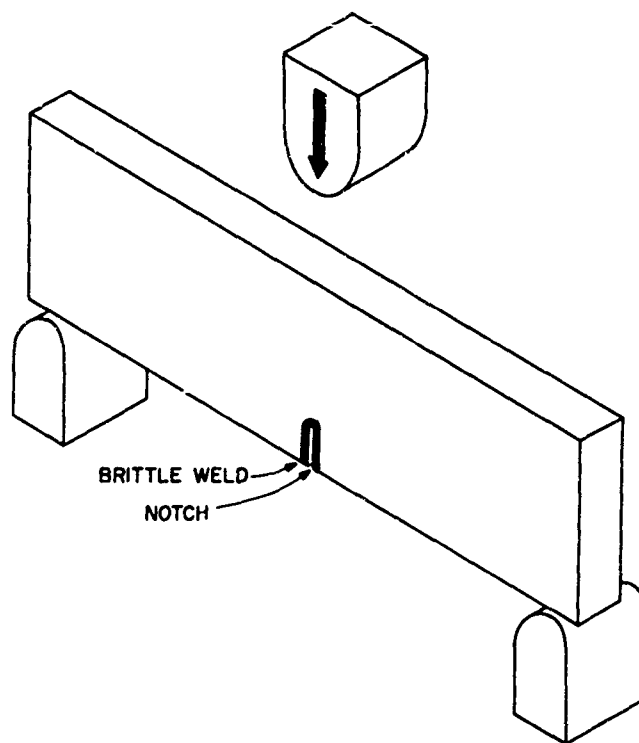


Fig. 1 — Schematic of the drop-weight tear test (DWTT)

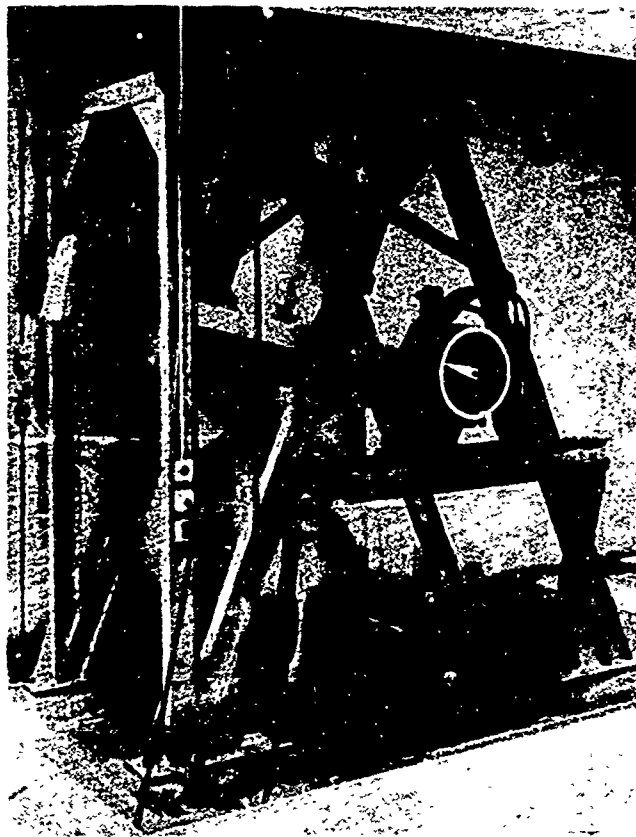


Fig. 2 — Impact machine of 5000 ft-lb capacity for testing 1 — and 2-in.-thick plates of high-strength materials

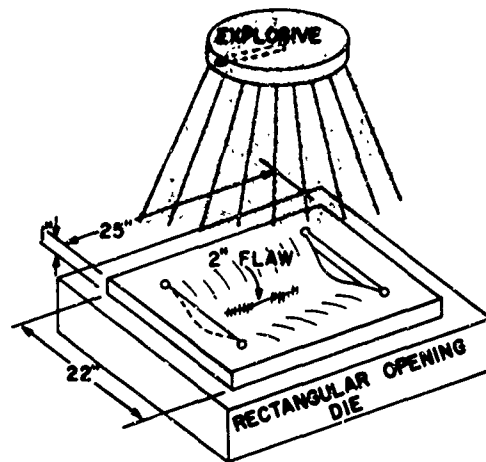


Fig. 3 — Schematic of explosion tear test (ETT)

as a structural prototype element test. The test features, depicted in Fig. 3, include:

a. a 12 in. $\times$ 18 in. restrained test section in a 22 in. $\times$ 25 in. plate that can be elastically or plastically loaded to a cylindrical configuration under a high rate of loading;

b. a system of premarked grid lines for measurement of the strain deformation pattern; and

c. a crack-like flaw for evaluation of fracture resistance when subjected to predetermined levels of elastic or plastic strain.

The ETT may be used to simulate a wide variety of service loadings in the presence of flaws of

various selected dimensions. Initial investigations centered on the use of a 2T 2-in. through-the-thickness crack as a practical flaw size of concern in large welded structures. Such flaws can develop during the fabrication process and remain undetected, or they can develop early in the service life of the structure under low-cycle fatigue processes. The relative ability of the hull material to undergo explosive depth charge attack with corresponding large or small amounts of plastic strain in the presence of these flaws, but without the occurrence of catastrophic failure due to high-speed propagation of a fracture from one of these flaws, was an item of primary interest. Three levels of fracture toughness are indicated in Fig. 4. The relative level of toughness is indicated by the amount of plastic strain that the plate can undergo, with arrest of the fracture originating from the sharp crack, within the test section.

The flaws in the DWTT specimens and in the ETT plates are provided by the brittle crack-starter weld which is made by melt diffusion of an embrittling element, such as iron (iron or stainless steel wire), using electron-beam welding techniques. The amount of energy required to develop the crack in the brittle weld for the DWTT is below 300 ft-lb.

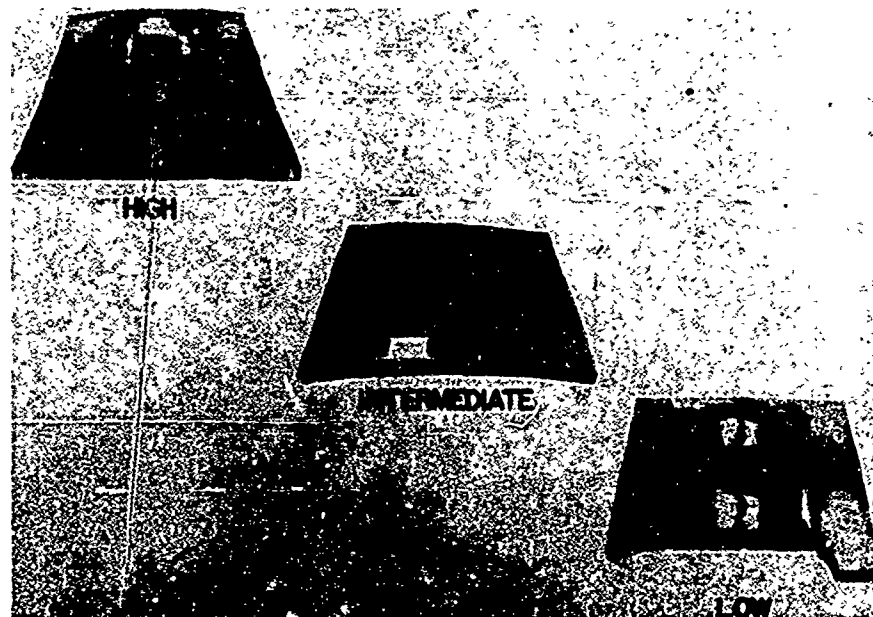


Fig. 4 — Explosion tear test plates showing high, intermediate, and low levels of fracture-toughness performance for titanium alloys

TEST RESULTS

Relationships of Charpy V-Notch Energy to Yield Strength and Temperature

The temperature dependence of C_v notch properties of the titanium alloys in different ranges of yield strength (ys) is indicated in Fig. 5. As would normally be expected, the C_v energy decreases with decreasing temperature and increasing ys. These energies are represented as bands for different ranges of ys. Generally, for each band the low ys values lie in the upper portion of the band and the high ys values in the lower portion of the band. The fact that there is no sharp transition in the curves over a narrow range of temperature can be seen in the individual curves for several of the more widely used commercially produced alloys at an 0.08 wt-% oxygen level (Fig. 6).

Charpy curves obtained using precracked specimens of high and low interstitial alloys have not provided any better interpretation of the C_v test on titanium alloys. The use of the precracked specimens shifts the C_v curves to lower energy values, as would be expected, but no other additional features are observed (Fig. 7). The curves obtained with the precracked speci-

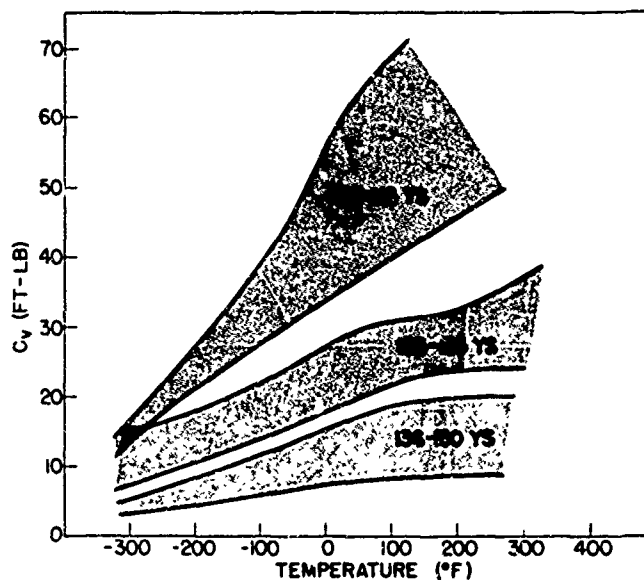


Fig. 5 — Relation of Charpy V-notch energy to temperature for different ranges of yield strength for high-strength titanium alloy plate material

mens essentially parallel those of the standard specimen for the same material. It is not shifted to higher or lower temperature values nor are any other features of the curve more accentuated.

Fractographic studies of fracture surfaces of a number of these alloys have shown that, over the extremes of fracture toughness, temperature,

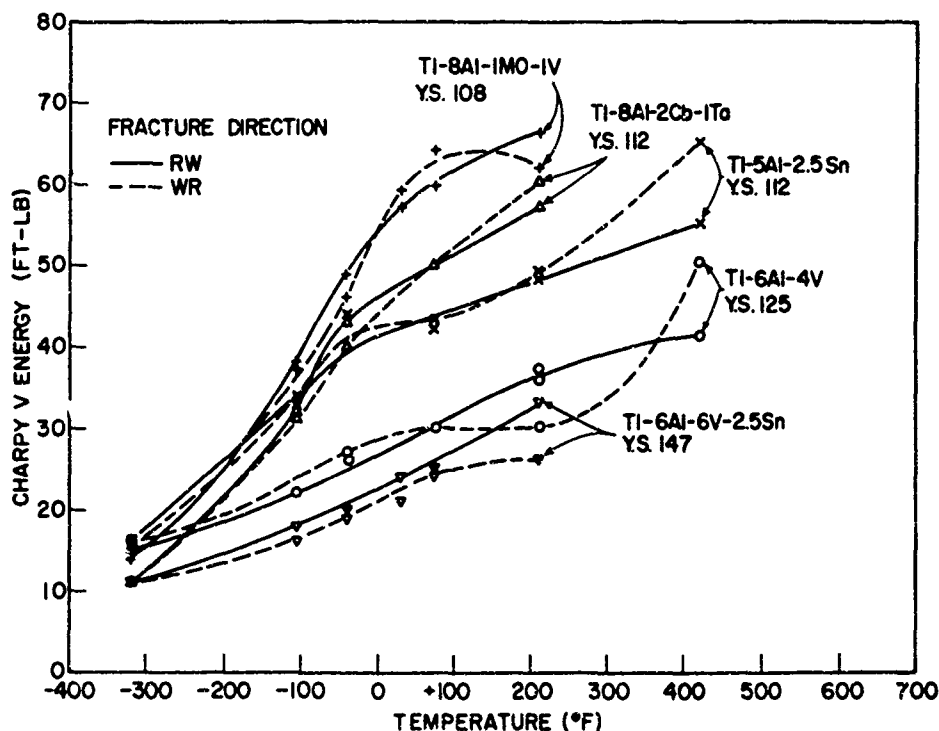


Fig. 6 — Fracture-toughness characteristics of some low interstitial titanium alloys as determined by Charpy V-notch energy

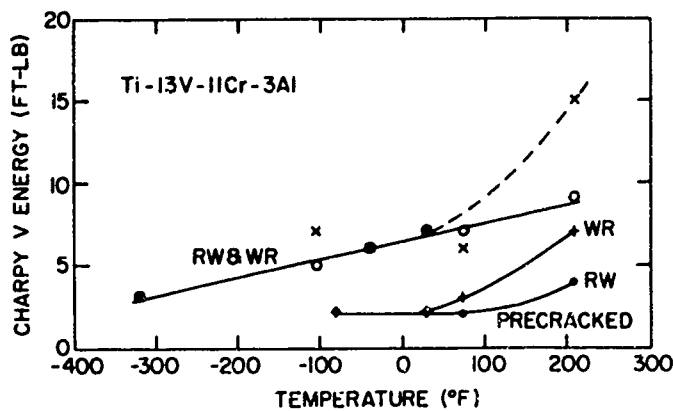
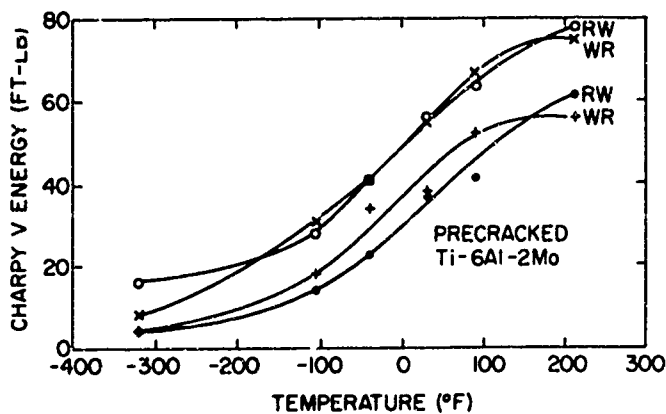


Fig. 7 — Standard and precrack Charpy V-notch properties of (a) low interstitial Ti-6Al-2Mo alloy, and (b) high interstitial Ti-13V-11Cr-3Al alloy

and interstitial levels, the mode of fracture is dimpled rupture—a ductile mode of fracture (2). A typical example of the appearance of the fracture surface for these materials is shown in the fractograph of a Ti-6Al-4V low interstitial alloy, shown in Fig. 8. The absence of a change in fracture mode may explain the lack of an abrupt transition in the C_v curve, as is usually the case for conventional structural steels.

Relation of Charpy V-Notch Energy with Drop-Weight Tear Energy

The relation between the C_v energy and DWTT energy at 30°F for a 1-in.-thick plate is shown in Fig. 9. The selection of this particular temperature to make this comparison is based on the intended use of this material. The lowest test temperature that a submerged hull structure could experience is approximately 30°F. A band is defined by the data points; it is noted that above 2500 ft-lb DWTT energy, there is a reasonably direct correlation between the two tests. Below the 2500 ft-lb DWTT energy value, the C_v test shows a decreased sensitivity to differences in fracture toughness as compared to the DWTT.

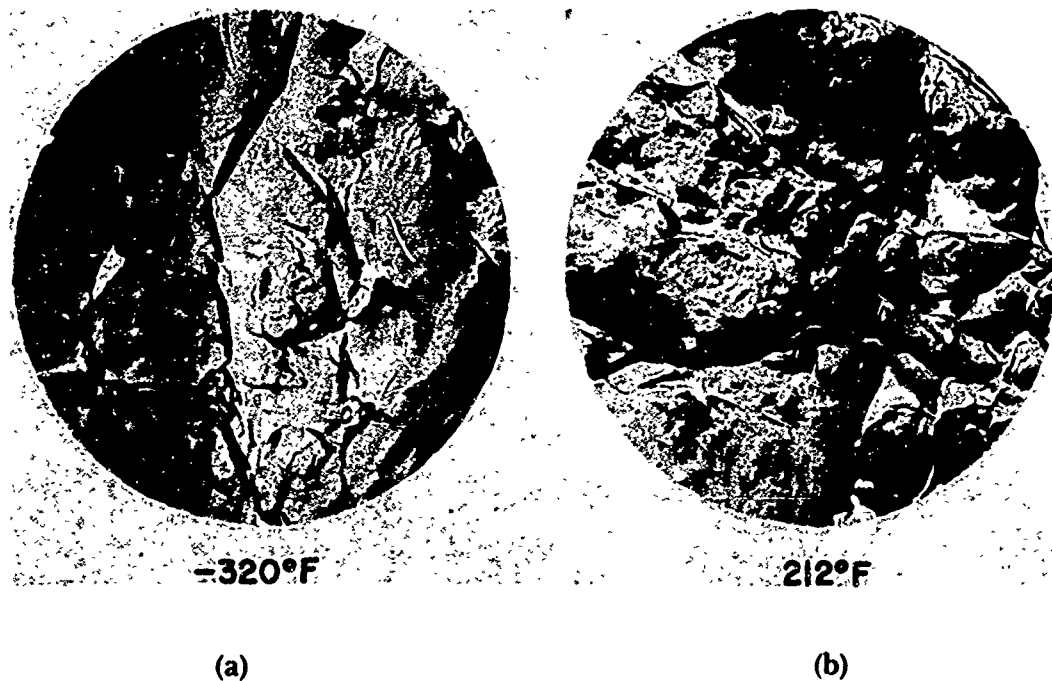


Fig. 8 — Electron microscope fractographs of a low interstitial Ti-6Al-4V alloy fracture surface showing a dimpled rupture. Fracture surface generated at (a) -320°F and (b) +212°F, original magnification 4000X; printing reduction 58-1/2%.

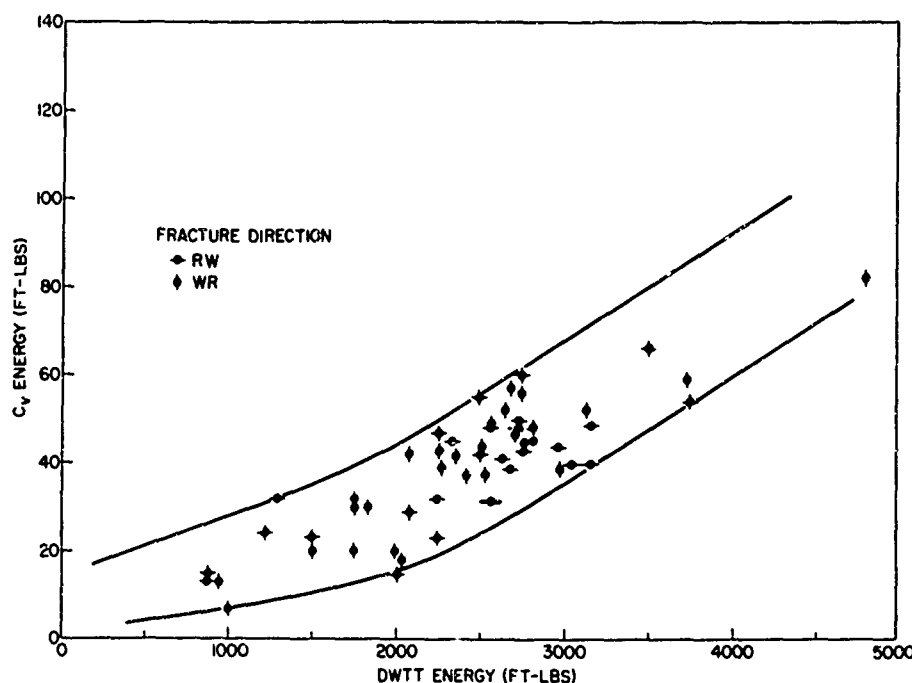


Fig. 9 — Relationship between Charpy V energy and drop-weight tear energy for 1-in.-thick titanium alloy plate

Unfortunately, this is also the region where most of the high-strength titanium alloys above 110 ksi ys lie.

Relation of Laboratory Tests with Explosion Tear Test

The significance of the DWTT energy values for the titanium alloys has been established by correlation with the performance in the ETT prototype element test. The correlation of these tests with the ys of the 1-in.-thick titanium alloy plate is presented in Fig. 10. It is noted that a wide range of fracture toughness can be developed by different alloys of the same strength level. The curve delineated by the maximum levels of fracture toughness for given yield strengths has been designated the "optimum material trend line" (OMTL). This limiting curve establishes a good reference point for evaluating alloys, for optimizing structural design, and for purchase specifications. Explosion tear tests of a limited number of specimens containing 2-in. flaws have tentatively established the plastic strain limits illustrated by the hatched lines. These limits indicate that materials having DWTT energy values below 1500 ft-lb will fracture under elastic loading conditions in the presence of the 2-in.

flaw. Above 2500 ft-lb a high level of plastic loading (5-7 percent plastic strain) can be attained in the presence of the 2-in. flaw with limited propagation of the fracture. Between these extremes, intermediate levels of plastic loading can be attained in the presence of the subject flaw. The relationship also suggests that no materials of over about 140 ksi ys are capable of withstanding plastic loading in the ETT in the presence of the 2-in. flaw without catastrophic failure. Titanium alloys up to about 125 ksi ys should be capable of withstanding a plastic strain of 5-7 percent with the development of a short (arrested) fracture. Between these ys limits, lesser amounts of plastic strain may be applied with resulting restricted fracture. The range of C_v energy values is also indicated for the corresponding DWTT values.

DISCUSSION

The test results have established for 1-in.-thick titanium plate that there is a useful engineering correlation between the C_v and DWTT results at high fracture-toughness levels. However, for lower levels of fracture toughness the DWTT is a more sensitive test than the C_v test.

ETT, a full-thickness structural prototype element test that incorporates a flaw of the acuity that would develop in fabrication and/or service, and plastic overloads that may be experienced in military service. The results of these studies show that it is possible to predict the expected structural performance of the titanium plate and forgings from the DWTT energy values through the correlation with the ETT. The relationships of the C_r test and the DWTT have been established for these materials. The relationships show that the sensitivity of the C_r test in measuring fracture-toughness differences is significantly less

than that of the DWTT for the strength levels of interest.

Certain titanium alloy plates have exhibited a high level of fracture toughness in a prototype acceptance test and at a strength-to-density ratio equivalent to 200-220-ksi ys steels.

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