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ABSTRACT

A progress report covering research studies in high strength hull structural materials, conducted in the period May 1964 to August 1964, is presented. These studies include the development of preliminary relationships of flaw size and stress for fracture of quenched and tempered steels, maraging steels, titanium, and aluminum. Preliminary information has also been developed in the relationship between the notch tensile test and the drop-weight tear test for aluminum alloys. The effects of corrosion environments on the crack rate propagation in HY-80 to HY-150 quenched and tempered steels have been examined under low cycle fatigue conditions. Preliminary results on a study of the directionality effects due to cross-rolling on the fracture toughness of quenched and tempered steels are presented. The fracture toughness properties of specially processed Ti-7Al-2Cb-1Ta, diffusion-bonded Ti-6Al-4V, forged Ti-5Al-2.5Sn, and titanium weldments are reported. The results of heat-treatment studies for improving the fracture toughness at specific levels of yield strength are reported for some titanium alloys.

PROBLEM STATUS

This is a progress report; work is continuing.

AUTHORIZATION

NRL Problem M01-05
Projects SR 007-01-02--0704, RR 007-01-46--5405, and WW 041-63R05-24A

NRL Problem M01-18
Projects RR 007-01-46--5420 and SR 007-01-01--0856

NRL Problem M03-01
Projects SR 007-01-01--0850 and SR 007-01-01--0854

Manuscript submitted October 5, 1964

METALLURGICAL CHARACTERISTICS OF HIGH STRENGTH STRUCTURAL MATERIALS (Fifth Quarterly Report)

INTRODUCTION

This is the fifth status report covering the U. S. Naval Research Laboratory's long-range program of determining the performance characteristics of high strength materials. The program is primarily aimed at determining the fracture toughness characteristics of these materials using standard and newly developed laboratory test methods and at establishing the significance of the laboratory tests for predicting the service performance of the materials in naval hull structures. Although the program is aimed at Navy requirements, the information that is developed is essentially basic to all structural use of these high strength materials. Quenched and tempered (Q&T) steels, maraging steels, titanium alloys, and aluminum alloys are the materials currently under investigation.

The level of fracture toughness required in a material is largely dependent upon the application for which it is intended. For deep-diving research submersibles, the hull material will be required to withstand only small plastic overloads, 1 to 2% plastic strain, such as may occur at points of complex geometry. Deep-diving combatant submarines may be subject to explosive depth charge attack; therefore, they require a hull material with a much higher level of fracture toughness. Experience has shown that present day inspection techniques will not detect all flaws that are present in a large welded structure, and that flaws may develop early in the service life of complex structures. Depending on the service, the hull material must be able to withstand various minimum levels of plastic strain in the presence of the flaws. Therefore, the program includes studies on the effect of flaw size on the fracture toughness characteristics of these materials through the use of a structural prototype element test in which a flaw of the acuity found in service can be introduced.

The laboratory test methods currently being used to determine the fracture toughness and which are being evaluated for possible use in predicting service performance are the Charpy V-notch test, the drop-weight tear test (DWTT), and the notched-tensile test. The structural prototype element test is the explosion tear test (ETT) in which the specimen is of a size large enough to be considered as a segment of the structure. The studies include the effect of chemistry, purity, processing variables, and heat treatment on strength and fracture toughness characteristics. Additional studies include welding procedures and crack rate propagation studies in low cycle fatigue. Fractography and metallographic studies are conducted in support of all these.

In this report, the effect of corrosion environments on crack rate propagation in HY-80 to HY-150 Q&T steels is examined under low cycle fatigue conditions. The corrosion media were distilled and salt water. The effect of the distilled water was influenced by strain range and strength level. As the total strain range increased and the strains approached the proportional limit for the Q&T steel materials, the growth of the fatigue cracks was four times that for air. Greater crack propagation rates were observed for all strain values studied in the salt water environment. These rates were from five to ten times faster than for air.

Preliminary relationships between the ETT and the DWTT, the Charpy V (C_V) test and yield strength (YS) for aluminum alloys are presented. Results of notched tensile tests are also compared to the performance of these materials in the DWTT. The results show that aluminum alloys with DWTT energy values as low as 300 ft-lb are capable of undergoing a small amount of plastic strain in the ETT in the presence of a 2-in. flaw. This corresponds to a notched strength ratio of about 1.2.

The directionality effects due to cross-rolling on the fracture toughness of Q&T steel plates are being investigated. These materials have been evaluated using the laboratory test methods and are now in evaluation in the ETT. For steels, the results obtained to date indicate that at any given strength level, an increase in "weak" direction and a decrease in "strong" direction fracture toughness results with increasing degrees of cross-rolling; full cross-rolling results in the greatest improvement of toughness in the "weak" direction.

The effects of processing variables on the fracture toughness properties as measured by the DWTT on a Ti-7Al-2Cb-1Ta alloy are reported. The DWTT energy values are higher than any obtained on other 721 alloys tested to date. The fracture toughness properties of a forged Ti-5Al-2.5Sn plate, and diffusion-bonded Ti-6Al-4V plates are also presented. Additional ETT data have established the approximate DWTT energy limit of 2500 ft-lb for 5-7% plastic strain with an expected YS of approximately 130 ksi. Welding studies show that welds of good toughness can be made in Ti-6Al-2Mo alloys when welding is followed by a post heat treatment at 1200°F. Heat-treatment studies for a number of alloys have been conducted. The commercially-produced Ti-6Al-4Sn-1V and Ti-6Al-2Mo alloys developed relatively high levels of fracture toughness, as measured by the C_V, in the 120-140 YS range. All the heat-treatment data obtained to date are presented.

LOW CYCLE FATIGUE CRACK PROPAGATION IN QUENCHED AND TEMPERED STEELS UNDER CORROSIVE ENVIRONMENTS

(T.W. Crooker, R.E. Morey, and E.A. Lange)

The safe and dependable application of modern high strength materials to large cyclically-loaded structures, such as pressure vessels and submersible vehicles, requires improved knowledge of low cycle fatigue. Small flaws and cracks invariably remain after the fabrication and manufacture of a large welded structure despite the careful use of modern processing methods and the best available nondestructive testing techniques. Since fabrication cracks are unavoidable, the only practical recourse is to provide design criteria for preventing the growth of such probable cracks to a critical size from the repeated application of service loads.

The aim of this investigation is to define and evaluate the factors which control the growth of cracks under low cycle fatigue conditions. The results of the current phase of this investigation are based on studies of crack propagation in center-notched, plate bend specimens, loaded in cantilever fashion. Previous reports have described preliminary evaluations of the low cycle fatigue characteristics of a variety of Q&T steels and 2024 aluminum alloy (1-3). Briefly, it has been observed that for a specific environment (air) and strain ratio, the growth rate of a low cycle fatigue crack is dependent upon applied total strain range, as expressed by the empirical relationship

$$\Delta L/\Delta N = K(\epsilon_T)^n$$

where $\Delta L/\Delta N$ = crack growth rate, microinches/cycle

ϵ_T = total strain range, microinches/cycle

K, n = constants

This relationship remains valid in the presence of mean strains other than zero; however, it has been observed that tensile mean strain accelerates the growth of cracks, and conversely, compressive mean strain retards the growth of cracks.

EXPERIMENTAL PROCEDURE AND MATERIALS

This report concerns the effects of selected corrosive environments on the growth of fatigue cracks in steels with nominal HY-80 composition which are heat-treated to various strength levels between 80 and 150 ksi YS. Specifically, the corrosive environments were aerated distilled water and 3.5% salt water. The information obtained with these two aqueous environments will be used for preliminary studies of fatigue crack growth for all structural materials. Materials which indicate significant environmental sensitivity will be subjected to a more refined examination.

The same loading conditions of strain-controlled, fully-reversed bending at rates of four to eight cycles per minute were employed as previously described for specimens fatigued in air, so as to provide a common basis for initial comparisons. For the new experiments involving an aqueous environment, a portion of the test specimen including the fatigue crack is covered by a corrosion cell as shown in Fig. 1. The cells are molded polyurethane which is relatively soft and flexes with the specimen. The corrosive solution is circulated through the corrosion cell from a reservoir where the solution is aerated and the composition is monitored. About half of the 2-1/2-in. width of the specimen is exposed to the aqueous environment in the cell.

The chemical composition and mechanical properties of the materials employed in this investigation are shown in Tables 1 and 2, respectively. Two of the materials, HY-80 (code EB4) and Q&T 150 YS (code FB5), have been the subject of previous investigations in an air environment (1,2). As a first step in the present study, the two new Q&T steels - 130 YS (code G13) and 150 YS (code G14) - were tested for crack propagation resistance in air, in order to provide a comparison with other Q&T steels and to provide a base line against which corrosion data could be measured. The new data (Fig. 2) are in excellent agreement with previously reported data for Q&T steels (1,2). They lend further support to the validity of the fourth power relationship between crack growth rate and applied total strain range previously observed for Q&T steels cyclically loaded to total strain values between 0.25% and 1.5%.

CORROSION FATIGUE EFFECTS

The influence of the distilled water and the salt water environments on the growth rates of fatigue cracks are shown in Figs. 3 and 4, respectively. The effect of the distilled water environment on the growth rate of low cycle fatigue cracks was influenced by both strain range and strength level. At strain ranges approximately one half that for the proportional limits of the respective steels, there appeared to be no significant effect from the water environment since the fatigue cracks grew at the same rate as they did in air (35-65% R.H.). The water environment effect became significant as strain range was increased and at strains approaching the proportional limit for the respective steels, the growth of fatigue cracks under water was four times that for air. Looking at the band in Fig. 3, this dependence upon strain range can be seen as an increase in slope of the band over the fourth power function of the base line for air. The influence of the distilled water appeared to be related to the amount of plastic strain in the load cycle, and the higher strength materials, therefore, were superior to the low strength materials on a total strain range basis at strain ranges in excess of 4,000 microinches/inch.

The salt water environment proved to be a substantially more hostile environment than distilled water, and greater crack propagation rates were observed for all strain values studied, Fig. 4. The quantitative effect of the salt water was to increase the growth rates five to ten times that for air. This substantial increase in crack growth rate suggests the introduction of an additional failure mechanism such as hydrogen embrittlement.

Laboratory observations of the fatigue crack included a large number of bubbles evolving from the fracture surface within the corrosion cell during fatigue cycling in salt water. These observations indicate that for corrosive environments hydrogen embrittlement may play an important role in fatigue crack propagation at high growth rates as has been indicated for low growth rates (5).

Several general observations and implications can be stated from a broad view of these corrosion fatigue data. It is apparent that the introduction of a corrosive environment can serve to significantly increase the growth rate of fatigue cracks, four to ten times that for air, and in addition a corrosive environment increases the scatter among the data. These factors tend to reduce the accuracy with which fatigue performance can be predicted. Previous data on Q&T steels obtained in an air environment consistently fell within a sufficiently narrow band to assign the plot a single relationship for Q&T steels of HY-80 composition at all strength levels tested (80-160 ksi YS). Although under corrosion conditions the data become more widely separated and each material is observed to follow a separate plot, the family of crack growth curves for each environment forms a band. An examination of these bands shows the curves to be separated more or less on the basis of strength level, with the higher strength materials possessing relatively superior crack propagation resistance at high strain ranges under the mild corrosive environment, distilled water. However, this difference in performance due to strength level in the range of 80 to 160 ksi YS was not evident under salt water and is small compared to the increase in crack growth rate due to the aqueous environment.

The general observation that the growth rate of fatigue cracks <u>when compared on a total strain range basis</u> is essentially the same for Q&T steels with 160 ksi YS as for Q&T steels with 80 ksi YS emphasizes the critical importance of the design of details when the use of a high strength steel is considered for increasing the performance of structures. Details used in current fabrication practice such as welded ribs or rings for stiffening purposes have caused few problems with low strength steels, but the same details have created many problems with 80-100 ksi YS Q&T steels. Satisfactory performance of structures with high strength materials is attained only when the design of details is refined to minimize strain intensification since the nominal elastic strains alone will be high. This precautionary view is even more pertinent when titanium or aluminum alloys with their relatively low moduli t elasticity are considered as replacement materials for steel.

The results of this seris of tests on Q&T steels under corrosion fatigue conditions offer the possibility that low cycle fatigue crack propagation in a corrosive environment is a specific process and the hostility of an environment cannot necessarily be judged on the basis of other corrosion criteria, such as surface corrosion. Several observations support this possibility. For example, the 160 ksi YS steel rusted and pitted more readily than the 90 ksi YS steel under the salt water, but there was no corresponding significant change in fatigue behavior. Previous studies indicate that cathodic protection which adequately prevents surface corrosion in a salt water environment can have little or no effect on the initiation or growth rate of cracks in cyclically loaded Q&T steel. A much broader study of low cycle fatigue crack propagation under corrosion conditions is needed to examine these observations. A wider variety of materials must be studied; a quantitative evaluation of the roles of the various fracture mechanisms, stress corrosion, hydrogen embrittlement, etc., must be made, and the actual service elements of time and natural seawater must be included.

FRACTURE TOUGHNESS EVALUATION OF ONE-INCH-THICK ALUMINUM ALLOY PLATES

(R.W. Judy, C.N. Freed, and R.J. Goode)

Aluminum alloys are being used for a variety of applications where the fracture toughness characteristics are of primary importance for the safe use of the material. However, no test has attained general acceptability for comparison of the fracture toughness characteristics of a particular aluminum alloy to other aluminum alloys, or to other materials. The Charpy V-notch test has been used for this purpose in steels and to some extent in titanium; however, the Charpy V (C_V) energy values for most aluminum are extremely low and do not show any significant change with a variation in temperature.

The purpose of this investigation is to establish the possible applicability of the drop-weight tear test (DWTT) and other tests for comparison of the fracture toughness characteristics of aluminum alloys in thick sections and to evaluate the significance of the values in terms of predicting service performance and structural reliability.

CORRELATION OF TENSILE, CHARPY, DROP-WEIGHT TEAR AND EXPLOSION TEAR TEST RESULTS

A series of small laboratory fracture toughness tests, including the C_V, the DWTT, and the smooth tensile test, have been conducted on 1100F, 2024-T4, 5456-H321, 6061-T651, and 7075-T6 alloys and have been reported previously (2). The same tests were conducted on alloys 5086-H112, 2219-T87, and 6061-T651. In addition, DWTT specimens of 2020, 2024, and 7075 were tested in the 5000 ft-lb pendulum-type impact machine. The results of these tests for the RW and WR orientations (7) are listed in Table 3. Notched and prefatigued notch tensile tests have been conducted on a number of the alloys as well to determine the significance of the notched tensile values obtained in terms of the DWTT results.

Charpy V-notch tests were conducted on 5086-H112, 6061-F651, and 2219-T87 with a variation of temperature between -320°F and 212°F. The results of these tests are shown in Fig. 5. The C_V energy values for 5086-H112 were considerably higher than any alloy tested to date due to the lower yield strength (YS), 25 ksi, and high ductility of this alloy. The results obtained for the 6061-T651 and 2219-T87 alloys showed values which did not change with temperature and were extremely low in comparison with other structural materials.

Figure 6 shows the relation between C_V energy and DWTT energy. It indicates that the DWTT is a more sensitive indicator of changes in fracture toughness than is the C_V notch test since a wide range of DWTT energy values corresponds to only a narrow range of C_V values.

The DWTT results followed the general inverse relationship between fracture toughness and strength as observed for steels and titanium. The higher YS alloys - 2219 and 7075 - had DWTT energy values lower than 300 ft-lb. The DWTT energy for 5086-H112 was in excess of 2000ft-lb with a YS of approximately 25 ksi. Figure 7 shows a comparison of DWTT and YS for all alloys tested to date. This chart shows the general trend of decreasing fracture toughness, measured by the DWTT energy, with increasing YS. The optimum materials trend line (OMTL) indicates the highest levels of fracture toughness for any YS based on the materials evaluated to date.

The results of limited explosion tear test (ETT) are also represented in Fig. 7. The percent plastic strain limits were conservatively estimated to be approximately 300 ft-lb for fracture below yield, and 750 ft-lb for 4% plastic strain before failure when ETT plates of 2219-T87 (DWTT 281 ft-lb) and 6061-T65 (DWTT 750 ft-lb) were loaded to the 1-3% strain deformation range with 2-in. brittle (electron beam) weld flaws. The 6061-T651 specimens were loaded to 2.9% plastic strain. The 6061-T651 specimen with the flaw showed no appreciable crack extension which indicates that material having a 750 ft-lb DWTT energy could probably withstand 4% plastic strain before failure. The 2219-T87 specimens were loaded to 1.2% plastic strain and the specimen with the flaw fractured completely after experiencing a small amount of plastic straining.

RESULTS OF NOTCHED TENSILE AND PRECRACKED TENSILE TESTS

The main purpose of this investigation is to determine whether a correlation exists between the DWTT and the notch-strength ratio for aluminum alloys. Since this ratio is about the only widely-used criterion for the determination of toughness of aluminum and considerable data have been generated with this test, it would be of considerable interest if the significance of the notched-tensile test could be established by correlation with the DWTT and the ETT. A secondary purpose is to discern if the acuity of the notch affects the notch-strength ratio.

Notched-tensile specimens were machined from five aluminum alloys which were chosen for the wide range of yield strengths which they represent. Half of the notched specimens were fatigued using a rotating-beam fatigue machine until a crack was initiated at the tip of the notch. Both the fatigue-cracked and the unfatigue-cracked specimens were broken in tensile loading, and the notch-strength ratios calculated. The test results are given in Table 4. Previously obtained yield strengths for each alloy in both the longitudinal and transverse directions were used in the computations.

Figure 8 presents a graph of the DWT energy versus both the notch-strength ratio and C_V values. It is evident that the DWT energy increases rapidly with an increasing notch-strength ratio. The anisotropy of the 2024, 5086, and 5456 alloys is more clearly indicated when they are compared with the DWT energy than when they are plotted against the notch-strength ratio; this pertains to both the fatigue-cracked and unfatigued specimens. The C_V relationships to DWTT data are also presented in Fig. 8 for comparison.

The DWT energy appears to be a more sensitive measurement of toughness than the notch-strength ratio. Whereas the DWT energy values vary over a wide range, the notch-strength ratio is limited to a relatively narrow band. Specimens which contained a fatigue crack produced slightly lower notch-strength ratios than specimens which were only notched. This is due to the increased acuity of the notch. Both types of specimens seem to be reliable indicators of anisotropy.

The results of correlations of various fracture toughness tests to date indicate that aluminum alloys having as low a DWTT energy value as 300 ft-lb will have a notch-strength ratio of at least 1.2 and will possess a capability of undergoing a small amount of plastic strain in the presence of 2-in. flaws.

HIGH STRENGTH STEELS
(P.P. Puzak and K.B. Lloyd)

A graphical summary of previously developed correlation data illustrating the significance of the findings for quenched and tempered (Q&T) and maraging steels ranging in yield strength (YS) from approximately 80 to 295 ksi is given in Fig. 9. The preliminary guidelines indicating relative fracture performance in the presence of 2-in. flaws for steels characterized by drop-weight tear test (DWTT) energy levels above, between, or below the strain levels indicated by the horizontal cross-hatched lines are illustrated by the legend and photographs appended to Fig. 9, right. The optimum materials trend line (OMTL) curves in this figure indicate the practicable upper limits of fracture toughness obtainable for any given strength level steel as a function of conventional or special mill processing (i.e., special melting and cross-rolling practices) variables.

It should be noted that the summary of the relationships given in Fig. 9 represents tests of fracture propagation in the "weak" direction of a rolled plate, provided such a direction exists. For plates having isotropic (same fracture toughness) properties in the two directions, the indicated values represent this fact. In other areas, all values represent the lowest level of fracture toughness for the indicated material. One of the early important findings of these studies was the observation of the significantly wide differences in fracture toughness that could be obtained for conventionally cross-rolled steel plate as a function of specimen orientation. In addition, reheat-treatment studies were conducted with various Q&T and maraging steels, and all were shown to exhibit decreasing levels of fracture toughness with increasing strength levels. This general effect is such that as the strength level of a given material is increased, a point is reached where the "weak" direction of a poorly cross-rolled material is characterized by such low toughness levels that "low-energy absorption tear fractures" may be developed in the presence of relatively small flaws and high elastic stress level loads. The OMTL curves in Fig. 9 depict the maximum "weak" direction fracture toughness values obtainable for presently definable steels of any given strength level. New data developed during this reporting period provide additional information relating to directionality effects.

EFFECT OF CROSS-ROLLING ON FRACTURE TOUGHNESS OF HIGH STRENGTH STEEL PLATE

To investigate the directionality effects that could be developed by extreme degrees of production cross-rolling, a series of thirteen Q&T steel plates were procured. These steels represent conventionally processed* material from a single electric furnace production heat conforming to the chemical composition requirements of "high-chemistry" HY-80, Table 5. Special handling by the mill in slab cutting and rolling to 1-in. plates was followed to obtain five degrees of cross-rolling ratios ranging from 30 to 1 (straightaway rolling parallel to ingot axis) to 1 to 1 (equivalent rolling parallel to and transverse to ingot axis) as shown in Table 5. The principal rolling direction and "weak" direction properties in the majority of these steels were parallel to the original ingot axis. Two of these plates (G80 and G81) were deliberately rolled to a 1 to 4 ratio such that the principal rolling direction and "weak" direction properties were transverse to the original ingot axis.

* Single oxidizing slag, air-melt practice.

Tension, Charpy V (C_V), and DWT tests on these steels were conducted with specimens in both orientations. The data are given in Table 6, and a graphical summary of the DWT and YS relationships for these steels is presented in Fig. 10. The data points labeled "N" in this illustration represent values obtained with specimens of these steels heat treated at the U.S. Naval Research Laboratory (NRL). In these cases, double (2 + 2 hr) temper heat treatments at 1150°F of the steels previously heat treated by the mill to 130 and 150 YS resulted in lowering the strength levels of these steels to the 110 to 120 ksi YS range. At this YS range, the comparatively small specimen blank and the significantly longer tempering times used for Laboratory heat-treated steels resulted in the development of higher fracture toughness levels than those of the steels heat treated by the mill to the 110 to 120 YS range. Full Q&T heat treatments were conducted by NRL with DWTT specimens of the 1 to 1 cross-rolled steels to obtain the data points that are shown in Fig. 10 at approximately 160 ksi YS.

The top and bottom curves illustrated in Fig. 10 depict the extreme differences in toughness that may be developed in the two directions of a given material of any strength level as a consequence of very large amounts of unidirectional rolling. As depicted by the center curve in Fig. 10, essentially equivalent (isotropic) fracture toughness properties are developed in the two directions of highly (1 to 1) cross-rolled plate. In general, the results given in Fig. 10 indicate that for any given strength level, an increase in "weak" direction and a decrease in "strong" direction fracture toughness occurs with increasing degrees of cross-rolling; however, full (1 to 1) cross-rolling is required for a significant improvement of toughness in the "weak" direction of rolled steel plate.

The "weak" direction data of Fig. 10 have been replotted as open diamonds in Fig. 11 to highlight the relative positions of these specially rolled steels in relation to that of the previously established correlation data summarized in Fig. 9. The fully (1 to 1) cross-rolled steels ranging from approximately 140 to 160 ksi YS are observed to be characterized by fracture toughness levels that are essentially equivalent to the maximum level depicted by the OWTL curve previously established for conventional melt practice steels. To correspond with new data presented herein, a slight adjustment of the previously established

OMTL curve for conventionally processed steels is given by the dashed portion of this curve in Fig. 11. By extrapolation to the indicated curves given in Fig. 11 for the presently defined conventionally processed steels, the maximum YS levels for which the development of 2 to 5% prefracture strains would be possible in the 2-in. flaw explosion tear test (ETT) is estimated to be approximately 145 ksi YS for straightaway rolled steels and 185 ksi YS for highly cross-rolled steels.

The correlation of DWTT energy values with C_V energy values has been previously shown to be surprisingly good for steels (8). The range of C_V values corresponding to indicated levels of DWTT values, Figs. 10 and 11 right, represent the values depicted by the data band which encompasses all relationships established to date. The specific relationships of C_V and DWTT energies for these specially rolled steels are given in Fig. 12. The data band illustrated in Fig. 12 is shifted slightly to the left of that given in previous publications depicting these relationships. The first preliminary correlations of C_V and DWTT energy values were based upon tests in which the DWTT energy value was determined by "bracketing" within an increment of 250 ft-lb. DWTT are now conducted with the new 5000 ft-lb pendulum-type impact machine resulting in a better definition of the data band as given in Fig. 12. It should be noted that the high end of the C_V correlation range must be specified as a minimum value to insure that a given steel will be characterized by the corresponding DWTT toughness levels.

The ETT studies with these specially rolled HY-80 steels are concerned with developing refinements of the preliminary guidelines established in previous investigations, and with providing for a more exact definition of flaw size-stress level for fracture relationships in steels characterized by DWTT energies ranging from approximately 2200 to 800 ft-lb. The ETT with these steels are being conducted with the material in the mill heat-treatment condition and with fracture propagation only in the "weak" direction. The "strong" direction DWTT values for the mill heat-treated plates range from approximately 2500 to 4500 ft-lb and ample demonstrations have been given in previous reports of the high level of fracture toughness of steels that have this range of DWTT values.

Although all ETT with these steels have not been completed at the time of this progress report, some preliminary results can be described. The 2-in. flaw ETT performances are illustrated for four steels that were subjected to varying explosive load applications aimed at developing approximately 1% (Fig. 13 top) and 5% (Fig. 13 bottom) plastic strains in the respective samples. For either of the given load applications, the increased tear lengths with decreasing DWTT values are apparent. Two of the steels shown in Fig. 13 are illustrated in Fig. 14 after ETT with load applications that resulted in approximately 8% deformation. The following summary may be made of the ETT results shown in Figs. 13 and 14:

(1) Steels that are characterized by DWTT values of approximately 2200 ft-lb require a fracture stress in the presence of 2-in. flaws that is higher than 8% plastic strain.

(2) Steels that are characterized by DWTT values of approximately 1725 ft-lb require a fracture stress in the presence of 2-in. flaws that is between 5 to 8% plastic strain.

(3) Steels that are characterized by DWTT values of approximately 1000 ft-lb can withstand load applications that develop approximately 1% prefracture strain but fracture is expected in the presence of 2-in. flaws for load applications that develop approximately 2 to 3% prefracture strains.

Additional ETT with these steels that are to be completed during the next progress report period are expected to provide further refinements of the preliminary guidelines to fracture performance illustrated by the correlation data given in Fig. 9.

EVALUATION OF TITANIUM ALLOYS
(R.W. Huber, D.G. Howe, and R.J. Goode)

Drop-weight tear tests have been conducted on a series of Ti-7Al-2Cb-1Ta alloy plates supplied by Reactive Metals Inc. (RMI); these tests included both the longitudinal and transverse rolling directions. These samples represented three processing variations in the forging and rolling schedules followed by three differing heat treatments. The heat treatments consisted of an $\alpha + \beta$ anneal for one hour and air-cooled, a β anneal for one hour and air-cooled, and a β anneal for one hour and water quench. The drop-weight tear test (DWTT) results, along with the Charpy V (C_V) data at 30°F and the 0.2% yield strength (YS) furnished by RMI, are listed in Table 7. All of these data were intended to provide guidelines for the titanium processing study being conducted by RMI under a Bureau of Ships contract.

The DWTT energy values obtained for these specially processed plates are all higher than those obtained on any other 721 alloys tested to date. The agreement between the DWTT and C_V is not consistent, particularly in the case of the as-rolled plate and the $\alpha + \beta$ anneal at 1650°F. A better combination of toughness and yield strength is afforded by the β anneal of 1940°F followed by air-cooling (2700 ft-lb at 106-110 ksi YS). Toughness levels above 2000 ft-lb are developed by the β anneal and water quench to a higher YS of 109-122 ksi. A comparison of the DWTT energy values with the optimum materials trend line (OMTL) established at the U.S. Naval Research Laboratory (NRL) for 1-in. thick titanium plates is shown in Fig. 15.

A forged piece of 2.5-in. thick Ti-5Al-2.5Sn alloy was supplied by Wyman-Gordon Co. for DWTT studies. Drop-weight tear test of a 1 x 3-1/2 in. section cut from a surface of the slab gave low energy absorption values of 339 ft-lb in the RW and WR orientations (7). The full section (2-1/2 x 6-5/8 in.) DWTT energy value was 1506 ft-lb. DWTT energy absorption values obtained for other 2-in. thick titanium alloy plates are listed in Table 8. The interstitial content of these alloys with the exception of T-50 are representative of commercial production for the DOD sheet rolling program. The oxygen content of T-50 is 0.08 wt-%.

The first DWTT on 2-in. T-50 resulted in only cracking the brittle weld at 5000 ft-lb (the present maximum capacity of the impactor). A subsequent DWTT, using a drop-weight machine, broke the 2 x 6-1/2 in. test section at 7500 ft-lb; however, it is estimated that a 7000 ft-lb blow would not have completely fractured the test specimen. Tabs of unalloyed titanium are being welded onto one half of the broken test specimen in order to retest this plate at the 7000 ft-lb DWTT energy level.

North American Aviation Inc. supplied a small piece of diffusion-bonded Ti-6Al-4V plate for examination. The specimen was prepared by hot pressing forty-five pieces of 0.063 in. sheet at 1700°F for four hours with an overall reduction in thickness of 33%. The C_v data obtained with a limited number of specimens are comparable to the low interstitial T-5 (6Al-4V) alloy (9). The ultimate tensile strength (UTS) determined from a single 1/4-in. specimen was 140 ksi, YS 130 ksi. The oxygen content as analyzed at NRL was 0.136 wt-%. Specimens with the notch parallel to the plane laminates gave slightly higher C_v values than those where the notch was perpendicular to the plane of the laminates. The C_v curves for this material are shown in Fig. 16. The specimens tested at 75°F experienced delamination. This probably accounts for the high C_v energy value obtained at that temperature for the specimen with the notch parallel to the laminant.

Aside from the delamination, there is a "layered structure" appearance on the fracture surfaces of the specimens in which the notch was parallel to the laminates (Fig. 17). This is not evident in the other orientation. A cross-section of the fracture surface of a specimen with the notch parallel to the laminate is shown in Fig. 18. Metallographic studies showed the diffusion-bonded plate to consist of equiaxed α and β with only a few areas showing any evidence of the "layered" structure of the plate. Figure 19 shows the general appearance of the microstructure (Fig. 19a) as well as an area in which the diffusion-bonded regions are easily seen (Fig. 19b). Preliminary work is now under way at NRL on preparing large diffusion-bonded DWTT specimens from titanium alloy sheet.

Incomplete explosion tear test (ETT) results were reported for an annealed and aged Ti-6Al-2Mo plate (T-22). The plate, which had a DWTT energy value of 2566 ft-lb, had withstood an estimated 6-7% plastic strain in the presence of a 2-in. flaw without complete fracturing. Further testing of the material in the "no flaw condition" has shown that 6% plastic strain was developed. Based on this new information, the preliminary correlation between C_v, DWTT, ETT, and YS presented in the last Quarterly Report (2), has been further modified and is shown in Fig. 20. It is estimated that approximately 130 ksi is the maximum strength level that can be attained for which it is estimated to be possible to develop plastic strains in the order of 5-7% in the presence of 2-in. flaws. This is considered a high level of fracture toughness in any high strength structural material.

WELDING TITANIUM ALLOY PLATE

Metal inert gas welding of some of the titanium alloys is being conducted in a dry box (vacuum evacuated and inert gas backfilled) to insure freedom from atmospheric contamination. Joint design in the 1-in. plate consists of a double "v" 30° bevel having a 1/8-in. face and allowing a 0.045-in. root gap. Single pass welds are made across the 5-in. dimension of a standard DWTT specimen. Ti-6Al-2Mo alloy welds using wire prepared from the plate have been tested and reported previously as having about 1500 ft-lb absorbed energy (2). Using the same welding procedures and vacuum annealing, the weldments at 1800°F for one hour increased the DWTT values to 1540 and 1600 ft-lb on duplicate specimens. This same type of weldment vacuum annealed at 1750°F for one hour and inert gas-cooled to room temperature followed by a two hour aging at 1100°F increased the DWTT value to 1784 ft-lb. Increasing the vacuum annealing or solution temperature to 1800°F for one hour, inert gas cooling, followed by aging at 1200°F for two hours, gave a DWTT value of 2874 ft-lb for the same type of alloy weldment. The large shear lips developed on this fracture surface coincided with the heat-affected-zone (HAZ) of the weld. This last heat treatment of weldment is being repeated in order to verify these results.

Simple annealing treatments employed with the 6Al-4Sn-1V alloy weldments have lowered the 1500 ft-lb DWTT of the as-welded material to below 1000 ft-lb. Results from other heat-treating studies of this alloy indicate that a water quench from the solution anneal followed by 1100-1200°F aging should improve the fracture toughness of this alloy.

HEAT-TREATMENT STUDIES

Heat-treatment studies on a number of titanium alloys have been continued in order to develop information on the stability of the alloys and to determine the heat treatments which will produce an optimum combination of strength and toughness.

The alloys under study include commercially produced Ti-8Al-1Mo-1V (T-19), Ti-6Al-4Sn-1V (T-20), and Ti-6Al-2Mo (T-22) with approximately 0.07 wt-% O_2; NRL produced and INFAB forged and rolled Ti-8Al-1Mo-1V (T-28) and Ti-7Al-2Mo (T-29) with approximately 0.04 wt-% O_2; and a commercially produced Ti-6.5Al-5Zr-1V (T-36), and a Ti-6Al-2Sn-1Mo-1V (T-37) with 0.08 wt-% O_2.

The titanium alloys were solution annealed and aged in an atmosphere of argon. The effect of the heat treatments on the C_V and YS properties are shown in Tables 9-15 and in earlier reports (1,2). The variation of fracture toughness with heat treatment was determined using the C_V test. The specimens were tested at -80°F and +32°F in the RW and WR orientation respective to the principal rolling direction of the "as-received" plate. The C_V and tensile (0.313 in. diam) specimens were prepared from the "as-received" material prior to heat treating and the tensile specimens were tested at a strain rate of 0.002 in./in./min.

The commercially produced Ti-6Al-4Sn-1V and Ti-6Al-2Mo alloys developed the highest levels of toughness when heat treated to 120-140 ksi YS. The C_V and YS values for some of the better heat treatments are shown in Fig. 21. The Ti-6Al-4Sn-1V alloy developed C_V energy values of over 55 ft-lb and a YS of about 120 ksi on annealing at about 40°F below the β transus followed by a water quench. Further aging at 1100°F for two hours then air cooling increased the YS to 128.5 ksi with C_V values between 40-45 ft-lb. Other solution annealing and aging treatments which resulted in about the same YS and C_V levels are shown.

The Ti-6Al-2Mo alloy annealed at approximately 40°F below the β transus followed by a water quench had a YS of about 135 ksi and corresponding C_V energy value of about 25 ft-lb. Subsequent aging at 1200°F for two hours then air cooling increased the YS to about 149 ksi with only a very slight decrease in the C_V energy. If the 1800°F anneal is followed by an air cool instead of a water quench, then the

YS is about 115 ksi with a corresponding C_v energy of 45-55 ft-lb for the annealed material. Subsequent aging of this material at 1200°F for one or two hours followed by a water quench increases the YS to 121-126 ksi. The C_v energy does not seem to be affected by the one hour aging treatment but is decreased to about 40 ft-lb on aging an additional hour. Solution annealing treatments at 1700 and 1750°F for one hour, then air cool, followed by aging at 1200 and 1100°F respectively for two hours and water quench, resulted in equally good strength and toughness properties.

These heat-treatment studies have shown that the low interstitial commercially produced Ti-6Al-4Sn-1V (T-20) and Ti-6Al-2Mo (T-22) alloys develop the best combinations of strength and toughness of the alloys investigated to date. These materials are being tested in the DWTT in the more promising heat-treated conditions and on the basis of these tests will be evaluated in the ETT.

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Table 1
Chemical Composition of Quenched and Tempered Steels (HY-80)

Material	Chemical Composition wt-%							
	C	Mn	Si	P	S	Ni	Cr	Mo
HY-80 (E84)	.19	.20	.23	.007	.007	2.18	1.29	.30
Q&T 130 YS (G13)	.14	.37	.27	.003	.009	3.03	1.72	.52
Q&T 150 YS (F65)	.19	.32	.33	.006	.013	3.28	1.69	.70
Q&T 150 YS (G14)	.16	.37	.29	.005	.010	3.03	1.69	.55

Table 2
Mechanical Properties of Quenched and Tempered Steels (HY-80)

Material	Cross-Roll	Direction of Test*	0.505 in. diam Tension Test				C_v (30°F) (ft-lb)	DWT (30°F) (ft-lb)
			(0.2%) (ksi)	UTS (ksi)	Elong in 2 in. (%)	RA (%)		
HY-80 (E84)	Highly Cross-Rolled	Weak	86	103	23	68	93	5000
		Strong	91	106	24	71	115	6200
Q&T 130 YS (G13)	4:1	Weak	133	142	18	58	62	2789
		Strong	-	-	-	-	88	4160
Q&T 150 YS (F65)	6.2:1	Weak	158	176	13	41	23	1000
		Strong	157	175	17	55	48	3250
Q&T 150 YS (G14)	2:3:1	Weak	152	165	17	54	42	2364
		Strong	-	-	-	-	63	4107

*Test direction is defined in terms of the fracture orientation with respect to the principal (or final) rolling direction, "weak" indicates a fracture parallel to the rolling direction, "strong" indicates a fracture perpendicular to the rolling direction.

Table 3
Properties of Aluminum Alloys

Alloy	Direction	YS (ksi)	UTS (ksi)	C_v (32°F) (ft-lb)	DWTT (ft-lb)
2020	RW	-	-	-	107
	WR	-	-	-	107
2219-T87	RW	57.9	72.0	5	281
	WR	55.2	72.0	5	281
2024-T4	RW	-	-	-	514
	WR	-	-	-	281
5086-H112	RW	26.5	43.6	35	~3000
	WR	24.2	43.0	22	~2000
5456-H321	RW	37.8	54.1	15	1900
	WR	34.0	55.0	8	990
6086-H112	RW	26.3	43.6	34	3013
	WR	24.2	43.0	22	2026
6061-T651	RW	38.0	41.5	10	1201
	WR	38.3	44.3	10	750
7075-T6	RW	-	-	-	167
	WR	-	-	-	83

Table 4
Results of Tensile,* Drop-Weight Tear, and Charpy V Tests on Some Aluminum Alloys

Alloy	Fracture Direction	YS (psi)	Notch Strength: Fatig. Cracked Specimens (psi)	Notch Strength: Uncracked Specimens (psi)	Notch Strength Ratio: Fatig. Cracked Specimens	Notch Strength Ratio: Uncracked Specimens	DWTT (ft-lb)	Charpy V (ft-lb)
6061 K	RW	41,700	67,400	73,750	1.61	1.77	1418	11
6061 K	WR	40,000	56,000	65,000	1.40	1.62	750	8
6061 G	RW	41,700	74,800	73,500	1.79	1.76	1418	11
6061 G	WR	40,000	62,400	68,500	1.56	1.71	750	8
2219 M	RW	57,900	74,600	80,800	1.29	1.40	281	5
2219 M	WR	55,200	69,000	75,900	1.25	1.37	281	5
5456 J	RW	37,800	67,800	66,200	1.80	1.75	1905	15
5456 J	WR	54,600	34,600	63,400	1.61	1.87	991	8
5086 L	RW	26,300	52,300	56,400	1.99	2.14	3013	34
5086 L	WR	24,200	51,600	52,800	2.13	2.18	2026	22
2024 H	RW	48,000	75,200	82,400	1.57	1.71	668	10
2024 H	WR	47,750	73,000	78,000	1.53	1.63	367	7

*(Smooth, notched, precracked)

Table 5
Chemical Compositions of Specially Rolled and Heat Treated
Type Ni-Cr-Mo Steel Plates

NRL Steel No.	Ingot & Slab	L/T	Composition - Wt. %							
			C	Mn	Si	P	S	Ni	Cr	Mo
F-60	5A	30/1	.20	.35	.32	.007	.010	3.20	1.69	.70
F-63	1AC	30/1	.18	.35	.33	.006	.010	3.16	1.62	.70
F-66	1AB	30/1	.19	.32	.33	.006	.012	3.20	1.66	.70
F-62	5B	13-1/4/1	.19	.35	.31	.008	.011	3.16	1.64	.71
F-65	1BC	13-1/4/1	.19	.32	.33	.006	.013	3.28	1.69	.70
F-68	1BB	13-1/4/1	.18	.32	.35	.006	.010	3.12	1.62	.71
F-61	5C	7-1/2/1	.19	.35	.31	.006	.011	3.20	1.65	.70
F-64	1CC	7-1/2/1	.21	.32	.33	.006	.011	3.20	1.65	.75
F-67	1CB	7-1/2/1	.21	.32	.34	.006	.014	3.28	1.67	.70
G-80	3AB	1/4	.19	.33	.33	.003	.014	3.24	1.54	.72
G-81	3AA	1/4	.19	.33	.33	.006	.014	3.12	1.59	.72
G-82	3J	1/1	.19	.33	.32	.006	.015	3.12	1.56	.73
G-83	3K	1/1	.19	.33	.34	.008	.015	3.12	1.56	.73

Rolling Ratio: $L/T = (W_I/W_P)^2\ T_I/T_P$ where W_I is Width of Ingot, W_P is Width of Plate, T_I is Thickness of Ingot, and T_P is Thickness of Plate.

Table 6
Test Data for Specially Rolled and Heat Treated HY-80 Type NI-CR-MO Steel Plates

NRL Steel No.	Temper (F)	L T	Direction of Test	0.505-in. dia. tension test data: 0.2% Y.S. (ksi)	T.S. (ksi)	El. in 2-in. (%)	R.A. (%)	Charpy V at 30 F (ft-lb)	Drop-weight at 30 F (ft-lb)
F-60	1150	30 1	Weak	113.0	128.3	19.7	53.7	45	2000
F-60	1150	30 1	Strong	118.8	135.7	21.7	69.0	102	5750
F-60	1100	30 1	Weak	131.8	151.6	14.5	45.8	30	1173
F-60	1100	30 1	Strong	132.0	151.2	19.0	66.8	82	4120
F-61	1150	7-1 2 1	Weak	114.6	129.8	20.0	58.2	56	2750
F-61	1150	7-1 2 1	Strong	120.4	136.0	21.7	64.1	86	4750
F-61	1100	7-1 2 1	Weak	133.1	150.2	16.3	54.7	42	1662
F-61	1100	7-1 2 1	Strong	134.3	151.4	18.3	63.9	71	3436
F-62	1150	13-1 4 1	Weak	114.0	129.8	19.5	57.0	50	2250
F-62	1150	13-1 4 1	Strong	118.4	134.5	22.0	65.8	92	5250
F-62	1100	13 1 4 1	Weak	134.0	152.1	14.5	46.0	30	1418
F-62	1100	13 1 4 1	Strong	134.0	152.2	18.5	64.5	76	3775
F-63	1150	30 1	Weak	110.7	126.4	19.5	57.6	47	2500
F-63	1150	30 1	Strong	115.7	130.1	22.0	70.0	102	5750
F-63	1050	30 1	Weak	151.0	166.4	14.0	49.2	28	991
F-63	1050	30 1	Strong	150.1	165.3	17.3	64.3	60	3122
F-64	1150	7-1 2 1	Weak	118.2	134.0	17.0	47.6	41	2500
F-64	1150	7-1 2 1	Strong	121.0	135.8	21.5	65.3	76	4250
F-64	1050	7-1 2 1	Weak	155.9	172.8	13.3	43.7	24	1173
F-64	1050	7-1 2 1	Strong	155.6	172.8	15.8	53.3	45	2498
F-65	1150	13-1 4 1	Weak	114.9	131.7	17.5	47.0	38	2500
F-65	1150	13-1 4 1	Strong	121.4	138.3	22.0	65.3	82	4500
F-65	1050	13-1 4 1	Weak	158.0	175.6	12.5	41.3	23	811
F-65	1050	13-1 4 1	Strong	156.6	175.2	17.0	54.6	48	2498
F-66	1150	30 1	Weak	112.6	134.9	16.5	48.3	42	1723
F-66	1150	30 1	Strong	111.9	130.6	21.5	71.5	86	4414
F-67	1150	7-1 2 1	Weak	120.0	138.2	17.0	51.4	40	2206
F-67	1150	7-1 2 1	Strong	117.9	137.5	21.5	65.4	75	3910
F-68	1150	13-1 4 1	Weak	112.6	137.9	[illegible]	51.9	41	1540
F-68	1150	13 1 4 1	Strong	116.7	136.4	20.0	[illegible]	75	3775
G-50	1120	1 4	Weak	138.2	153.4	15.8	47.6	[illegible]	1596
G-50	1120	1 4	Strong	136.6	152.3	19.0	61.8	63	[illegible]
G-51	1100	1 4	Weak	142.6	159.5	14.8	47.7	30	1228
G-51	1100	1 4	Strong	143.4	160.3	17.5	58.8	67	3542
G-51	[illegible]	1 4	Weak	151.7	168.4	14.0	47.0	28	1173
G-52	1120	1 1	Weak	139.9	153.4	17.0	56.2	52	2066
G-52	[illegible]	1 1	Strong	140.4	155.2	17.8	60.0	51	
[illegible]	[illegible]	[illegible]	Weak	160.0	179.8	14.4	47.6	35	1534
[illegible]	[illegible]	[illegible]	Weak	162.0	185	14.0	44.5	27	1474
[illegible]	[illegible]	[illegible]	Strong	162.2	[illegible]	14.5	49.4	29	1529
[illegible]	[illegible]	[illegible]	Weak	[illegible]	[illegible]	[illegible]	53.0	45	1905
[illegible]	[illegible]	[illegible]	Strong	[illegible]	[illegible]	16.8	57.3	53	

Table 7
Mechnical Properties of Specially Processed Ti-7Al-2Cb-1Ta Alloy Plate

Heat Treatment and Mechanical Properties	Specimen A		Specimen B		Specimen C	
	Long.	Trans.	Long.	Trans.	Long.	Trans.
As Forged & Hot Rolled						
DWTT	2958	2325				
	3105	2498				
Average	3032	2410	2676	2498	2560	2353
C_V at 30°F (ft-lb)*	39.8	37.7	38.7	43.7	48.0	41.5
0.2% YS (ksi)*	102	105	107.5	112	106	113.5
Annealed 1650°F/1hr AC						
DWTT	3228	2780				
	2674	3150				
Average	2950	2965	3148	2526	3150	2705
C_V at 30°F (ft-lb)*	43.5	38.5	39.7	37.5	48.5	46.5
0.2% YS (ksi)*	102.8	114.5	104.7	114.2	108.7	111.2
Annealed 1940°F 1hr AC						
DWTT	2676	2846				
	2780	2733				
Average	2728	2790	2733	2733	2733	2566
C_V at 30 F (ft-lb)	48.5	45	47.8	43.8	48.0	48.5
0.2% YS (ksi)	110	111.2	105.7	106.7	106.5	108.7
Annealed 1940 F 1hr WQ						
DWTT	2676	2958				
	2733	2526				
Average	2705	2742	2325	2266	2266	2026
C_V at 30 F (ft-lb)	41	44.6	45	39	31.5	28.0
0.2% YS (ksi)*	112.5	120.5	108.7	115.7	120.5	122

*Data furnished by Reactive Metals Inc.

Table 8
Drop Weight Tear Test of 2-inch Titanium Plate

Alloy	Composition	Test Section (in.)	DWTT (ft-lb)
T-7B	Ti-5Al-2.5Sn (BuShips)	6-9/16 × 2-1/8	1784
T-8B	Ti-6Al-4V (BuShips)	6-1/2 × 2	4875
T-9B	Ti-11V-13Cr-3Al (BuShips)	6-5/8 × 2-1/8	1324
T-51	Ti-5Al-2.5Sn (Wyman-Gordon)	6-5/8 × 2-1/2	1506
T-50	Ti-7Al-2Cb-1Ta (Reactive Metals)	6-1/2 × 2	7500*

*To be retested at 7000 ft-lb DWTT energy level

Table 9

Test Data for Solution Annealing and Aging Treatments on the Alloy Ti-8Al-1Mo-1V (T-19)

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb) -80°F	Long. (RW) C_v Impact Energy (ft-lb) +32°F	Trans. (WR) C_v Impact Energy (ft-lb) -80°F	Trans. (WR) C_v Impact Energy (ft-lb) +32°F	YS (0.2%) (ksi)	UTS (ksi)	Elong.	RA (%)
As Received		19.0	23.0	19.0	24.5	122.2(L)	132.6(L)	12.1	20.0
						122.7(T)	130.9(T)	10.7	21.2
1850°F/1hr/AC	-	30.5	40.5	32.0	45.0				
1850°F/1hr/AC	1100°F/2hr/WQ	31.0	37.0	30.0	40.0				
1850°F/1hr/AC	1200°F/2hr/WQ	31.5	34.0	28.0	37.5				
1800°F/1hr/AC	-	29.0	40.0	32.5	46.0	110.9(L)	126.3(L)	10.7	25.1
						111.6(T)	127.6(T)	14.3	25.7
1800°F/1hr/AC	1100°F/2hr/WQ	27.5	[illegible]	31.5	36.5	116.8(L)	128.3(L)	12.9	21.2
						117.5(T)	129.9(T)	12.1	18.3
1800°F/1hr/AC	1200°F/2hr/WQ	28.0	36.0	27.5	34.0	120.2(L)	129.1(L)	11.4	21.9
						120.9(T)	130.4(T)	10.7	18.3
1750°F/1hr/AC	-			32.0	46.5	110.6(L)	127.3(L)	14.3	25.1
						108.7(T)	125.2(T)	10.7	29.0
1750°F/1hr/AC	1100°F/2hr/WQ	30.5	[illegible]	30.0	36.0	117.9(L)	129.4(L)	10.7	21.2
						118.2(T)	129.4(T)	13.6	21.2
1750°F/1hr/AC	1200°F/2hr/WQ			28.0	41.5	120.4(L)	129.3(L)	8.6	16.6
						119.6(T)	128.8(T)	9.3	22.4
1750°F/1hr/AC	1100°F/2hr/AC					127.6(L)	135.8(L)	8.6	11.1
						[illegible](T)	136.1(T)	5.0	11.8
1750°F/1hr/AC	1200°F/2hr/AC					128.[illegible](L)	136.2(L)	5.7	10.0
						129.8(T)	137.0(T)	5.0	10.0
1700°F/1hr/AC	-					111.3(L)	127.0(L)	11.4	22.9
						111.6(T)	127.3(T)	11.4	22.9
1700°F/1hr/AC	1100°F/2hr/WQ					115.2(L)	127.6(L)	14.3	24.0
						118.1(T)	127.[illegible](T)	10.7	22.9
1700°F/1hr/AC	1200°F/2hr/WQ					120.1(L)	129.6(L)	12.1	21.7
						121.4(T)	130.9(T)	12.1	21.2

* transus 1885°F ± 15°F.

Table 10
Test Data for Solution Annealing and Aging Treatments on the Alloy Ti-6Al-4Sn-1V (T-20)*

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb) -80°F	Long. (RW) C_v Impact Energy (ft-lb) -32°F	Trans. (WR) C_v Impact Energy (ft-lb) -80°F	Trans. (WR) C_v Impact Energy (ft-lb) -32°F	YS (0.2%) (ksi)	UTS (ksi)	Elong. (%)	RA (%)
As received		15.0	21.0	25.5	29.0	132.0(L)	134.2(L)	11.4	41.4
						128.4(T)	133.0(T)	14.3	39.1
1700°F 1hr AC		33.0	49.0	30.0	44.0	114.2(L)	118.5(L)	16.4	52.1
						113.8(T)	118.7(T)	17.1	46.4
1700°F 1hr AC	1100°F 2hr WQ	19.0	32.0	21.0	36.0	116.3(L)	116.3(L)	14.3	47.2
						115.8(T)	117.1(T)	17.9	37.8
1700°F 1hr AC	1200°F 2hr WQ	21.0	35.0	21.0	35.0	116.8(L)	118.8(L)	15.0	50.3
						117.8(T)	120.7(T)	14.3	45.7
1750°F 1hr AC	-	47.0		29.0	51.0	114.5(L)	118.8(L)	15.7	47.9
						115.0(T)	120.6(T)	16.4	34.9
1750°F 1hr AC	1100°F 2hr WQ	25.0	44.0			118.2(L)	121.2(L)	14.3	31.8
						119.9(T)	121.2(T)	16.4	41.4
1750°F 1hr AC	1200°F 2hr WQ	28.0	38.0	22.0	39.0	117.6(L)	120.2(L)	15.0	37.9
						116.9(T)	119.9(T)	18.4	39.9
1750°F 1hr WQ	1100°F 2hr AC	29.0	44.0	24.0	36.0	121.4(L)	124.3(L)	15.0	41.8
						124.3(T)	126.0(T)	15.0	41.2
1800°F 1hr AC	-	48.0	55.0			113.0(L)	120.2(L)	14.3	32.8
						112.6(T)	119.2(T)	17.1	41.4
1800°F 1hr AC	1100°F 2hr WQ	34.0	60.0			114.5(L)	117.1(L)	15.0	43.2
						115.6(T)	118.2(T)	15.7	40.4
1800°F 1hr AC	1200°F 2hr WQ	30.0	45.0			114.9(L)	118.5(L)	13.6	32.2
						116.6(T)	119.9(T)	15.0	35.4
1825°F 1hr AC						111.6(L)	117.5(L)	15.0	29.5
						111.9(T)	119.1(T)	15.7	43.7
1825°F 1hr WQ	1100°F 2hr WQ	38.0	62.0			114.0(L)	118.6(L)	14.3	38.3
						115.5(T)	118.5(T)	15.0	45.2
1825°F 1hr AC	1200°F 2hr WQ					114.5(L)	117.5(L)	12.9	41.8
						116.3(T)	119.6(T)	15.7	32.8
1750°F 1hr WQ		47.0	56.5	39.0	54.0	116.9(L)	126.8(L)	14.3	42.8
						114.9(T)	127.6(T)	15.0	42.7
1750°F 1hr WQ	1100°F 2hr AC	29.0	44.0	24.0	36.0	121.4(L)	124.3(L)	15.0	41.8
						124.3(T)	125.0(T)	15.0	41.2
1750°F 1hr WQ	1200°F 2hr AC	26.0	45.0	24.5	41.0	119.6(L)	122.2(L)	15.0	44.3
						120.4(T)	123.0(T)	14.3	28.9
1800°F 1hr WQ	-	46.0	57.0	52.5	59.5	119.2(L)	135.0(L)	13.6	36.4
						119.0(T)	134.6(T)	12.9	42.6
1800°F 1hr WQ	1100°F 2hr AC	23.5	40.0	25.0	44.5	128.4(L)	132.7(L)	[illegible]	27.4
						128.4(T)	13[illegible](T)	12.9	29.9
1800°F 1hr WQ	1200°F 2hr AC	24.0	43.0	25.5	37.5	125.0(L)	127.6(L)	12.1	38.4
						126.3(T)	130.[illegible](T)	15.7	38.4
1825°F 1hr WQ						115.3(L)	139.1(L)	12.9	49.7
						116.7(T)	139.1(T)	12.9	48.9
1825°F 1hr WQ	1100°F 2hr AC	25.5	40.0	25.5	43.5	131.4(L)	139.3(L)	12.1	22.4
						130.9(T)	139.1(T)	11.4	29.5
1825°F 1hr WQ	1200°F 2hr AC				34.5	127.9(L)	13[illegible](L)	10.7	33.2
						129.4(T)	134.7(T)	12.1	32.3

* [illegible]

Table 11
Test Data For Solution Annealing and Aging Treatments on the Alloy Ti-6Al-2Mo(T-22) *

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb)		Trans. (WR) C_v Impact Energy (ft-lb)		YS (0.2%) (ksi)	UTS (ksi)	Elong. (%)	RA (%)
		-80°F	+32°F	-80°F	+32°F				
As Received	-	16.0	20.0	16.0	19.5	130.3(L) 125.6(T)	131.8(L) 129.4(T)	12.2 12.5	43.8 43.0
1850°F/1hr/AC	-	29.0	30.0	22.5	31.5	117.4(L) 121.2(T)	133.6(L) 136.7(T)	10.7 10.0	26.1 25.4
1850°F/1hr/AC	1100°F/2hr/AC	26.0	31.0	22.0	24.5	124.0(L) 126.7(T)	136.5(L) 138.6(T)	9.3 9.3	20.7 14.3
1800°F/1hr/AC	-	37.5	54.0	29.5	43.5	115.8(L) 114.3(T)	125.7(L) 126.5(T)	12.9 14.3	40.3 38.3
1800°F/1hr/AC	1100°F/2hr/AC	37.5	42.5	25.0	34.0	124.3(L) 120.2(T)	130.6(L) 129.1(T)	12.9 12.1	37.8 35.4
1800°F/1hr/AC	1100°F/1hr/WQ	23.0	38.0	24.5	49.0	118.6(L) 119.9(T)	128.8(L) 127.8(T)	13.3 13.6	37.4 37.9
1800°F/1hr/AC	1100°F/2hr/WQ	28.5	32.5	28.5	36.5	125.5(L) 115.8(T)	132.4(L) 126.0(T)	11.4 12.9	25.2 30.5
1800°F/1hr/AC	1100°F/4hr/WQ	25.0	44.5	20.0	34.0	124.5(L) **	129.1(L) 131.3(T)	12.9 15.7	39.9 43.0
1800°F/1hr/AC	1200°F/1hr/WQ	29.0	55.5	34.0	45.5	123.2(L) 120.6(T)	127.4(L) 126.1(T)	13.3 12.9	39.5 36.4
1800°F/1hr/AC	1200°F/2hr/WQ	29.5	39.5	28.0	40.5	123.2(L) 124.8(T)	128.7(L) 130.0(T)	11.4 11.4	28.3 32.3
1800°F/1hr/AC	1200°F/4hr/WQ	30.0	37.5	31.0	41.5	125.7(L) 113.3(T)	127.8(L) 122.5(T)	12.9 12.1	39.6 35.8
1750°F/1hr/AC	-	27.5	44.0	22.5	36.0	121.0(L) 114.9(T)	128.6(L) 126.6(T)	15.0 12.9	43.5 33.8
1750°F/1hr/AC	1100°F/2hr/WQ	21.0	34.0	22.0	31.5	123.7(L) 126.1(T)	131.8(L) 135.9(T)	13.6 13.6	34.8 27.8
1750°F/1hr/AC	1100°F/2hr/WQ	36.0	40.0	31.5	35.5	125.9(L) 123.0(T)	131.7(L) 131.2(T)	12.5 12.9	35.7 32.7
1750°F/1hr/AC	1100°F/4hr/WQ	28.0	31.5	26.0	35.0	127.3(L) 122.4(T)	131.6(L) 129.0(T)	12.9 13.2	41.5 35.0
1750°F/1hr/FC	-	28.0	37.0			119.2(T)	126.3(T)	14.6	46.2
1750°F/1hr/FC	1100°F/1hr/WQ	26.0	33.0			122.9(T)	129.7(T)	14.6	37.9
1750°F/1hr/AC	1200°F/1hr/WQ	29.5	34.0			126.2(L) 119.8(T)	131.1(L) 127.0(T)	11.4 13.5	34.4 36.3
1750°F/1hr/AC	1200°F/4hr/WQ	26.0	37.0	26.5	34.0	123.5(L) 125.8(T)	126.1(L) 130.4(T)	13.6 13.6	40.2 37.9
1700°F/1hr/AC	-	25.0	39.0	23.0	34.0	125.0(L) 122.7(T)	131.2(L) 132.6(T)	12.1 10.7	32.2 35.4
1700°F/1hr/AC	1100°F/2hr/WQ	20.5	25.0	21.0	33.0	128.9(L) 122.5(T)	132.2(L) 129.8(T)	12.9 12.1	39.8 39.9
1700°F/1hr/AC	1200°F/2hr/WQ	27.0	45.0	27.0	50.0	124.5(L) 125.3(T)	128.[illegible](L) 130.2(T)	15.0 12.9	37.7 34.8
1700°F/1hr/WQ	-	19.0	30.0	23.0	35.0	100.5(L) 105.4(T)	130.9(L) 133.7(T)	15.0 16.4	41.2 46.6
1700°F/1hr/WQ	1100°F/2hr/AC	11.5	15.5	10.5	16.0	137.7(L) 138.1(T)	149.5(L) 152.8(T)	7.9 5.7	17.1 9.4
1700°F/1hr/WQ	1200°F/2hr/AC	19.0	23.0	20.0	25.0	133.5(L) 133.8(T)	140.1(L) 142.3(T)	11.4 10.7	34.3 30.0
1750°F/1hr/WQ	-	24.0	27.0	26.0	37.0	111.0(L) 115.2(T)	135.7(L) 136.8(T)	14.3 15.0	44.8 36.3
1750°F/1hr/WQ	1100°F/2hr/AC	15.0	16.5	14.5	14.5	137.5(L) 133.3(T)	150.1(L) 146.6(T)	8.6 9.3	19.5 24.0
1750°F/1hr/WQ	1200°F/2hr/AC	18.0	22.5	17.5	23.0	135.5(L) 137.4(T)	144.0(L) 146.6(T)	10.0 9.3	28.4 25.7
1800°F/1hr/WQ	-	21.0	23.5	23.0	27.0	136.0(L) 135.0(T)	156.1(L) 155.5(T)	9.3 9.3	29.5 24.5
1800°F/1hr/WQ	1100°F/2hr/AC	16.0	16.0	16.0	19.0	152.5(L) 154.1(T)	162.0(L) 164.3(T)	6.4 3.6	16.6 5.[illegible]
1800°F/1hr/WQ	1200°F/2hr/AC	17.0	21.5	20.0	22.0	148.2(L) 148.9(T)	156.1(L) 157.4(T)	7.1 8.6	10.5 21.7

* Transus 1840°F ± 15°F

** Malfunction of equipment prevented determination of yield point

Table 12

Test Data For Solution Annealing and Aging Treatments on the Alloy Ti-8Al-1Mo-1V (T-28)*

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb) -80°F	Long. (RW) C_v Impact Energy (ft-lb) +32°F	Trans. (WR) C_v Impact Energy (ft-lb) -80°F	Trans. (WR) C_v Impact Energy (ft-lb) +32°F	YS (0.2%) (ksi)	UTS (ksi)	Elong. (%)	RA (%)
As Received	-	37.0	46.0	30.0	36.5	109.4(L)	123.8(L)	9.3	29.0
						112.9(T)	126.3(T)	11.4	30.6
1850°F/1hr/AC	1100°F/2hr/WQ	66.0	67.0	35.5	51.0	104.7(T)	117.7(T)	12.1	25.1
1850°F/1hr/AC	1200°F/2hr/WQ	69.0	66.5	47.0	69.0	107.9(L)	117.0(L)	8.6	16.0
1850°F/1hr/AC	-	36.0	41.0	45.0	57.0	107.3(T)	116.8(T)	9.3	13.4
1800°F/1hr/AC	1100°F/2hr/WQ	58.5	63.0	29.0	45.0	110.2(T)	122.2(T)	12.9	26.7
1800°F/1hr/AC	1200°F/2hr/WQ	67.0	59.0	40.0	40.5	106.0(T)	116.7(T)	16.4	32.1
						113.8(L)	123.9(L)	12.9	21.2
1800°F/1hr/AC	-	33.0	38.0	25.5	38.0	111.8(T)	120.9(T)	13.6	29.9
1750°F/1hr/AC	1100°F/2hr/WQ	29.0	37.5	34.0	40.5	112.6(T)	127.6(T)	11.4	26.4
						113.5(L)	124.7(L)	14.3	34.3
1750°F/1hr/AC	1200°F/2hr/WQ	48.0	56.5			112.9(T)	120.4(T)	10.0	31.1
						114.1(L)	123.8(L)	10.0	21.0
1750°F/1hr/AC	-	30.0	37.5	29.0	45.0	119.3(T)	128.75(T)	10.7	23.9
1750°F/1hr/AC	1200°F/4hr/WQ	26.5	33.0	27.5	39.5	111.25(T)	124.7(T)	10.7	24.6
						116.8(L)	123.4(L)	6.4	24.0
1820°F/2hr/AC	-	26.5	30.0			127.3(T)	133.8(T)	12.1	25.7
1700°F/1hr/AC	1200°F/2hr/WQ	27.0	31.0	21.0	27.0	114.0(L)	122.9(L)	11.0	18.8
1700°F/1hr/AC	1100°F/2hr/WQ	30.0	32.0	26.0	37.5	115.5(T)	123.0(T)	14.3	33.2
1700°F/1hr/AC	-	30.0	30.0	32.0	45.0				
1750°F/1hr/WQ	-								
1750°F/1hr/WQ	1100°F/2hr/AC					102.7(T)	129.6(T)	12.1	28.4
						115.4(L)	124.3(L)	10.0	23.6
1750°F/1hr/WQ	1200°F/2hr/AC					122.1(T)	133.5(T)	12.9	26.8
						113.9(L)	125.7(L)	7.9	17.7
1800°F/1hr/WQ	-					121.2(T)	130.8(T)	7.9	10.5
1800°F/1hr/WQ	1100°F/2hr/AC					116.2(T)	138.4(T)	11.4	27.9
1800°F/1hr/WQ	1200°F/2hr/AC					126.2(T)	143.6(T)	10.7	19.0
						122.7(L)	135.5(L)	5.7	15.4
						133.8(T)	149.5(T)	12.9	11.8

*β transus 1885°F ± 15°F.

Table 13
Test Data for Solution Annealing and Aging Treatments on the Alloy Ti-7Al-2Mo (T-29)*

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb) -80°F	Long. (RW) C_v Impact Energy (ft-lb) +32°F	Trans. (WR) C_v Impact Energy (ft-lb) -80°F	Trans. (WR) C_v Impact Energy (ft-lb) +32°F	YS (0.2%) (ksi)	UTS (ksi)	Elong. (%)	RA (%)
As Received	-		43.0			104.0(L)	118.5(L)	10.7	20.7
						118.0(T)	129.4(T)	12.9	28.3
1850°F/1hr/AC	-			31.5	51.0				
1825°F/1hr/AC	-			43.0	64.0				
1825°F/1hr/AC	1100°F/1hr/WQ			47.0	49.5				
1825°F/1hr/AC	1200°F/1hr/WQ			53.5	59.5				
1800°F/1hr/AC	-	55.0	63.5	55.0	53.0	114.2(T)	126.6(T)	12.1	35.9
1800°F/1hr/AC	1100°F/1hr/WQ	39.5	48.0	61.5	57.5	96.9(L)	114.8(L)	11.4	23.4
						115.2(T)	127.6(T)	11.4	26.2
1800°F/1hr/AC	1100°F/4hr/WQ	46.0	56.5	47.0	55.0	96.2(L)	117.9(L)	10.7	24.8
						112.2(T)	125.5(T)	**	28.0
1800°F/1hr/AC	1200°F/4hr/WQ			49.0	57.0	98.5(L)	115.1(L)	12.9	32.6
1800°F/1hr/AC	1200°F/1hr/WQ			54.5	51.0	104.7(L)	118.5(L)	11.4	39.8
1750°F/1hr/AC	-					104.8(L)	123.0(L)	7.1	14.9
						115.3(T)	128.8(T)	12.9	28.4
1750°F/1hr/AC	1100°F/1hr/WQ	51.0	56.0	48.0	57.0	105.3(L)	119.3(L)	11.4	31.6
						111.9(T)	125.3(T)	12.1	25.0
1750°F/1hr/AC	1100°F/4hr/WQ	50.5	54.0	52.5	54.0	108.9(T)	121.6(T)	11.4	23.4
1750°F/1hr/AC	1200°F/1hr/WQ	46.0	51.0	52.5	57.5	111.8(L)	122.2(L)	11.4	31.1
1750°F/1hr/AC	1200°F/4hr/WQ	52.5	55.0	45.5	60.0	105.3(L)	118.7(L)	10.0	29.9
						111.3(T)	119.8(T)	12.9	34.2
1750°F/1hr/WQ	1100°F/2hr/AC					123.5(T)	137.7(T)	8.6	18.0
1700°F/1hr/AC	-					102.1(L)	120.7(L)	7.9	23.9
						112.2(T)	126.3(T)	10.7	32.2
1700°F/1hr/AC	1100°F/2hr/WQ					100.1(L)	115.4(L)	9.3	21.9
						111.3(T)	123.4(T)	12.1	29.5
1700°F/1hr/AC	1200°F/2hr/WQ					107.1(L)	119.7(L)	10.0	18.4
						114.6(T)	124.5(T)	10.7	30.2

* β transus 1860°F ± 15°F.
** Broke at index mark.

Table 14
Test Data For Solution Annealing and Aging Treatments on the Alloy Ti-6.5Al-5Zr-1V (T-36)*

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb)		Trans. (WR) C_v Impact Energy (ft-lb)		YS (0.2%) (ksi)	UTS (ksi)	Elong. (%)	RA (%)
		-80°F	+32°F	-80°F	+32°F				
As Received	-			13.0	17.0	109.9(L) 113.2(T)	117.4(L) 120.7(T)	11.4 10.7	23.9 24.0
1750°F/1hr/AC 1750°F/1hr/AC	- 1100°F/4hr/WQ			13.5	20.5	108.3(T) 112.9(L)	120.9(T) 121.1(L)	8.6 9.3	25.1 24.6
1800°F/1hr/AC 1800°F/1hr/AC	- 1100°F/2hr/WQ			15.0	22.0	106.8(T) 114.3(L)	121.3(T) 123.8(L)	10.7 10.7	21.2 22.9
1800°F/1hr/AC	1100°F/4hr/WQ					115.2(T) 115.5(L)	124.0(T) 124.3(L)	9.3 8.6	22.4 22.9

*β transus 1835°F ± 15°F.

Table 15

Test Data for Solution Annealing and Aging Treatments on the Alloy Ti-6Al-2Sn-1Mo-1V (T-37)*

Solution Heat Treatment	Aging Heat Treatment	Long. (RW) C_v Impact Energy (ft-lb)		Trans. (WR) C_v Impact Energy (ft-lb)		YS (0.2%) (ksi)	UTS (ksi)	Elong. (%)	RA (%)
		-80° F	+32° F	-80° F	+32° F				
As Received	-				27.0				
1800° F/1hr/AC	1100° F/2hr/WQ			34.0	35.5	110.3(L)	123.4(L)	10.7	23.4
1800° F/1hr/AC	1100° F/2hr/WQ					115.9(L)	127.8(L)	11.4	20.2
						122.5(T)	132.5(T)	11.4	24.7
1800° F/1hr/AC	1200° F/1hr/WQ			31.5	37.0	119.4(T)	128.6(T)	10.0	28.0
1800° F/1hr/AC	1200° F/2hr/WQ					116.6(L)	126.5(L)	12.1	22.9
						119.1(T)	128.3(T)	12.1	29.5
1800° F/1hr/AC	1200° F/4hr/WQ			28.0	35.0				
1750° F/1hr/AC	1100° F/1hr/WQ			31.5	41.0	112.0(L)	126.2(L)	11.4	25.2
1750° F/1hr/AC	1100° F/2hr/WQ					118.6(T)	130.4(T)	10.0	20.7
1750° F/1hr/AC	1100° F/4hr/WQ			27.5	37.5	112.0(L)	123.5(L)	11.4	28.5
1750° F/1hr/AC	1200° F/1hr/WQ					116.6(T)	127.5(T)	12.9	30.2
1750° F/1hr/AC	1200° F/2hr/WQ			28.5	40.0	117.6(L)	126.8(L)	12.1	29.0
						121.2(T)	132.8(T)	11.4	20.8

*β transus 1835°F ± 15°F.

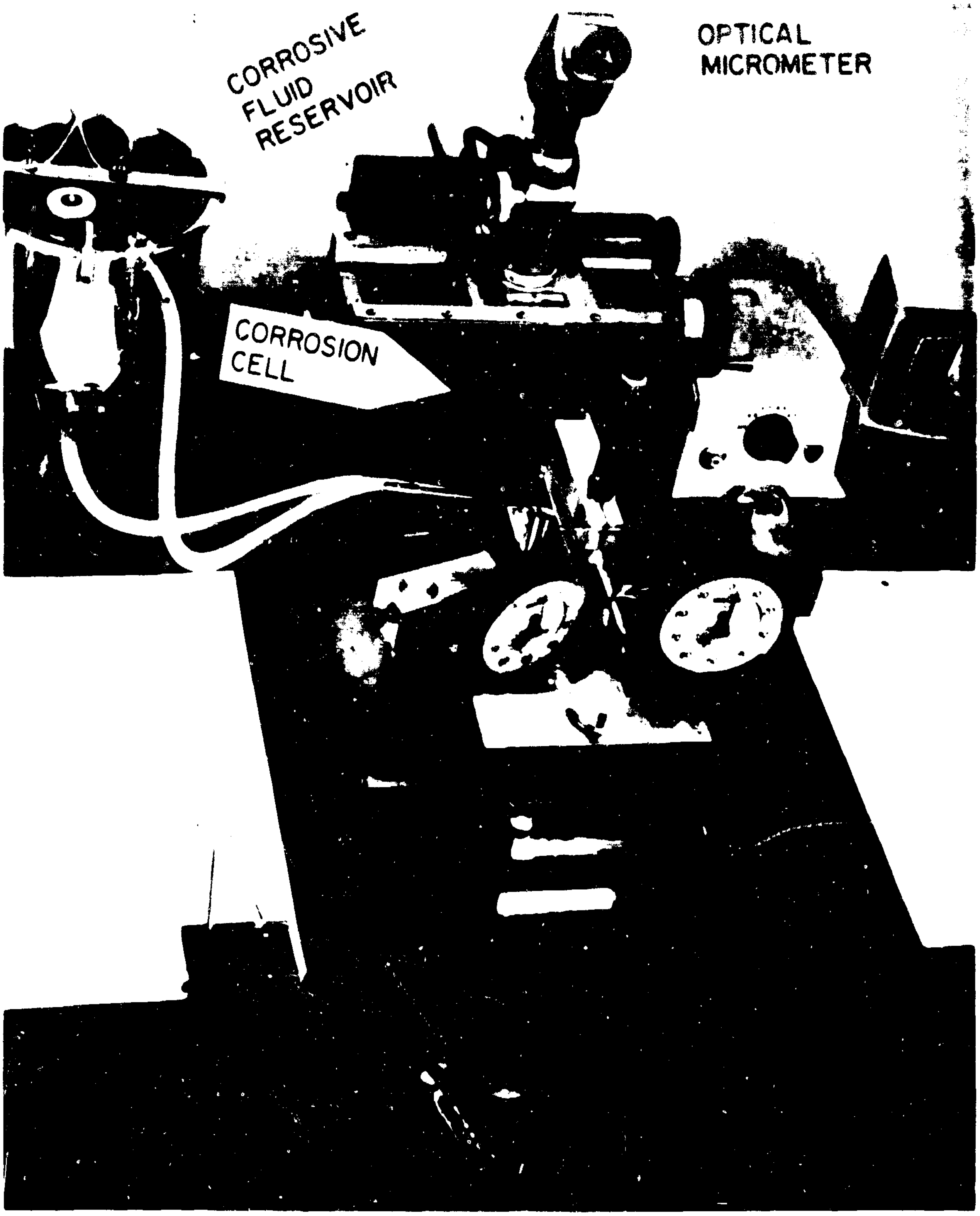

Fig. 1 - Photograph of NRL low cycle fatigue plate bend test adapted for corrosion fatigue studies. Corrosion cell and corrosive fluid reservoir are indicated.

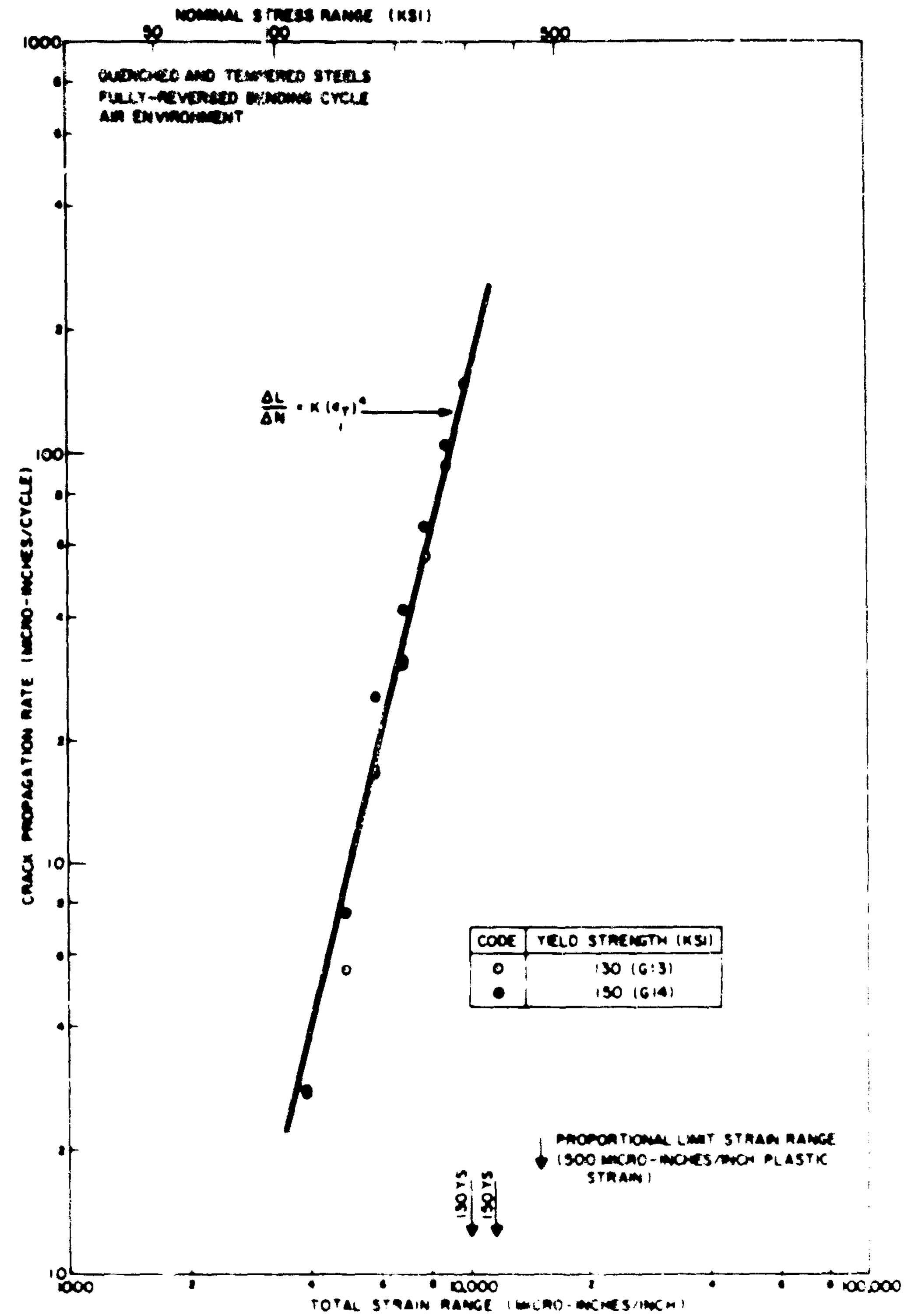

Fig. 2 - Log-log plot of total strain range versus crack propagation rate data in air environment for two Q& T steels not previously tested

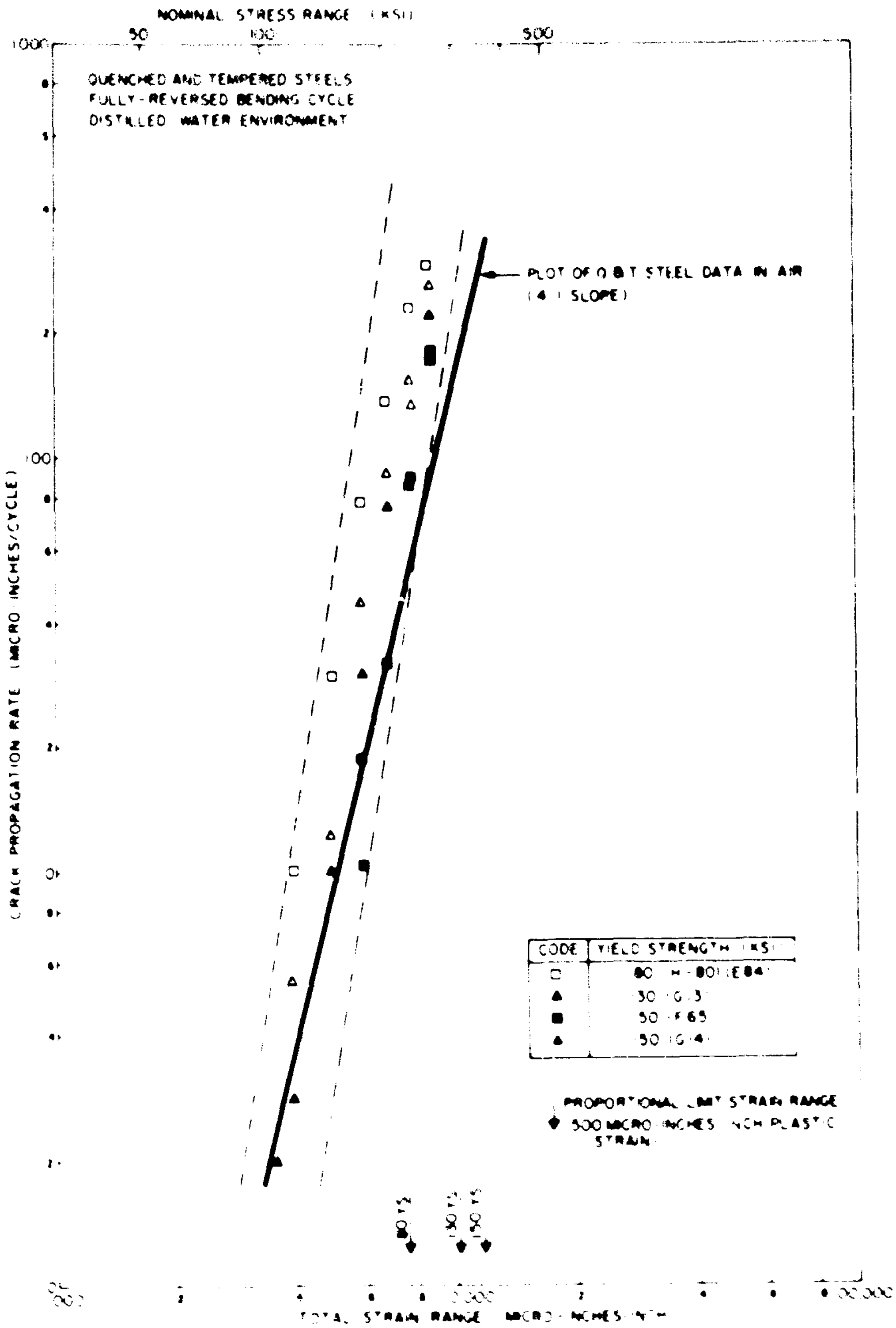

Fig. 3 - Log-log plot of total strain range versus crack propagation rate data for four Q& T steels in a distilled salt water environment. The plot of Q& T steel data in air is shown for reference.

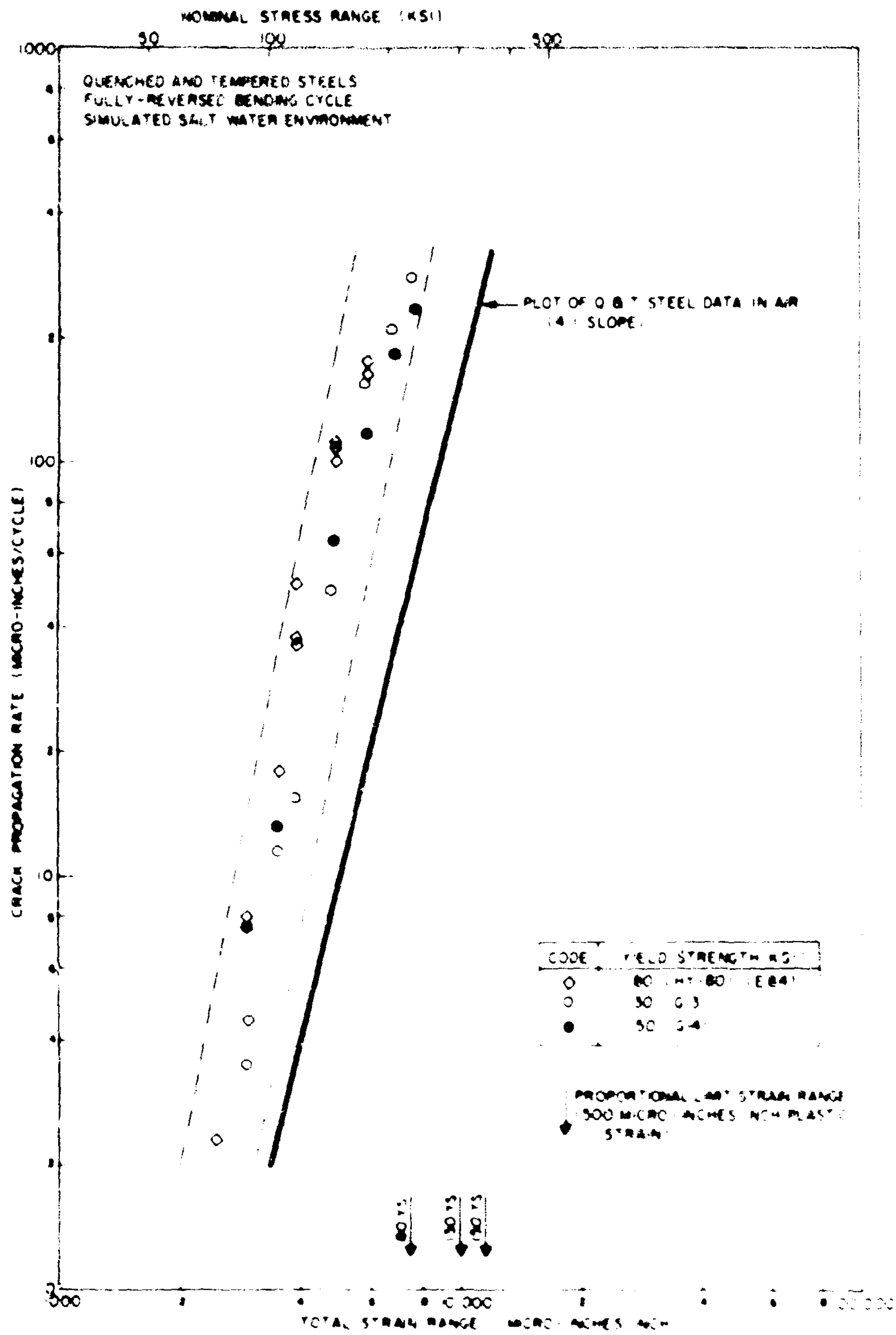

Fig. 4 - Log-log plot of total strain range versus crack propagation rate data for three Q&T steels in a simulated salt water environment. The plot of Q&T steel data in air is shown for reference.

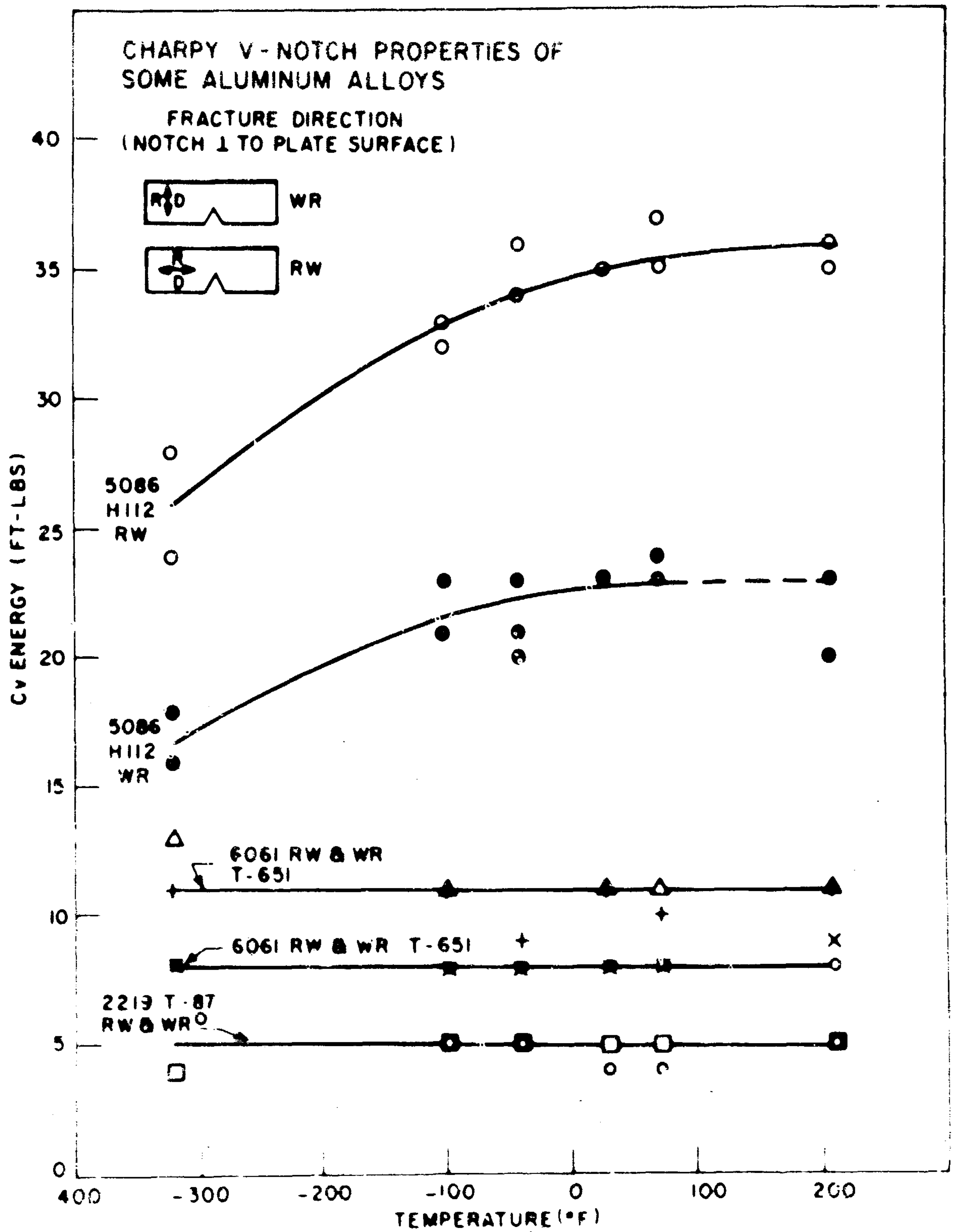

Fig. 5 - Charpy V-notch properties of 5086, 6061, and 2219 aluminum alloys

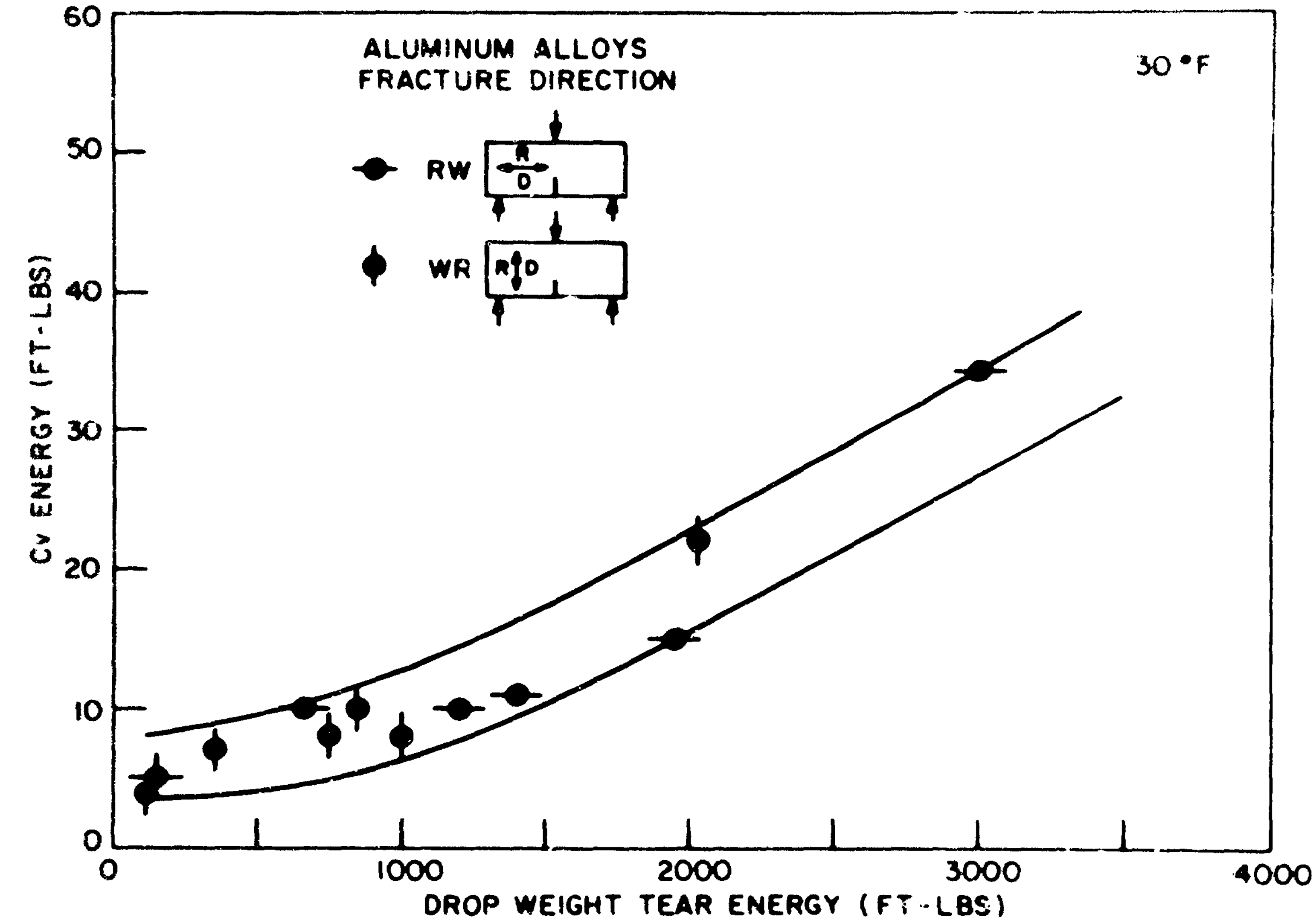

Fig. 6 - Charpy V-notch and DWTT energy relationship for 1-in. thick aluminum alloy plate

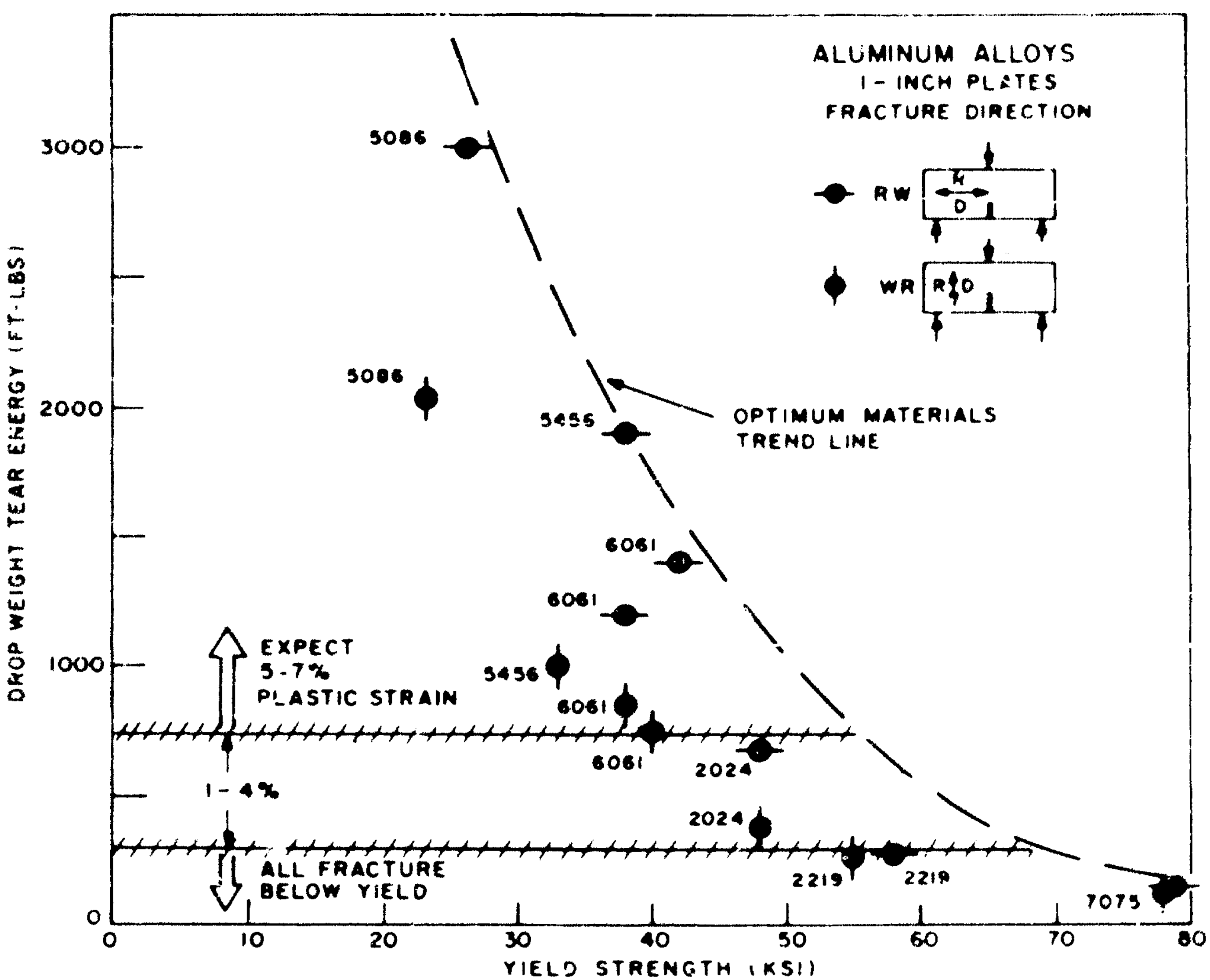

Fig. 7 - Drop-weight tear test, explosion tear test, and yield strength relationship for 1-in. thick aluminum alloy plate

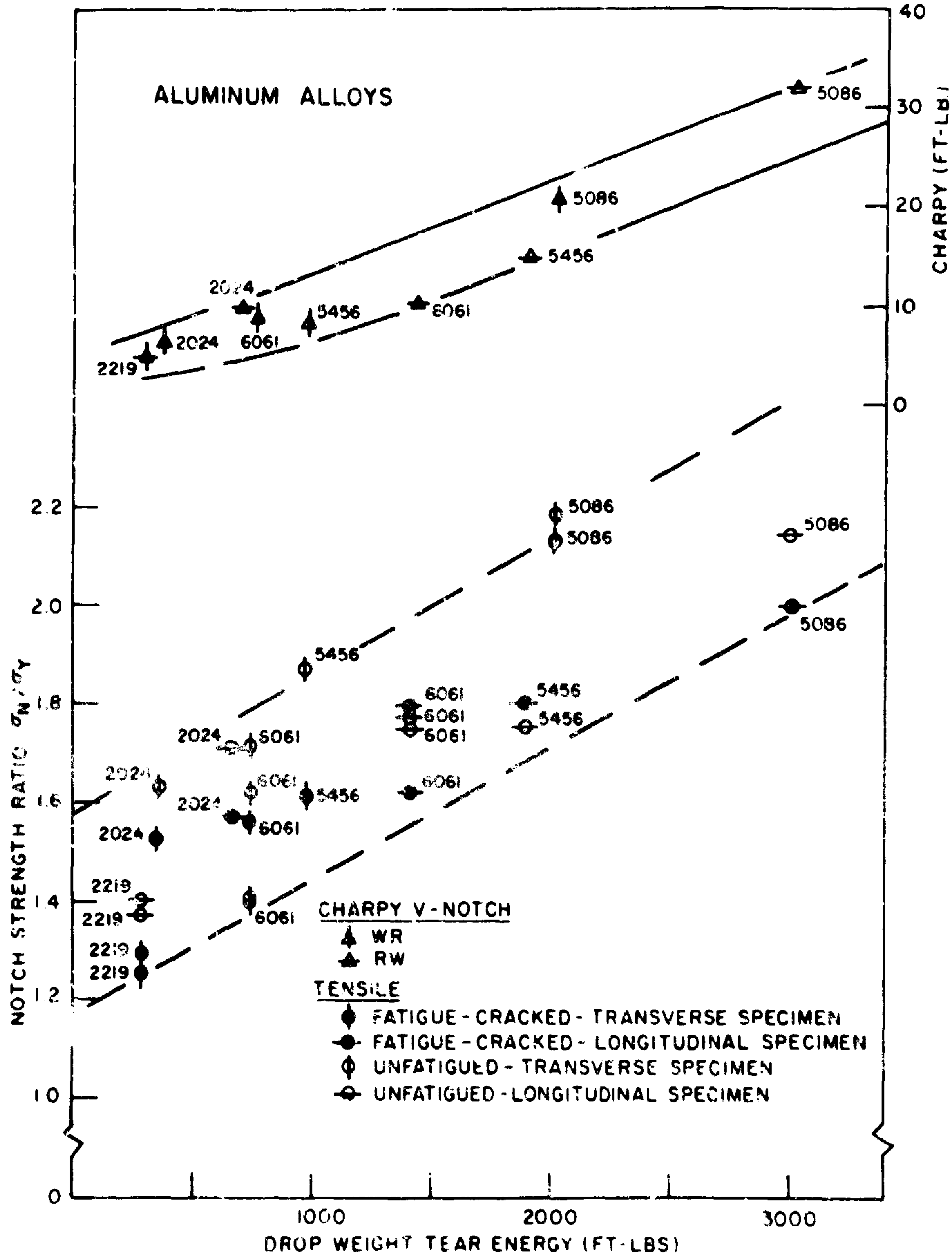

Fig. 8 - Notch-strength ratio and drop-weight tear test relationship for 1-in. thick aluminum alloy plate material. Charpy V-notch and drop-weight tear test relationship shown for comparison.

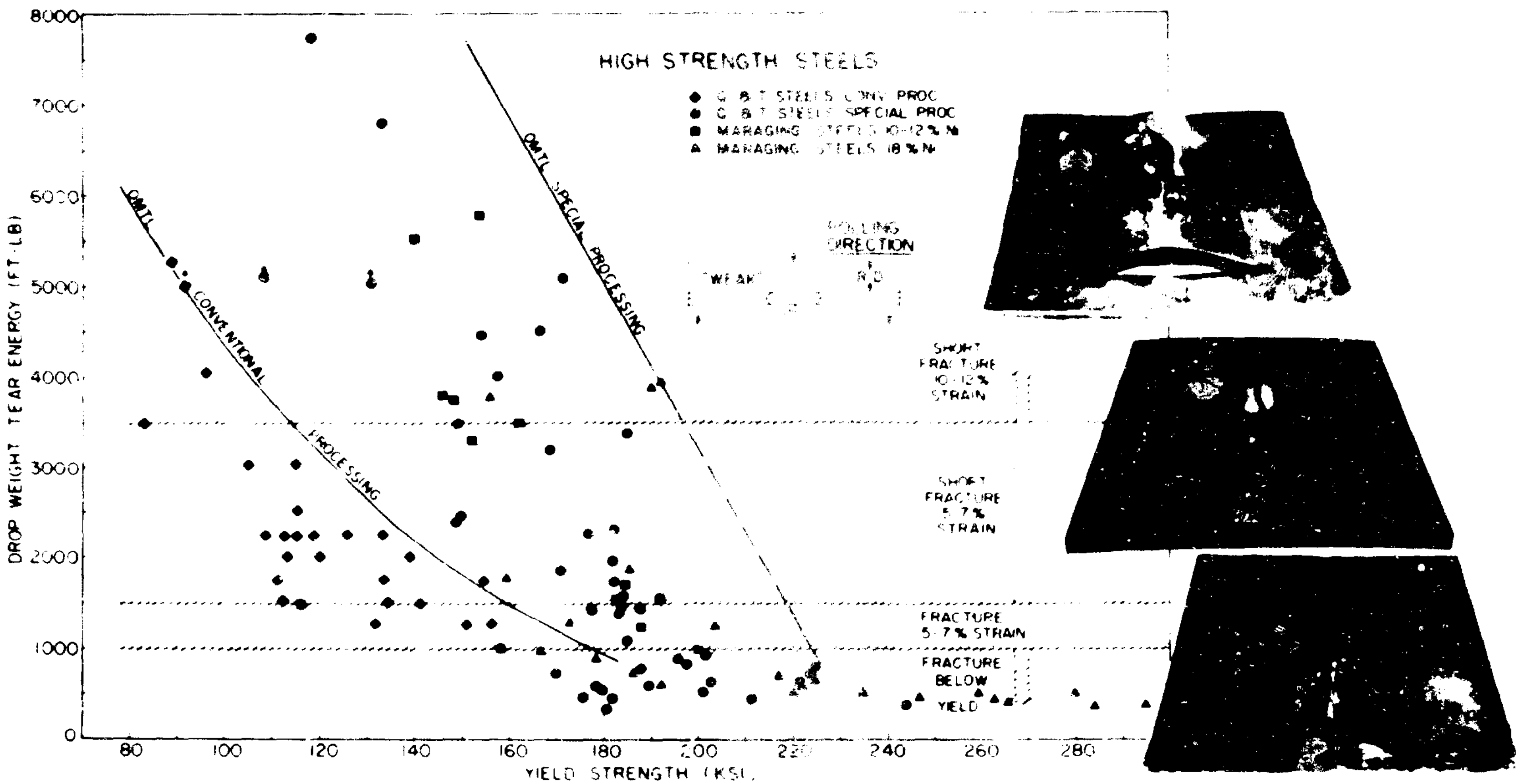

Fig. 9 - Summary of drop-weight tear and yield strength relationships for all steels tested to date. The correlations with performance in the explosion tear test in the presence of 2-in. flaws are indicated by the cross-hatched lines, the photographs, and the legend at the lower right side of the illustration.

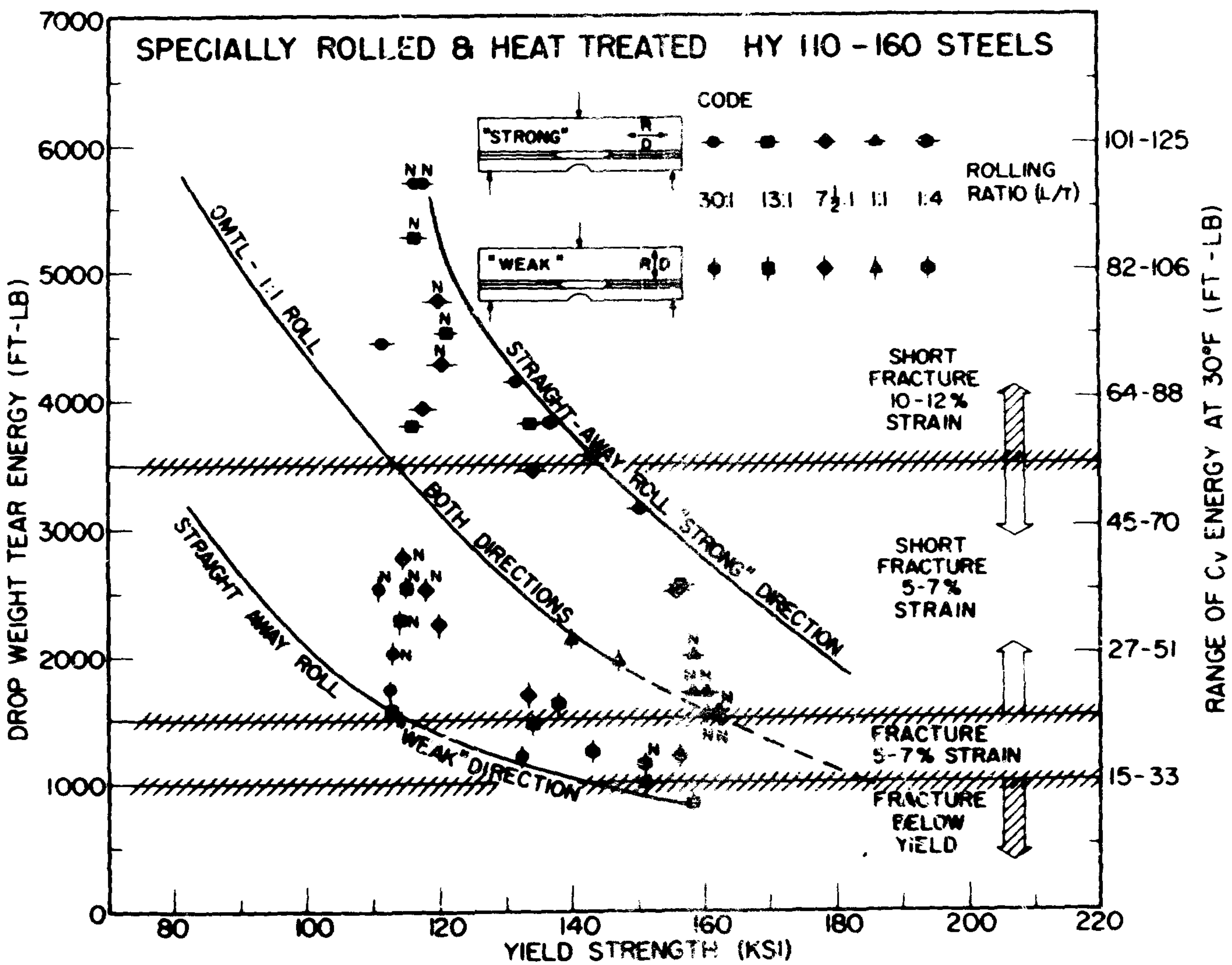

Fig. 10 - Summary of drop-weight tear energy absorption and yield strength relationships for steel plates of same heat processed to varied cross-rolling ratios and yield strengths

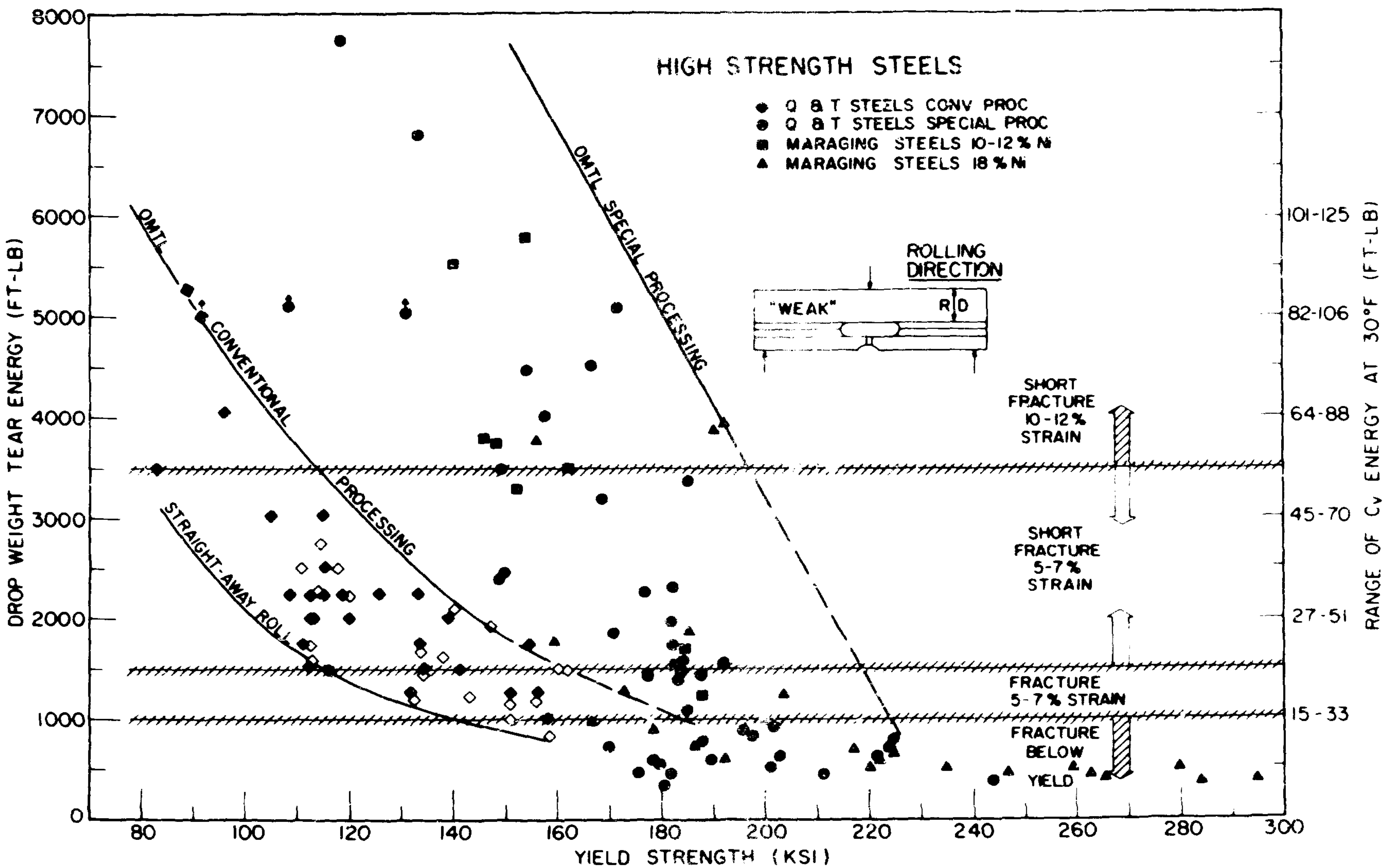

Fig. 11 - Comparison of drop-weight tear and yield strength relationships for specially processed steel plates with those of previously tested steels. The correlations with performance in the explosion tear test in the presence of 2-in. flaws are indicated by cross-hatched lines and the legend at the lower right side of the illustration.

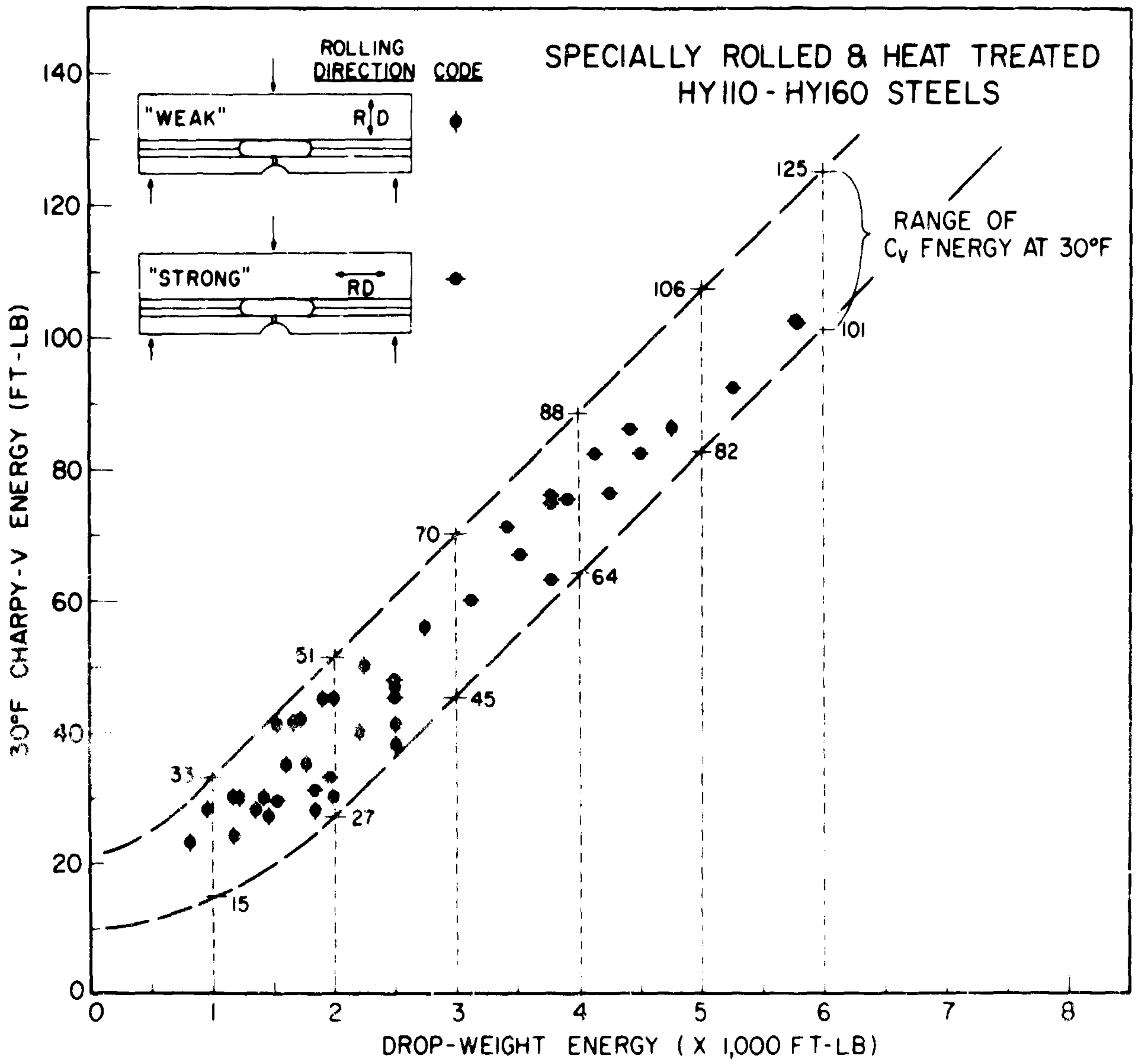

Fig. 12 - Correlation of drop-weight tear test energy absorption with 30°F Charpy V test energy values

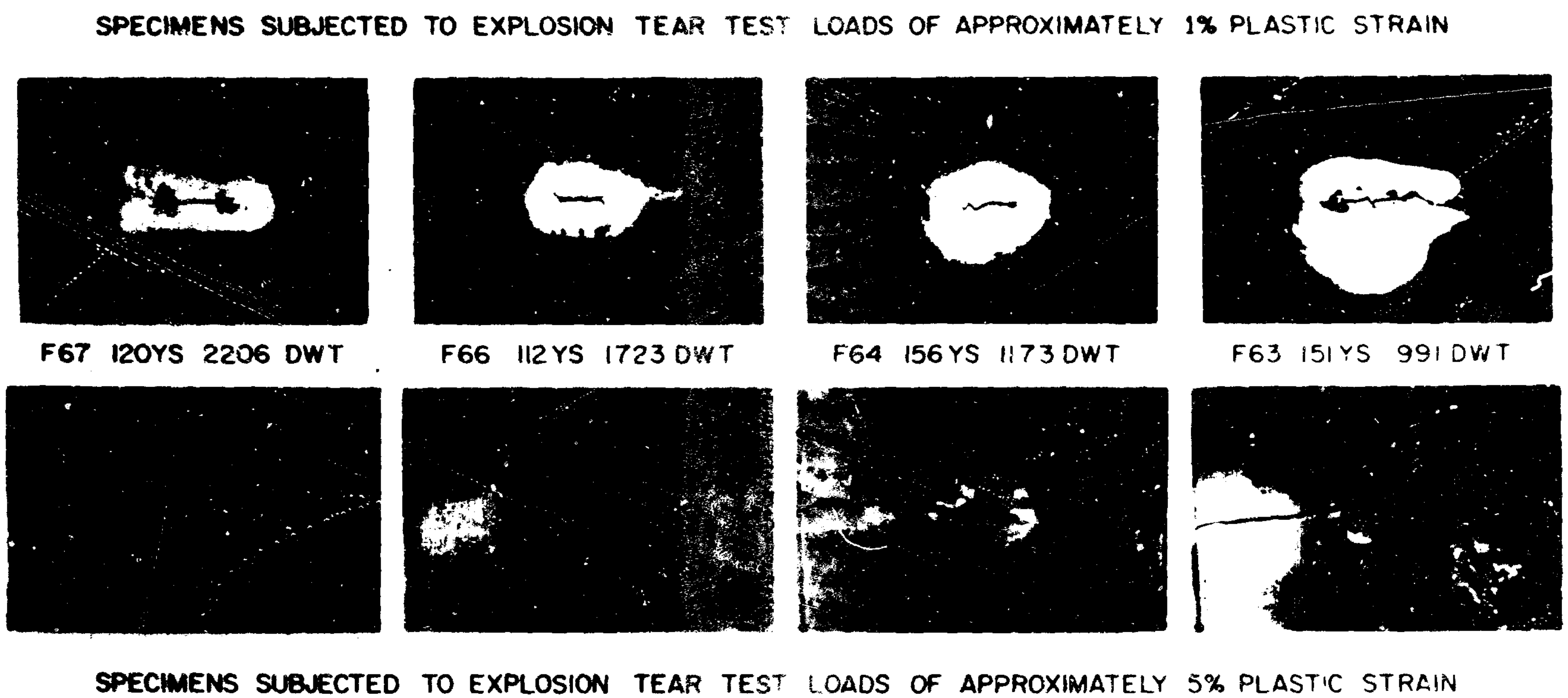

Fig. 13 - Explosion tear test specimens of specially processed steel plates illustrating increased change in fracture toughness with decreasing drop-weight tear test energies

F67 120YS 2206DWT

F66 112YS 1723DWT

Fig. 14 - Two explosion tear test specimens from steels of Fig. 13 illustrating increased tear lengths resulting from 8% strain

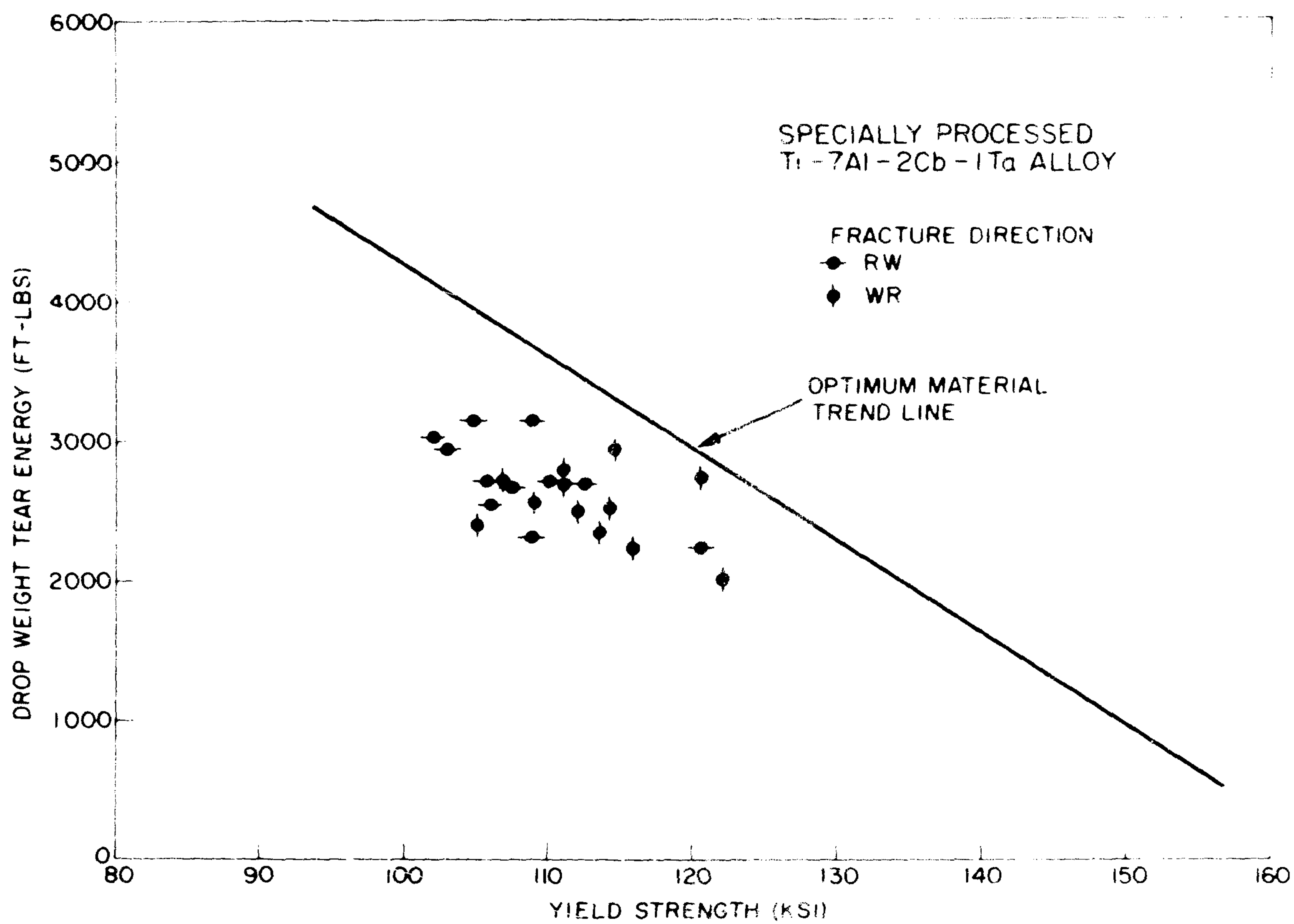

Fig. 15 - Comparison of drop-weight tear test energy values and yield strength of the specially processed Ti-7Al-2Cb-1 Ta alloy with the optimum materials trend line established for 1-in. thick titanium alloy plate

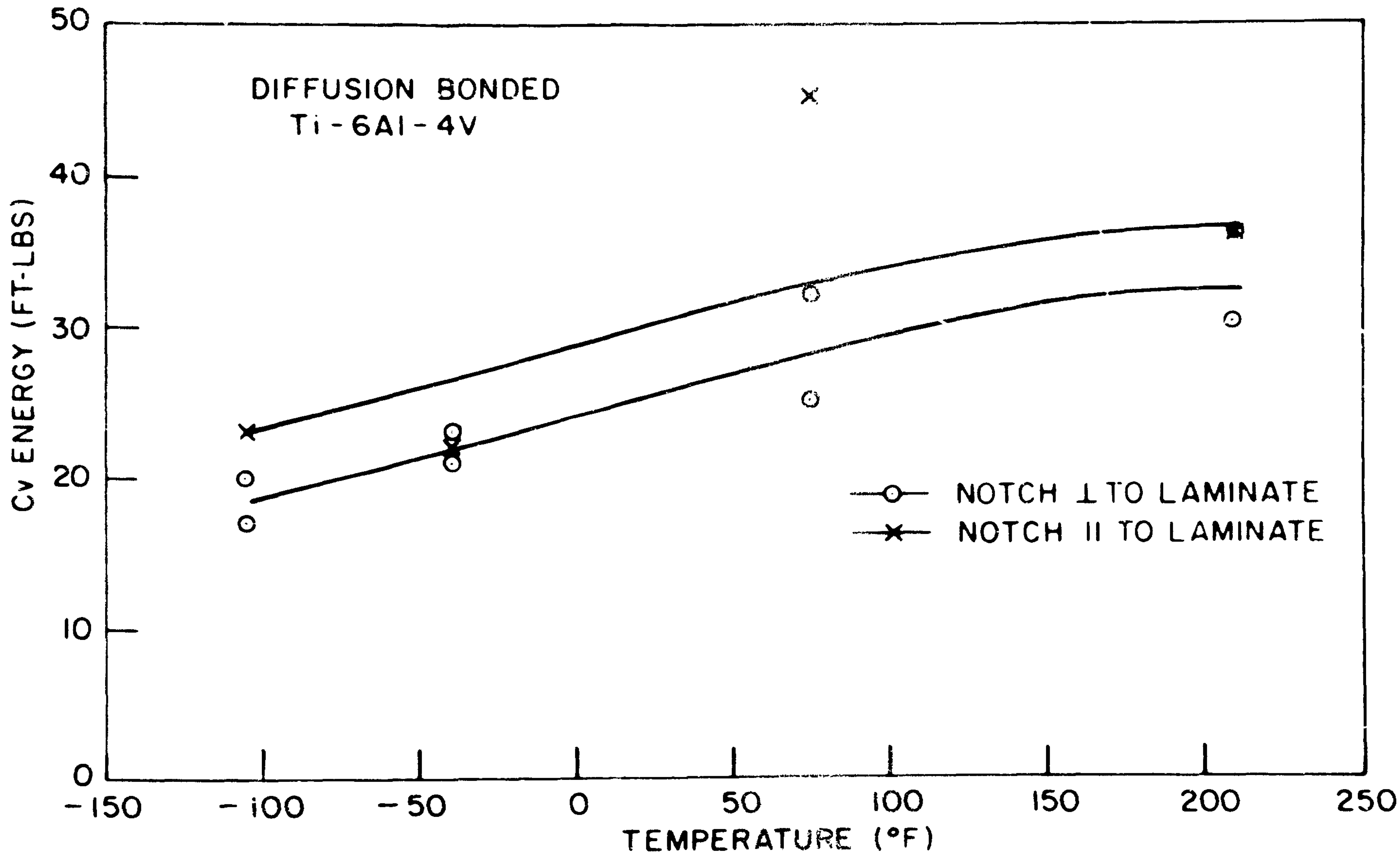

Fig. 16 - Fracture toughness of diffusion-bonded Ti-6Al-4V plate material as measured by the Charpy V-notch impact test

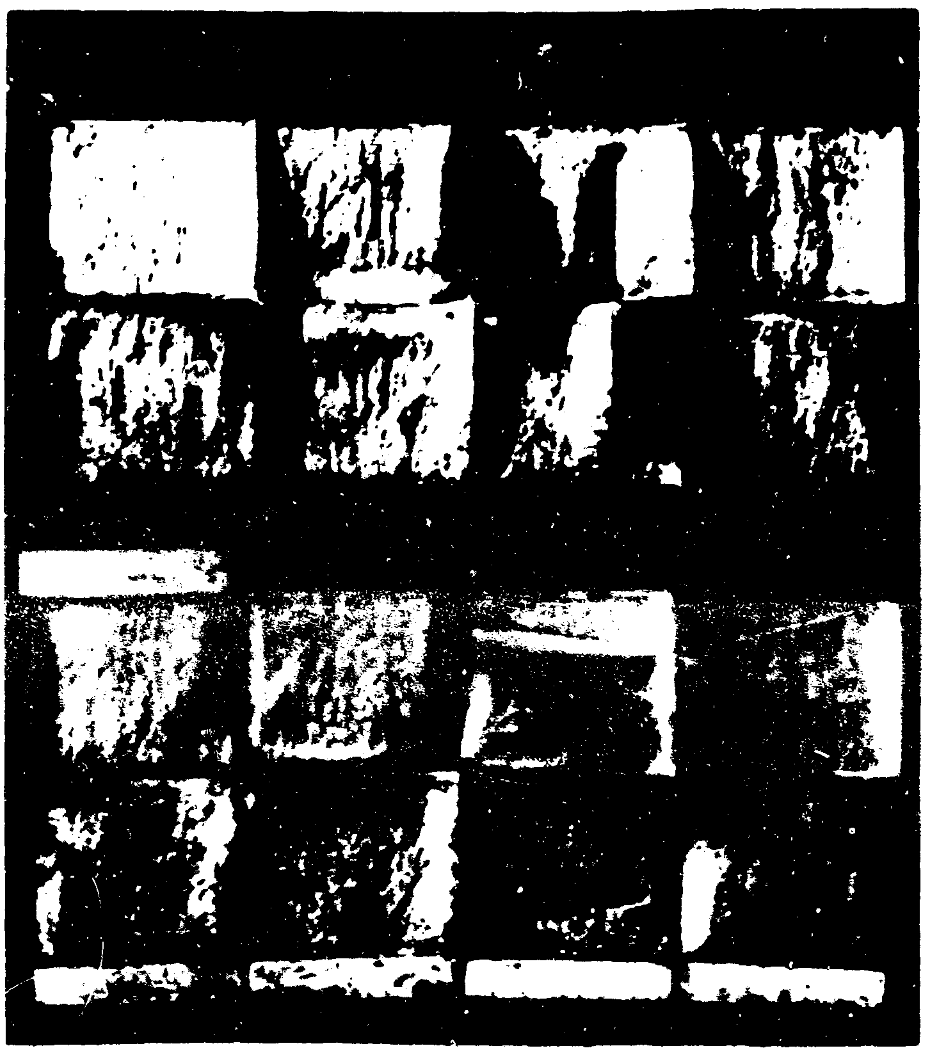

Fig. 17 - Fracture surface appearance of diffusion-bonded Ti-6Al-4V plate material. Fracture surfaces generated at different temperatures in the Charpy V-notch impact test.

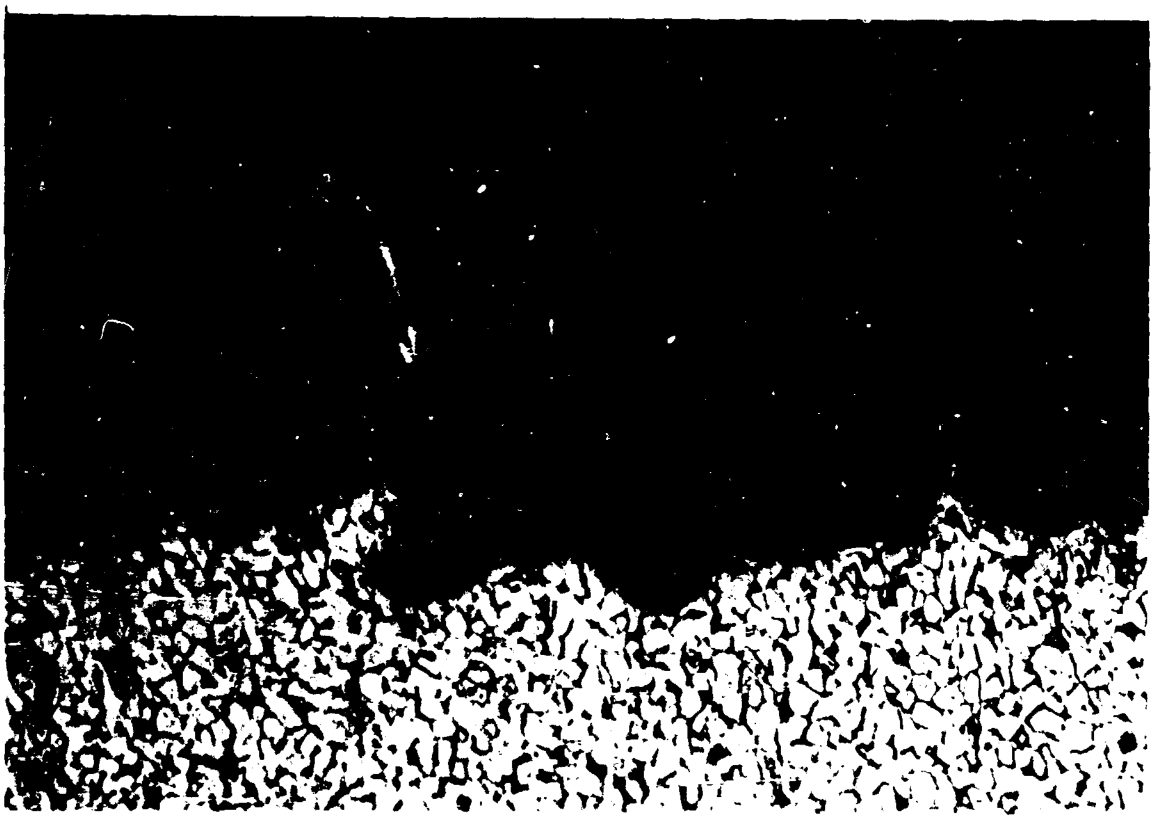

Fig. 18 - Fracture surface of diffusion-bonded Ti-6Al-4V plate tested in the Charpy V-notch impact test with the notch parallel to the layers. Fracture propagated from left to right. Etchant: 3HF, $6HNO_3$, $90H_2O$. Magnification: 250X.

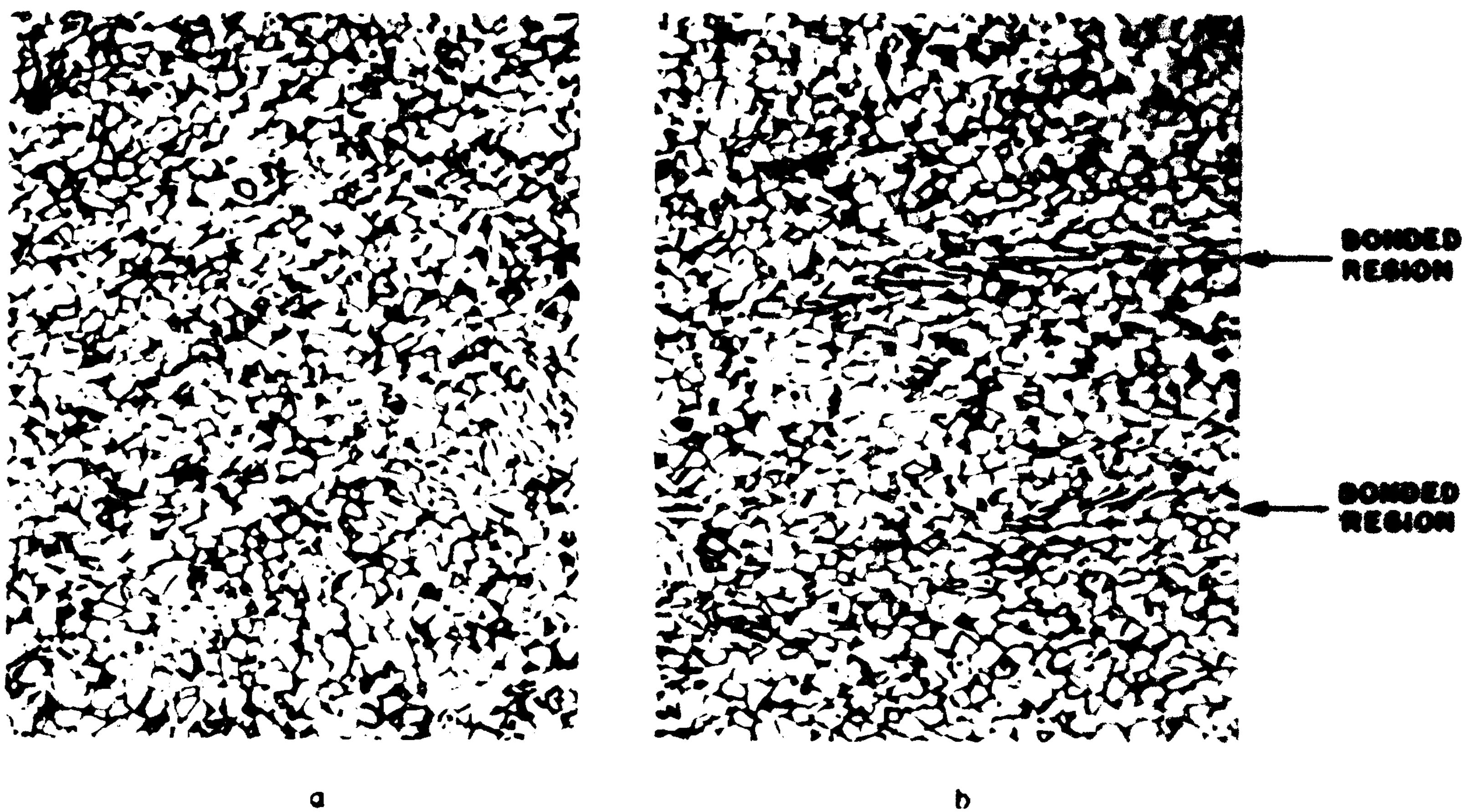

Fig. 19 - Photomicrograph of diffusion-bonded Ti-6Al-4V plate material showing (a) equiaxed $\alpha + \beta$ structure and no clear evidence of bonded regions, and (b) equiaxed $\alpha + \beta$ structure and slightly elongated α grains in bonded regions. Etchant: 3HF, $6HNO_3$, $90H_2O$. Magnification: 250X.

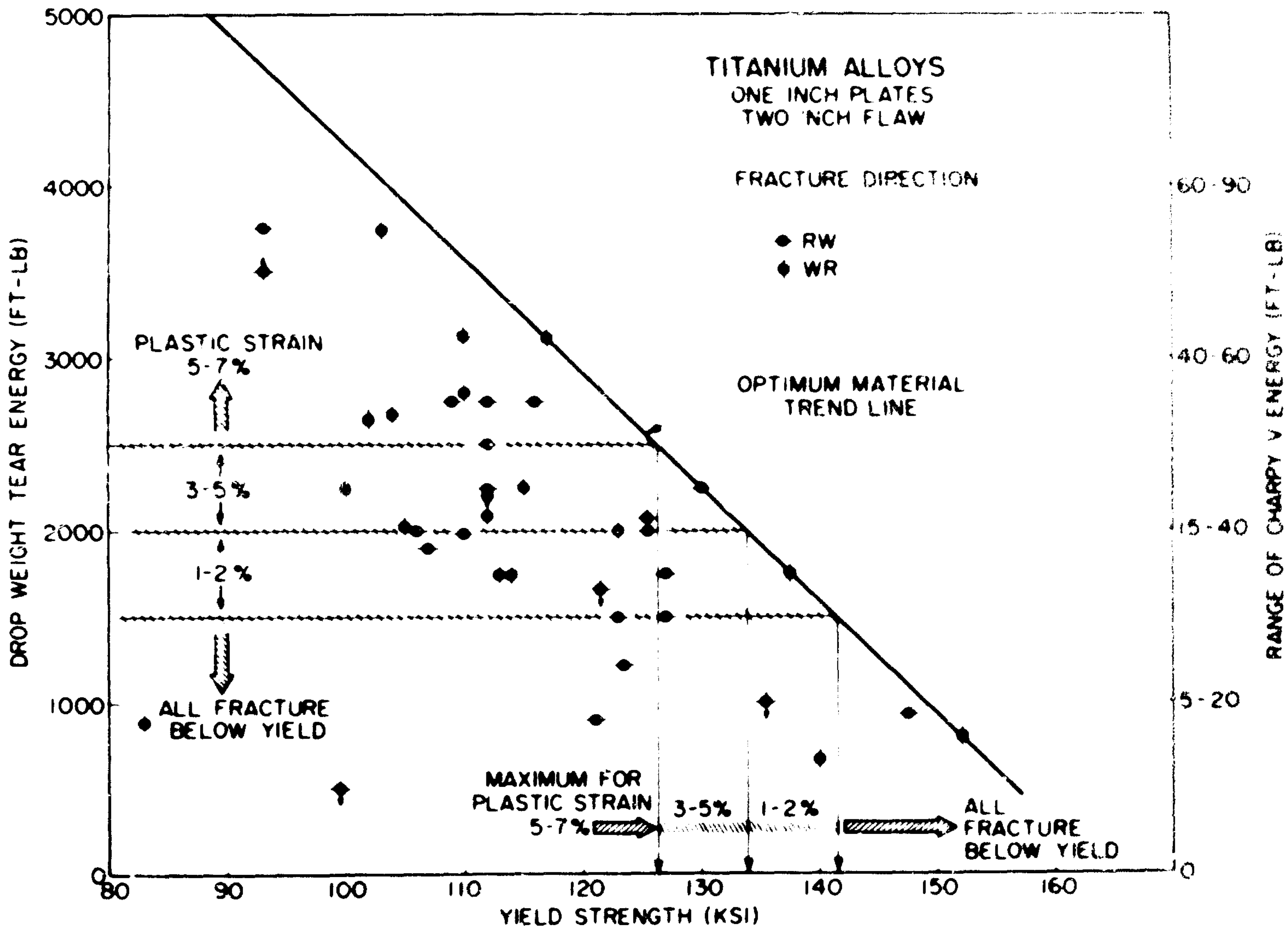

Fig. 20 - Correlation of drop-weight tear test, Charpy V, explosion tear test, and yield strength results for 1-in. thick titanium alloy plates. Optimum materials trend line indicates highest level of strength for any given level of toughness.

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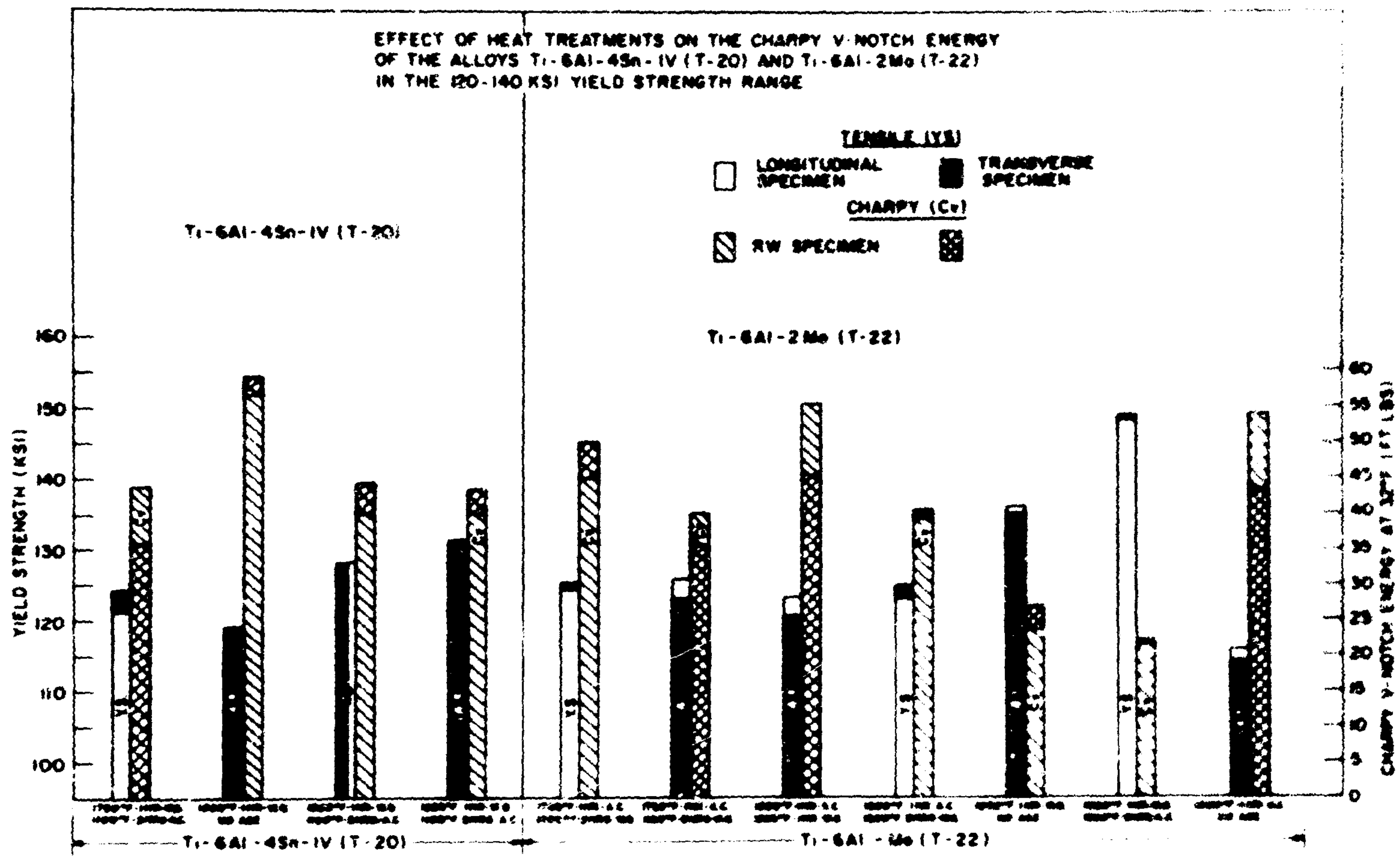

Fig. 21 - Effect of heat treatments on the Charpy V-notch impact energy of the alloys Ti-6Al-4Sn-1V (T-20) and Ti-6Al-2Mo (T-22) in the 120-140 ksi yield strength range

Security Classification

DOCUMENT CONTROL DATA - R&D

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1. ORIGINATING ACTIVITY (Corporate author) U.S. Naval Research Laboratory Washington, D.C. - 20390	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

METALLURGICAL CHARACTERISTICS OF HIGH STRENGTH STRUCTURAL MATERIALS (Fifth Quarterly Report)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

An interim report on one phase of the problem.

5. AUTHOR(S) (Last name, first name, initial)

Crooker, T.W.	Judy, R.W.	Puzak, P.P.	Howe, D.G.
Morey, R.E.	Freed, C.N.	Lloyd, K.B.	Pellini, W.S.
Lange, E.A.	Goode, R.J.	Huber, R.W.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1964	59	9

8a. CONTRACT OR GRANT NO. 63M01-05, M01-18, and M03-01, 63R05-24A b. PROJECT NO. SR 007-01-01,0850,0854, 0856 RR 007-01-46-5420 c. SR 007-01-02-0704 d. RR 007-01-46-5405, WW041	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6196 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Unlimited availability

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Dept. of the Navy (Bureau of Ships and Office of Naval Research)

13. ABSTRACT

A progress report covering research studies in high strength hull structural materials, conducted in the period May 1964 to August 1964, is presented. These studies include the development of preliminary relationships of flaw size and stress for fracture of quenched and tempered steels, maraging steels, titanium, and aluminum. Preliminary information has also been developed in the relationship between the notch tensile test and the drop-weight tear test for aluminum alloys. The effects of corrosion environments on the crack rate propagation in HY-80 to HY-150 quenched and tempered steels have been examined under low cycle fatigue conditions. Preliminary results on a study of the directionality effects due to cross-rolling on the fracture toughness of quenched and tempered steels are presented. The fracture toughness properties of specially processed Ti-7Al-2Cb-1Ta, diffusion-bonded Ti-6Al-4V, forged Ti-5Al-2.5Sn, and titanium weldments are reported. The results of heat-treatment studies for improving the fracture toughness at specific levels of yield strength are reported for some titanium alloys.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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