SSC-244

FRACTURE-CONTROL GUIDELINES FOR WELDED STEEL SHIP HULLS

SHIP STRUCTURE COMMITTEE

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High-strength structural steels that are extremely tough at ship service temperatures are available. However, because of economic considerations, the ship designer generally does not want to select a structural steel that has more toughness than is required for a particular application. The problem of "how much toughness is sufficient" is a difficult question to answer, and establishing performance criteria has long been a problem for ship designers.

With this question in mind, the Ship Structure Committee undertook a program to develop and confirm rational toughness criteria for ship steels.

The first project in this program has been to review and synthesize a number of test methods and data on various steels to propose a fracture criteria. The validity and applicability of this criteria will be tested by subsequent projects. Modifications will be developed if they are indicated.

The enclosed report contains the results of this work. Comments on this report or suggestions for other projects in the ship structure area will be welcomed.

W.M. BENKERT
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

FINAL REPORT

on

Project SR-202, "Fracture Criteria"

FRACTURE-CONTROL GUIDELINES FOR WELDED STEEL SHIP HULLS

by

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under

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ABSTRACT

This report presents the results of a study of fracture-control guidelines for welded steel ship hulls. The main body of the report is preceded by a Synopsis which summarizes the rationale behind the fracture-control guidelines for welded ship hulls and emphasizes the importance of implementing an overall fracture-control plan that requires a specific level of material toughness and the use of crack arresters. This Synopsis is directed toward those persons who are responsible for implementing fracture-control guidelines in welded steel ship hulls but who may not be concerned with the details involved in developing them.

The Report provides a comprehensive toughness criteria for welded ship hulls that can be used for steels of all strength levels. Because of the fact that stress concentrations are always present in large complex welded structures and therefore high stresses as well as discontinuities or flaws will be present in welded ship hulls, primary emphasis in the proposed fracture-control guidelines is placed on the use of steels with moderate levels of notch-toughness and on the use of properly designed crack arresters. In general, concepts of fracture mechanics are used to develop the material toughness level that is required for fail-safe operation of welded ship hulls. This toughness level is estimated to be a K_{ID}/σ_{yD} level of 0.9 at 32°F (0°C), where K_{ID} is the critical material toughness under conditions of dynamic loading and σ_{yD} is the yield strength of the material under the same dynamic loading. Because this level of toughness cannot be measured directly using current fracture mechanics tests, these requirements are established in terms of the NDT (nil-ductility transition) temperature and DT (dynamic tear) test values for base metal, weld metal, and heat-affected-zone materials used in primary load-carrying members. Emphasis is also placed on the proper spacing and proportioning of crack arresters fabricated from steels with very high levels of notch toughness to provide a fail-safe design.

Although the criteria presented in this report are primarily material specifications, the importance of proper design (avoiding details that lead to stress concentrations) and proper fabrication (good quality welding and inspection) is emphasized.

In general, the results of this investigation have developed material-toughness requirements for ship steels of all strength levels which, in combination with properly designed crack arresters, should result in rational fracture-control guidelines that will minimize the probability of brittle fractures in welded ship hulls consistent with economic realities.

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NOTES

SYNOPSIS

During the past 25 years, considerable research on the problem of brittle fracture has helped to identify the factors that contribute to brittle fractures in welded ship hulls. As a result of this research, various changes in design, fabrication, and materials have been made so that the incidence of brittle fractures in welded ship hulls has been reduced considerably. Nonetheless, brittle fractures still occur in welded ship hulls fabricated with ordinary-strength steels and as the use of higher strength steels increases, there is a definite concern that brittle fractures may occur in these steels also. Currently there are no specific fracture-control guidelines or toughness criteria available for the practicing naval architect to follow in the design of welded ship hulls. Therefore, an investigation was conducted using concepts of fracture mechanics to establish rational fracture-control guidelines for the selection of steels used in welded ship hulls.

As expected, the results of this investigation show that numerous factors (e.g., service temperature, residual stresses, design, welding, material toughness, fatigue, etc.) can contribute to brittle fractures in welded structures such as ship hulls. However, there are three primary factors that control the susceptibility of a welded structure to brittle fracture. These three primary factors are:

1) Material toughness at the particular service temperature, loading rate, and plate thickness;

2) Size of flaw at the point of fracture initiation regardless of whether the flaw is an arc strike or a large fatigue crack;

3) Stress level, including residual stress.

All three factors can be interrelated by concepts of fracture mechanics to predict the susceptibility of a structure to brittle fracture. If the particular combination of stress and flaw size in a structure (which can be described by K_I, the stress intensity factor) reaches the K_c level (the critical stress intensity factor for a particular specimen thickness, temperature and loading rate) fracture can occur. Thus, there are many combinations of stress and flaw size that may cause fracture in a structure which is fabricated from a steel weldment having a particular value of K_c at the service temperature, loading rate, and plate thickness. Conversely, there are many combinations of stress and flaw size that cannot cause fracture of the same steel weldment.

Welded ship hulls can be subjected to dynamic loads of yield point magnitude when the effects of residual stresses and strain concentrations are considered. Furthermore, the probability of large (through-thickness) undetected flaws being present at some time during the life of welded ship hulls exists because of current limitations in fabrication practice and inspection at shipyards. Because welded ship hulls can be subjected to high stresses and can have large flaws, the primary method of fracture control should be to use steels with high levels of notch toughness. Consequently, to prevent the occurrence of brittle fractures in welded ship hulls, the steels and weldments used in conventional ship hull fabrication should exhibit a high level of notch toughness at 32°F (0°C). (A statistical study of the minimum service temperature of conventional ships indicates that 32°F (0°C) is a reasonable minimum service temperature). Translating the above notch-toughness requirement into specific test values would indicate that the NDT (nil-ductility transition) temperature of steels and weldments should be very low and the resistance to fracture at 32°F (0°C) should be quite high (essentially fully plastic) so that any crack growth in a ship hull subjected to dynamic loading of yield point

magnitude at 32°F (0°C) is ductile rather than brittle. However, this is an economically severe material requirement that does not recognize the contribution of good design and fabrication to the prevention of brittle fracture in welded ship hulls and is not necessary.

To prevent brittle fractures of complex welded structures, the designer has several alternatives as follows: 1) use a material that will not fracture in a brittle manner at the service temperature (such as described above), 2) provide multiple-load fracture paths (which may not be possible for welded ship hulls) so that a single fracture cannot lead to complete failure, or 3) use a fail-safe philosophy that provides for crack arresters to arrest propagating brittle fractures should any initiate. The fundamental problem in a realistic fracture-control plan for welded ship hulls is to optimize the above performance criteria with cost considerations so that the probability of complete structural failure in welded ship hulls is very low. In that sense, the toughness criterion proposed in this report is based on the third alternative, which is an attempt to optimize satisfactory performance with reasonable cost, following a fail-safe philosophy.

The need for such fracture-control guidelines can be established by a brief review of the problem of brittle fractures in welded steel hulls:

1) As has been well documented during the past 30 years, the definite possibility of brittle fracture in welded ship hulls exists because welded ship hulls are complex structures that can be subjected to local dynamic loading of yield point magnitude at temperatures as low as 32°F (0°C).

2) Because of current limitations in fabrication practice and inspection at shipyards, a large probability exists that undetected flaws will be present at some time during the life of welded ship hulls. Even with improvements in control of welding quality during fabrication, some discontinuities can still be present prior to the service life of the structure and these discontinuities may grow in size by fatigue during the life of the structure. Thus, it must be assumed that flaws are present in all welded ship hulls.

3) The naval architect generally does not have absolute control over the fabrication of a welded ship hull. Thus, he should establish material and design controls during the design process that are adequate to prevent the occurrence of brittle fractures in welded ship hulls. Although the designer tries to avoid details that act as stress raisers, this is an impossible task in large complex welded structures. Hence, the emphasis in this fracture-control plan is on the choice of proper materials (toughness specifications for steels and weldments) and design (proper use of crack arresters), even though quality fabrication and inspection of welds are extremely important.

4) Although specifying only the metallurgy and manufacturing process, including composition, deoxidization practice, heat treatment, etc., has been used as one method of controlling the level of notch toughness in a steel, the only method of measuring the actual toughness of a steel is a toughness test. A direct measure of toughness is better for the user because he is ultimately concerned with the performance of the steel or weldment, and this performance can best be revealed by a notch-toughness test. Also, a specification based on a notch-toughness test would appear to be more equitable for steelmakers in that it leaves them some latitude to adopt the process best suited to their particular operation for satisfying the toughness requirement. However, a toughness test does have the disadvantage in that a test value pertains to only one location in a plate whereas <u>proper</u> processing control <u>should</u> pertain

to the entire plate. However, because this may not always be true, a toughness test is no less effective as an indication of the service performance of the entire plate.

5) Because of the difficulties in conducting a toughness test on a composite weldment, notch-toughness specimens should be taken from each of the following regions: base metal, weld metal, and heat-affected zone. While there is no "one" heat-affected zone, an average measure of toughness can be obtained by notching the test specimen so that the tip of the notch is approximately at the center of the heat-affected zone.

At the minimum service temperature the materials used in primary load-carrying members in the main-stress regions must exhibit a satisfactory level of notch toughness. Using concepts of fracture mechanics, this satisfactory level of toughness is estimated to be a K_{ID}/σ_{yD} level of 0.9 at 32°F (0°C). (K_{ID} is the critical material toughness under conditions of impact loading and σ_{yD} is the yield strength of a material under the same impact loading conditions. The K_{ID}/σ_{yD} ratio is a relative index of material toughness that is proportional to the critical crack size for unstable fracture.) This level of toughness is above the limits of dynamic plane-strain behavior and cannot be measured directly using current fracture-mechanics tests. However, this level of toughness can be achieved by specifying that base metal, weld metal, and heat-affected zone material satisfy the following requirements:

a) Maximum NDT temperature be 0°F (-18°C)

b) Minimum dynamic tear-test (DT) energy measured at 75°F (24°C) for each yield strength level be as follows:

ACTUAL STATIC YIELD STRENGTH		ABSORBED ENERGY REQUIREMENTS FOR 5/8-inch (15.9 mm) thick DT SPECIMENS	
ksi	MN/m²	ft-lb.	J
40	276	250	339
50	345	290	393
60	414	335	454
70	483	375	508
80	552	415	563
90	621	460	624
100	689	500	678

The reason for using the NDT specimen is to insure that the transition from brittle to ductile behavior begins below the minimum service temperature. The reason for using the DT specimen is to closely approximate conditions in a welded ship hull that may lead to fracture, i.e., sharp cracks subjected to dynamic loading.

Because of the wide-spread use of CVN impact test results, equivalent CVN values corresponding to the required DT values were determined using various empirical correlations. These equivalent CVN values (at 32°F, 0°C) range from 20 to 44 ft-lb (27 to 60 J) for steels and weldments having yield strengths of 40 to 100 ksi (276 to 689 MN/m²) respectively.

To insure that the resistance to fracture of the steels and weldments whose NDT is 0°F (-18°C) (or lower) is actually increasing at 32°F (0°C) (compared with 0°F, -18°C), the DT test is to be conducted at 75°F (24°C) (room temperature). This temperature (75°F, 24°C) is chosen rather than 32°F (0°C) because it is difficult to measure the change in resistance to fracture reliably over a 32°F interval (18°C). This requirement should assure the designer that the material is exhibiting some reasonable level of elastic-plastic behavior at service temperatures.

At the minimum service temperature the materials used in primary load-carrying members in secondary stress regions must also exhibit a satisfactory level of notch toughness. Stresses in these members are less than one-half the maximum value in the main stress regions and accordingly the required K_{ID}/σ_{yD} level is 0.6 at 32°F (0°C). This level of toughness is just within the limits of dynamic plane-strain behavior and is defined by the NDT temperature. This requirement can be achieved by specifying that base metal, weld metal, and heat-affected zone material satisfy the single requirement that the maximum NDT temperature be 20°F (-7°C). This criterion is less stringent than that developed for main stress members and does not require the use of an auxiliary test procedure to evaluate transition behavior. Therefore, the NDT test is conducted at 20°F (-7°C) rather than 32°F (0°C) to insure that $K_{ID}/\sigma_{yD} \geq 0.6$ at 32°F (0°C).

As stated previously, the above material specifications will not guarantee the complete absence of brittle fractures in welded ship hulls. Therefore, a fail-safe philosophy must also incorporate properly designed crack arresters fabricated from steels with very high levels of notch toughness. To be properly designed, crack arresters must satisfy three criteria:

1) Proper location within the hull cross-section;

2) Proper detail;

3) Proper level of steel toughness. This level of toughness should be obtained using a DT specimen tested at 32°F (0°C). The specified values are as follows:

ACTUAL STATIC YIELD STRENGTH		ABSORBED ENERGY REQUIREMENTS FOR 5/8-inch (15.9 mm) THICK DT SPECIMENS	
ksi	MN/m^2	ft-lb.	J
40	276	600	813
50	345	635	861
60	414	670	908
70	483	700	949
80	552	735	997
90	621	770	1044
100	689	800	1085

The above toughness criteria, based primarily on material and design considerations, do not alter the necessity of good quality welding and inspection. It is possible that actual weld metal in the welded hull structure (which is not tested) has toughness values below those of the welded test plates that are tested. Obviously this condition violates the required fracture criterion, even though it is not detected. In addition to contributing to brittle fractures, poor quality welding also can lead to operation problems and repairs that reduce the efficiency of operation. Thus, proper welding procedures must be maintained to obtain sound weldments.

Although the *emphasis* is to develop toughness criteria for welded ship hulls, this report also describes the history of specification development for toughness of ship hull steels. The general service conditions of ship hulls are discussed and the rationale for a specific fracture-control plan including criteria for material selection and crack arresters is developed. The criteria are compared with test results on ship steels published in the literature, as well as analyses of actual ship failures. Preliminary analysis indicates that existing ABS Grade C normalized, CS, D, and E steels should *easily meet* this specification although this observation must be verified experimentally. Many plates of ABS Grades B and C steels should also meet this specification. Limited test results available for 100 ksi (689 MN/m^2) yield strength steels indicate that they are capable of meeting this requirement.

A preliminary analysis of the economic aspects of meeting the proposed toughness requirements is presented which indicates that the additional cost of the proposed toughness criterion should be a very small percentage of the total cost of any particular ship. In view of the fact that the proposed toughness criterion should lead to safer ships that are more resistant to catastrophic brittle fractures, this increase in cost would appear to be justified.

TECHNICAL REPORT

I. GENERAL PROBLEM OF BRITTLE FRACTURE IN SHIPS

Although welded ship failures have occurred since the early 1900's, it was not until the large number of World War II ship failures that the problem was fully appreciated[1]. Of the approximately 5,000 merchant ships built during World War II, over 1,000 had developed cracks of considerable size by 1946. Between 1942 and 1952, more than 200 ships had sustained fractures classified as serious, and at least nine T-2 tankers and seven Liberty ships had broken completely in two as a result of brittle fractures. The majority of fractures in the Liberty ships started at square hatch corners or square cutouts at the top of the sheerstrake. Design changes involving rounding and strengthening of the hatch corners, removing square cutouts in the sheerstrake, and adding riveted crack arresters in various locations led to immediate reductions in the incidence of failures [2]. Most of the fractures in the T-2 tankers originated in defects in bottom shell butt welds. The use of crack arresters and improved workmanship reduced the incidence of failures in these vessels.

Studies indicated that in addition to design faults, steel quality also was a primary factor that contributed to brittle fracture in welded ship hulls[3]. Therefore, in 1947, the American Bureau of Shipping introduced restrictions on the chemical composition of steels and in 1949, Lloyds Register stated that "when the main structure of a ship is intended to be wholly or partially welded, the committee may require parts of primary structural importance to be steel, the properties and process of manufacture of which have been specially approved for this purpose [4]."

In spite of design improvements, the increased use of crack arresters, improvements in quality of workmanship, and restrictions on the chemical composition of ship steels during the later 1940's, brittle fractures still occurred in ships in the early 1950's[5]. Between 1951 and 1953, two comparatively new all-welded cargo ships and a transversely framed welded tanker broke in two. In the winter of 1954, a longitudinally framed welded tanker constructed of improved steel quality using up-to-date concepts of good design and welding quality broke in two[6].

During the 1950's, seven Classification Societies responsible for the classification of ships (American Bureau of Shipping, Bureau Veritas, Germanischer Lloyd, Lloyd's Register of Shipping, Nipon Kaiji Kyokai, Det Norske Veritas, and Registro Italianno Navale) held numerous meetings and in 1959 published the Unified Requirements for Ship Steels[4]. These requirements specified various manufacturing methods, chemical composition, or Charpy V-Notch impact requirements for five grades of steel. A general description of these unified requirements is presented in Appendix **A**.

Since the late 1950's (although the actual number has been low) brittle fractures have still occurred in ships as is indicated by Boyd's description of ten such failures between 1960 and 1965 and a number of unpublished reports of brittle fractures in welded ships since 1965[7].

Therefore, although it has been approximately 30 years since the problem of brittle fracture in welded ship hulls was first recognized as a significant problem for the ship-building industry, brittle fractures still occur in ships. While it is true that during this time considerable research has led to various changes in design, fabrication, and materials so that the incidence of brittle fractures in welded ship hulls has been reduced markedly[8], nonetheless, brittle fractures continue to occur in welded ship hulls fabricated with ordinary-strength steels. With the use of higher-strength steels, there is a definite concern that brittle fractures may occur in these steels also.

Currently there are no specific fracture-control guidelines or overall toughness criteria available for the practicing naval architect to specify in designing welded steel ship hulls of all strength levels. Therefore, the purpose of this report is to provide rational fracture-control guidelines consistent with economic realities which, when implemented, will minimize the probability of brittle fractures in welded ship hulls. Although the fact is rarely stated, the basis of structural design in all large complex welded structures is an attempt to optimize the desired performance requirements relative to cost considerations (materials, design, fabrication) so that the probability of failure (and its economic consequences) is low.

For reasons developed in the following sections, the guidelines are primarily material oriented. This does not relieve the naval architect of responsibility for good ship design, but recognizes the fundamental importance of using good quality structural steels in large complex welded structures.

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II. GENERAL PROBLEM OF BRITTLE FRACTURE IN WELDED STRUCTURES

An overwhelming amount of research on brittle fracture in welded steel structures has shown that numerous factors (e.g., service temperature, material toughness, design, welding, residual stresses, fatigue, constraint, etc.) can contribute to brittle fractures in large welded structures such as ship hulls[5-16]. However, the recent development of fracture mechanics[16-20] has shown that there are three primary factors that control the susceptibility of a structure to brittle fracture. These three primary factors are:

1) Material Toughness (K_c, K_{Ic}, K_{ID})

Material toughness can be defined as the ability to deform plastically in the presence of a notch and can be described in terms of the static critical stress-intensity factor under conditions of plane stress (K_c) or plane strain (K_{Ic}). K_{ID} is a widely accepted measure of the critical material toughness under conditions of maximum constraint (plane strain) and impact-loading. In addition to metallurgical factors such as composition and heat treatment, the notch toughness of a steel also depends on the application temperature, loading rate, and constraint (state-of-stress) ahead of the notch as discussed in Appendix B.

2) Flaw Size (a)

Brittle fractures initiate from flaws or discontinuities of various kinds. These discontinuities can vary from extremely small cracks within a weld arc strike, (as was the case in the brittle fracture of a T-2 tanker during World War II) to much larger weld or fatigue cracks. Complex welded structures are not fabricated without discontinuities (porosity, lack of fusion, toe cracks, mismatch, etc.), although good fabrication practice and inspection can minimize the original size and number of flaws. Thus, these discontinuities will be present in all welded ship hull structures even after all inspections and weld repairs are finished, Furthermore, even though only "small" flaws may be present initially, fatigue stressing can cause them to enlarge, possibly to a critical size.

3) Stress Level (σ)

Tensile stresses, (nominal, residual, or both) are necessary for brittle fractures to occur. The stresses in ship hulls are difficult to analyze because ships are complex structures, because of the complexity of the dynamic loading, and because of the stress concentrations present throughout a ship which increase the local stress levels. The probability of critical regions in a welded ship hull being subjected to dynamic yield stress loading (σ_{yD}) is fairly high, particularly in regions of stress concentrations where residual stresses from welding may be present.

All three of these factors must be present for a brittle fracture to occur in structures. All other factors such as temperature, loading rate, residual stresses, etc. merely affect the above three primary factors.

Engineers have known these facts for many years and have reduced the susceptibility of structures to brittle fractures by applying these concepts to their structures qualitatively. That is, good design (lower stress levels by minimizing discontinuities) and fabrication practices (decreased flaw size because of proper welding control), as well as the use of materials with good notch-toughness levels (e.g., as measured with a Charpy V-notch impact test) will and have minimized the probability of brittle fractures in structures. However, the engineer has not had specified design guidelines to evaluate the relative performance and economic tradeoffs between design, fabrication and materials in a quantitative manner.

The recent development of fracture mechanics as an applied science has shown that all three of the above factors can be interrelated to predict (or to design against) the susceptibility of a welded structure to brittle fracture. Fracture mechanics is a method of characterizing fracture behavior in terms of structural parameters familiar to the engineer, namely, stress and flaw size. Fracture mechanics is based on stress analysis and thus does not depend on the use of empirical correlations to translate laboratory results into practical design information. Fracture mechanics is based on the fact that the stress distribution ahead of a sharp crack can be characterized in terms of a single parameter K_I, the stress-intensity factor, having units of ksi $\sqrt{\text{inch}}$ ($MN/m^{3/2}$). Various specimen geometries have been analyzed, and theoretical expressions for K_I in terms of applied stress and flaw size have been developed. Three examples are presented in Figure 1. In all cases, K_I is a function of the nominal stress and the square root of the flaw size. By knowing the critical value of K_I at failure, K_c, for a given steel of a particular thickness and at a specific temperature and loading rate, the designer can determine flaw sizes that can be tolerated in structural members for a given design stress level. Conversely, he can determine the design stress level that can be safely used for a flaw size that may be present in a structure.

This general relation is presented in Figure 2 which shows the relationship between material toughness (K_c), nominal stress (σ), and flaw size (a). If a particular combination of stress and flaw size in a structure (K_I) reaches the K_c level, fracture can occur. Thus there are many combinations of stress and flaw size (e.g., σ_f and a_f) that may cause fracture in a structure that is fabricated from a steel having a particular value of K_c at a particular service temperature, loading rate, and plate thickness. Conversely, there are many combinations of stress and flaw size (e.g., σ_o and a_o) that will not cause failure of a particular steel. A brief development and numerical example of the concepts of fracture mechanics is presented in Appendix B.

At this point, it should be emphasized that (fortunately) the K_c levels for most steels used in ship hulls are so high that they cannot be measured directly using existing ASTM standardized test methods. Thus, although concepts of fracture mechanics can be used to develop fracture-control guidelines and desirable toughness levels, the state of the art is such that actual K_c values cannot be measured for most ship hull steels at service temperatures. As will be described later, this fact dictates that auxiliary test methods must be used to insure that ship hull materials perform satisfactorily under service conditions.

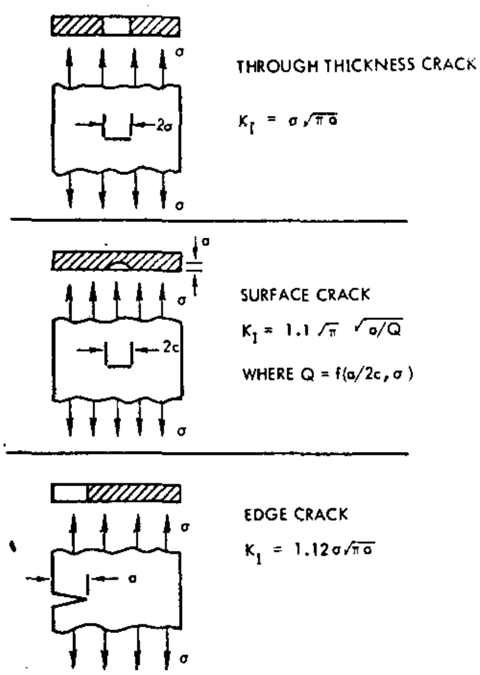

Fig. 1. K_I Values for Various Crack Geometries

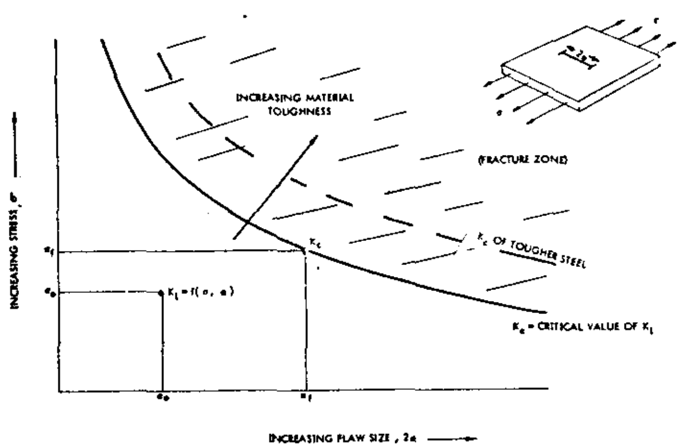

Fig. 2. Schematic Relation Between Stress, Flaw Size, and Material Toughness

III. DEVELOPMENT OF SPECIFIC FRACTURE-CONTROL CRITERIA FOR WELDED STEEL SHIP HULLS

General

In the previous chapter, concepts of fracture mechanics were introduced as the best method for developing fracture-control guidelines for welded steel structures. In this chapter, fracture-mechanics concepts are used to develop specific criteria to prevent catastrophic fractures in welded steel ship hulls. Concepts of fracture mechanics are emphasized rather than linear elastic fracture mechanics used in existing ASTM test methods because steels for ship hulls should have higher toughness levels than can currently be measured using ASTM specification test methods.

Service Conditions

A review of current practice of designing ship hulls indicates that the actual loadings are not well known[21,22]. Therefore, general rules of proportioning the cross section of ships have been developed, primarily on the basis of experience. Recent developments in analytical techniques and actual measurements of ship loadings have led to improvements in the understanding of the structural behavior of ships[23]. However, the design of ship hulls is primarily an empirical proportioning based on satisfactory past experience rather than a systematic analytical design and therefore calculated design stresses for specific sea states are rarely found.

Strain measurements on actual ships have indicated that the maximum vertical wave-bending-stress excursion (peak-to-trough) ever measured was about 24 ksi (165 MN/m^2). Also the maximum bending stress for slender cargo liners is about 10 ksi (69 MN/m^2) and for bigger ships such as tankers and bulk carriers, about 14 ksi (97 MN/m^2)[22,24]. Therefore, 14 ksi (97 MN/m^2) appears to be a reasonable maximum nominal stress level in ship hulls. Although this stress is less than one-half the yield stress of most ship hull steels, the local stress at stress concentrations reaches the yield strength level, particularly when the additional effects of residual stress are considered. Furthermore, because of the particular nature of ship hull loadings and the number of brittle fractures that have occurred in service, it is reasonable (and conservative) to assume that ships can be loaded under impact conditions, i.e., the loads can be applied rapidly enough so that the dynamic yield stress is reached. As discussed in Appendix B, the dynamic yield stress under impact loading is approximately 20 ksi (138 MN/m^2) higher than the static yield stress as measured in standard tension tests. The actual loading rate for ship hulls is probably between the limits of "static" loading (strain rate approximately $10^{-5} sec^{-1}$) and dynamic or impact loading (strain rate approximately 10 sec^{-1}). However, in view of the general service behavior of ships, and the lack of information on specific loading rates, the conservative assumption that ships are loaded dynamically is made.

Studies have shown that ships operate at temperatures less than 32°F (0°F) only about 3% of the time, Figure 3[25]. Therefore, a design service temperature of 32°F (0°C) for welded steel ship hulls appears realistic. For special applications, such as icebreakers, the design service temperature should be lower.

Therefore, from a fracture-control standpoint, the probability is very high that critical regions in welded ship hulls can be subjected to impact loadings at 32°F (0°C) such that the dynamic yield stress of the material can be reached. Thus, the use of dynamic fracture parameters, K_{ID}/σ_{yD} (see Appendix B), rather than static fracture parameters, K_{Ic}/σ_{ys}, is justified.

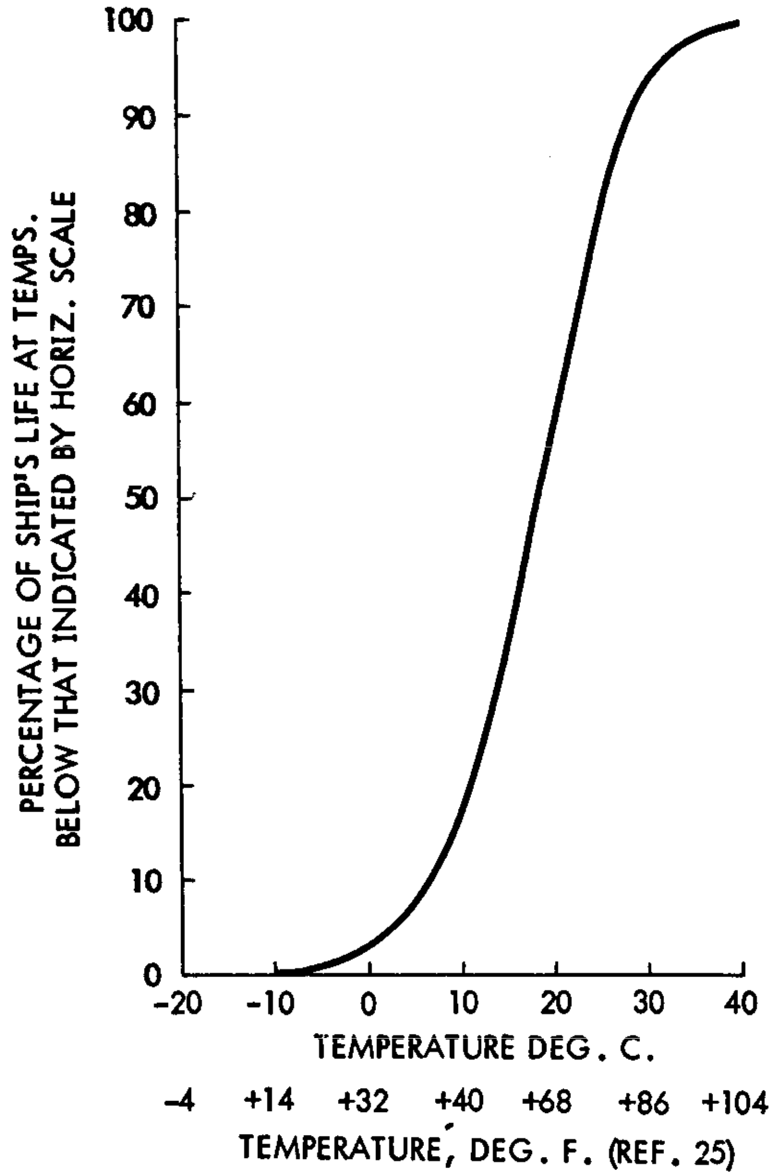

Fig. 3. Distribution of Service Temperature for Ships (Ref. 25).

Required Performance Characteristics

Previously, it has been shown that brittle fractures occur because of particular combinations of material toughness, flaw size, and tensile stresses. If this basic principle is combined with the realistic fact that the stress level in critical parts of a ship hull will reach yield stress magnitude and that flaws or discontinuities will be present in the hull, the naval architect is faced with three possible solutions to prevent catastrophic brittle fractures in ships[26]:

1) Develop multiple-load paths within the hull so that failure of any one part of the cross section does not lead to total failure of the ship. Although this solution is satisfactory for other types of welded structures such as stringer-type bridges with concrete decks, it does not appear to be feasible for monolithic welded steel ship hulls.

2) Use extremely notch-tough steels so that no brittle fractures can initiate or propagate even at very high stress levels. Although this solution would eliminate the problem of brittle fracture in welded steel ship hulls, it is economically unfeasible because such extreme levels of notch toughness actually are not required. Furthermore, even notch-tough materials can fail if the loading is severe enough.

3) Provide a fail-safe design using steels with moderate levels of notch-toughness in combination with properly designed crack-arresters, so that even if a crack initiates, it will be arrested before catastrophic failure occurs.

The fundamental problem in a realistic fracture-control plan for welded ship hulls is to optimize the above possible performance criteria with cost considerations so that the probability of complete structural failure due to brittle fracture in welded ship hulls is very low. In that sense, the toughness criterion proposed in this report is an attempt to optimize satisfactory performance with reasonable cost, following a fail-safe philosophy.

Thus, the third solution, namely the use of steels and weldments with moderate levels of notch toughness combined with properly designed crack arresters, is recommended as a fracture criterion for welded ship hulls.

In line with this general fracture-control plan, the following items are noted.

1) As has been well documented during the past 30 years, the definite possibility of brittle fracture in welded ship hulls exists because welded ship hulls are complex structures that can be subjected to local dynamic loading of yield point magnitude at temperature as low as 32°F (0°C).

2) Because of current limitations in fabrication practice and inspection at shipyards, a large probability exists that large undetected flaws will be present at some time during the life of welded ship hulls. Even with improvements in control of welding quality during fabrication, some discontinuities will still be present prior to the service life of the structure and fatigue may cause these discontinuities to grow in size during the life of the structure. Thus, it is assumed that flaws are present in all welded ship hulls.

3) The naval architect generally does not have absolute control over the fabrication of a welded ship hull. Thus, he should establish material and design controls during the design process that are adequate to prevent the occurrence of brittle fractures in welded ship hulls. Although the designer tries to avoid details that act as stress raisers, this is an impossible task in large complex welded structures. Hence, the emphasis in this fracture-control plan is on the choice of proper materials (toughness specifications for steels and weldments) and design (proper use of crack arresters), even though quality fabrication and inspection of welds are extremely important.

4) Although specifying solely the metallurgy and manufacturing process, including composition, deoxidization practice, heat treatment, etc., has been one method of controlling the level of notch toughness in a steel, the only method of measuring the actual toughness of a steel is a toughness test. A direct measure of toughness is better for the user because he is ultimately concerned with the performance of the steel or weldment, and this performance can best be determined by a notch-toughness test. Also a specification based on a notch-toughness test would appear to be more equitable for steelmakers in that it leaves them some latitude to adopt the process best suited to their particular operation in satisfying the toughness requirement. However, a toughness test does have the disadvantage in that a test value pertains to only one location in a plate whereas proper processing control should pertain to the entire plate. However, because this may not always be true, a toughness test is no less effective as an indication of the service performance of the entire plate.

5) Because of the difficulties in conducting a toughness test on a composite weldment, notch-toughness specimens should be taken from each of the following regions: base metal, weld metal, and heat-affected zone. While there is no "one" heat-affected-zone, an average measure of toughness can be obtained by notching the test specimen so that the tip of the notch is approximately at the center of the heat-affected-zone region. Existing ABS Rules[27] specify that five sets of impact specimens be taken during welding Procedure Qualification Testing for weldments used for very low-temperature service. The notches for the specimens are located at the centerline of the weld, on the fusion line, and in the heat-affected-zone, 0.039-in (1 mm), 0.118-in (3 mm), and 0.197-in (5mm) from the fusion line. For weld qualification tests it may be desirable to follow this practice.

The specific requirements to implement these fail-safe fracture-control guidelines consist of 1) establishing a satisfactory level of notch toughness in the steels and weldments, and 2) developing of properly designed crack arresters. These requirements are presented in the following two chapters. It should be re-emphasized that improper fabrication can still lead to structural failure regardless of the level of notch-toughness. Thus good quality welding and inspection practices must be followed.

IV. MATERIALS PERFORMANCE CHARACTERISTICS

General

In general, the primary load-carrying members of steel ship structures are the plate members within the center .4L of the hull that comprise the upper deck, bottom shell, side plating, and longitudinal bulkheads. Because these members are the primary load-carrying members, material toughness requirements should be specified for them. Although stiffeners can also be primary load-carrying members, they are not connected to each other and thus failure of one stiffener should not lead to failure of adjacent stiffeners. Therefore, they need not be subject to the proposed criteria.

Stresses in a ship hull vary from extreme levels in the upper deck and bottom shell to essentially zero at the neutral axis as indicated in Fig. 4, which illustrates an idealized stress distribution in the section. An shown schematically in Fig. 2, the critical crack size for a given material is influenced by the nominal tensile stress level. Because stresses in the main-stress regions (Fig. 4) can reach critical levels, the materials performance characteristics of the primary load-carrying plate members in these areas should be specified by a toughness requirement. Stresses in the secondary-stress region are somewhat lower, and for primary load-carrying plate members in this area, a less-stringent toughness requirement is needed.

Development of Toughness Requirement for Main-stress Regions

Traditionally, the fracture characteristics of low- and intermediate- strength steels have been described in terms of the transition from brittle to ductile behavior as measured by impact tests. This transition in fracture behavior can be related schematically to various fracture states as shown in Fig. 5. Plane-strain behavior refers to fracture under elastic stresses with little or no shear-lip development and is essentially brittle. Plastic behavior refers to ductile failure under general yielding conditions with very large shear-lip development. The transition between these two extremes is the elastic-plastic region which is also referred to as the mixed-mode region.

For static loading, the transition region occurs at lower temperatures than for impact (or dynamic) loading, depending on the yield strength of the steel. Thus, for structures subjected to static loading, the static transition curve should be used to predict the level of performance at the service temperature. For structures subjected to impact or dynamic loading, the impact transition curve should be used to predict the level of performance at the service temperature.

For structures subjected to some intermediate loading rate, an intermediate loading rate transition curve should be used to predict the level of performance at the service temperature. Because the actual loading rates for ship hulls are not well defined, and to be conservative, the impact loading curve (Fig. 5) is used to predict the service performance of ship hull steels. As noted on Fig. 5, the nil-ductility transition (NDT) temperature generally defines the upper limit of plane-strain under conditions of impact loading.

A fundamental question to be resolved regarding a fracture criterion for welded ship hull steels is: "What level of material performance should be required for satisfactory performance in a ship hull subjected to dynamic loading?" That is, as shown schematically in Fig. 6 for impact loading, one of the following three general levels of material performance must be established at the service temperature for the steels that are primary load-carrying members:

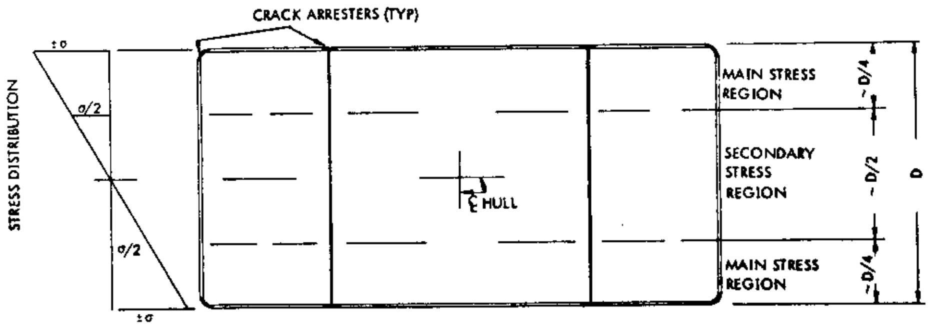

Fig. 4. Schematic Cross Section Showing Primary Load-Carrying Members in Main - and Secondary Stress Regions

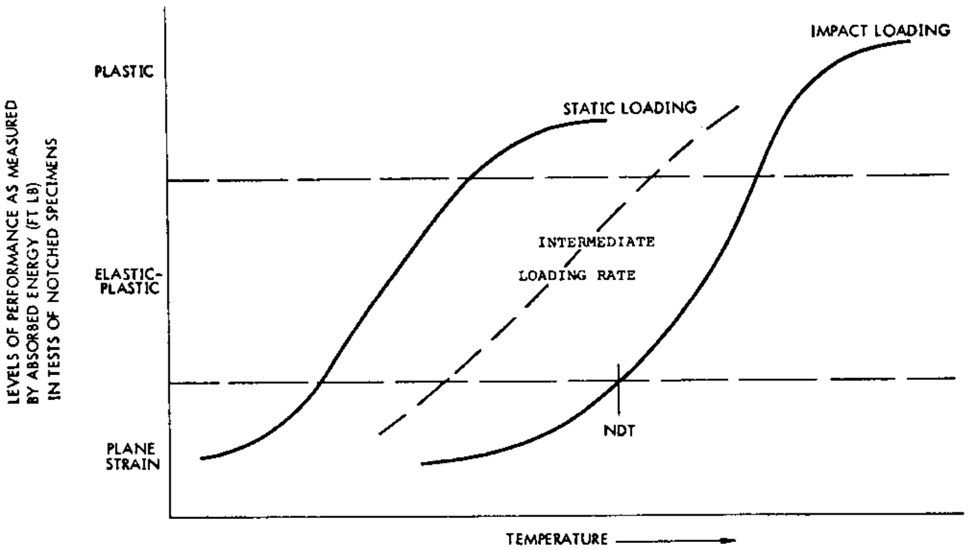

Fig. 5. Schematic Showing Relation Between Notch-Toughness Test Results and Levels of Structural Performance for Various Loading Rates

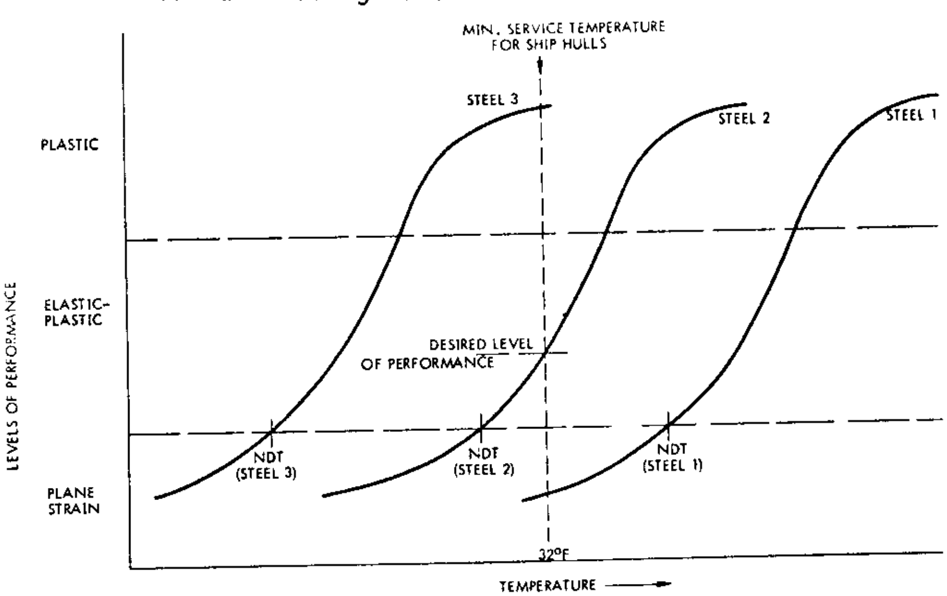

Fig. 6. Schematic Showing Relation Between Level of Performance as Measured by Impact Tests and NDT for 3 Arbitrary Steels

1) Plane-strain behavior - Use steel (1) - Fig. 6

2) Elastic-plastic behavior - Use steel (2) - Fig. 6

3) Fully plastic behavior - Use steel (3) - Fig. 6

Although fully plastic behavior would be a very desirable level of performance for ship hull steels, it may not be necessary, or even economically feasible. A reasonable level of elastic-plastic behavior (steel 2 - Fig. 6) should be satisfactory to prevent initiation of most brittle fractures. (If fractures do initiate, they should not lead to catastrophic failure of a ship as long as properly designed crack arresters are used.) Specifying that the NDT temperature of all steels and weldments used in primary load-carrying members in the center 0.4L of ships be equal to or less than 0°F (-18°C) (32°F (18°C) below the minimum service temperature) should establish the required performance level, if the materials follow the general behavior of steel 2 in Fig. 6.

Thus, the primary material specification in an overall fracture-control plan for welded steel ship hulls is that all steels and weldments used in primary load-carrying plate members in the main stress regions of ships have a maximum NDT of 0°F (-18°C) as measured by ASTM Test Method E-208-69[28].

Although necessary, this primary NDT requirement alone is not sufficient, since an additional toughness requirement is necessary to insure that the resistance to fracture of the steels and weldments whose NDT is 0°F (-18°C) (or lower) is actually satisfactory at 32°F(0°C). That is, this additional requirement is necessary to guarantee that materials follow the general performance level shown in Fig. 6, rather than exhibit a low-energy shear behavior. Fig. 7 shows the relationship of low-energy performance to normal behavior and very-high level behavior (HY-80 type behavior for military applications).

Low-energy shear behavior usually does not occur in low-strength steels but is sometimes found in high-strength steels. Thus the additional toughness requirement is necessary to eliminate the possibility of low-energy shear failures, primarily in the higher-strength steels.

In terms of fracture-mechanics concepts, the critical dynamic toughness, K_{ID}, is approximately equal to $0.6\sigma_{yD}$ at NDT, where σ_{yD} is the dynamic yield strength of the material. Thus for the ship hull materials that satisfy the criterion that NDT be equal to or less than 0°F (-18°C),

$$\frac{K_{ID}}{\sigma_{yD}} \simeq 0.6 \text{ at } 0^{\circ}\text{F } (-18^{\circ}\text{C})$$

At the minimum service temperature of 32°F (0°C)

$$\frac{K_{ID}}{\sigma_{yD}} \quad \text{is estimated to be about 0.9}$$

because of the rapid increase in K_{ID} with temperature in the transition temperature region. Although the value of 0.9 cannot be established theoretically, experimental results for various steels[29], including ABS-C and ASTM A517 steels, Figures 8 and 9, indicate that this is a realistic value.

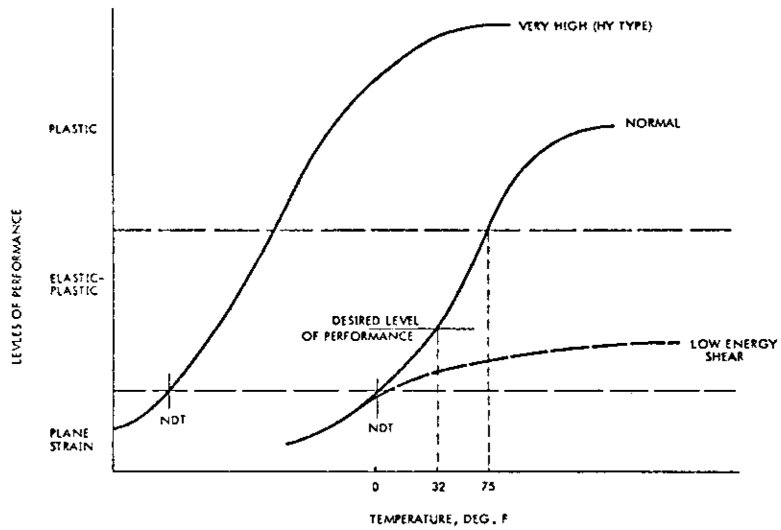

Fig. 7 . Schematic Showing Relation Between Normal-, High-, & Low-Energy Shear Levels of Performance as Measured by Impact Tests

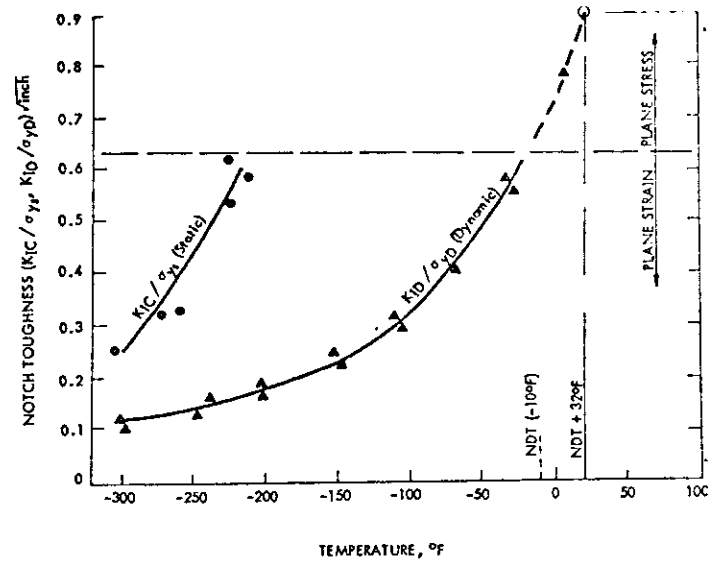

Fig. 8 . Crack-Toughness Performance for ABS-C Steel

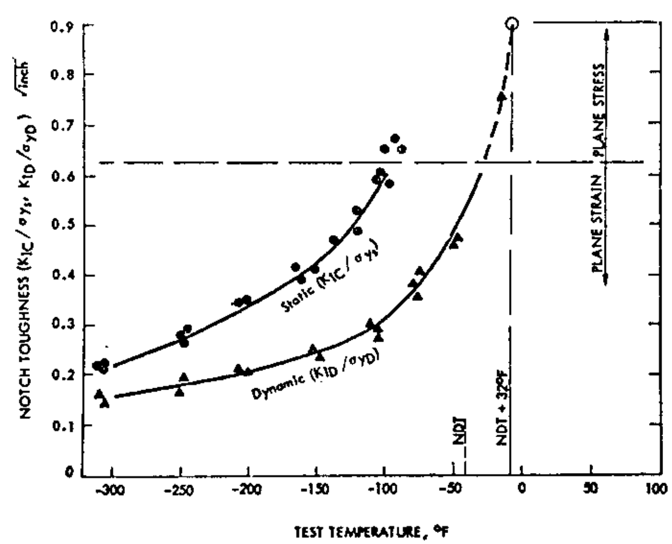

Fig 9. Crack-Toughness Performance for A517-F Steel

It should be emphasized that although concepts of fracture mechanics have been used to develop an auxiliary toughness requirement that $\frac{K_{ID}}{\sigma_{yD}} \geq 0.9$ (for 1-inch-thick (25.4mm) plates), materials satisfying this criterion will exhibit elastic-plastic, non-plane-strain behavior. Therefore, this toughness level cannot be measured using existing state-of-the-art fracture-mechanics tests as specified by ASTM[30]. That is, for 1-inch-thick (25.4 mm) plates, the upper limit of dynamic plane-strain behavior is

$$1.0 = 2.5\left(\frac{K_{ID}}{\sigma_{yD}}\right)^2$$

or $K_{ID}/\sigma_{yD} = 0.63$. Thus NDT (where $K_{ID}/\sigma_{yD} \geq 0.6$) is the upper limit of dynamic plane-strain behavior for 1-inch-thick (25.4 mm) plates.

At 32°F (0°C), K_{ID}/σ_{yD} is specified in this criterion to be 0.9, which is beyond the limits of dynamic plane-strain behavior for 1-inch-thick (25.4 mm) plates.

For 2-inch-thick (50.8 mm) plates,

$$2.0 = 2.5\left(\frac{K_{ID}}{\sigma_{yD}}\right)^2$$

or $K_{ID}/\sigma_{yD} = 0.89$ is the limit of dynamic plane-strain behavior. Thus, a 2-inch-thick (50.8 mm) plate, loaded dynamically to the full yield stress of a material in the presence of a sharp flaw at 32°F (0°C) would be at the limit of dynamic plane-strain behavior. Because the probability of all these factors occurring simultaneously is minimal, the requirement that $K_{ID}/\sigma_{yD} \geq 0.9$ appears to be satisfactory for all thicknesses of plate 2 inches (50.8 mm) or less. However, the required toughness levels for plates thicker than 2 inches (50.8 mm) should be increased.

Using concepts of fracture mechanics, as well as engineering experience, the following observations can be made regarding the level of performance at 32°F (0°C) for steels and weldments that satisfy the primary toughness requirement of NDT ≤ 0°F (-18°C) and the auxiliary toughness requirement that $K_{IC}/\sigma_{yD} \geq 0.9$ at 32°F (0°C):

1) The start of the transition from brittle to ductile behavior will begin below the minimum service temperature of 32°F (0°C). Therefore, at the minimum service temperature, the materials will exhibit some level of elastic-plastic non-plane-strain behavior in the presence of a sharp crack under dynamic loading.

2) Although not specified in the proposed toughness requirement, the materials will exhibit some percentage of fibrous fracture appearance at 32°F (0°C). Service experience has shown that fracture appearance is an effective indicator of the resistance to brittle fracture. Thus, this criterion is consistent with service experience of ship hulls.

3) Although precise stress-flaw size calculations cannot be made for material exhibiting elastic-plastic behavior, estimates of critical crack sizes for 40 ksi (276 MN/m^2) yield strength steels can be made as follows:

   a) For a $K_{ID} \simeq 0.9\ \sigma_{yD}$ and a nominal stress of 14 ksi (97 MN/m^2) the critical crack size at 32°F (0°C) is estimated to be 8-10 inches (203-254 mm) as shown in Fig. 10.

   b) For one of the largest stress ranges (peak to trough) ever recorded ships, i.e., about 24 ksi (165 MN/m^2), the critical crack size is estimated to be 3 inches (76 mm).

   c) For the worst possible cases of dynamic loading of yield point magnitude, the dynamic critical crack size is estimated to be 1/2 inch (12.7 mm).

Ideally, the auxiliary toughness requirement that $K_{ID}/\sigma_{yD} \geq 0.9$ at 32°F (0°C) should be established by conducting a KID test at 32°F (0°C). Unfortunately, no inexpensive standard K_{ID} test specimen exists. Furthermore, research test procedures to obtain K_{ID} values directly are currently too complex for use in specifications. Thus some other test specimen must be used to insure that $K_{ID}/\sigma_{yD} \geq 0.9$ at 32°F (0°C).

The test specimen should be loaded dynamically, easy to use, standardized, and the results should be readily interpretable. In addition, the specimen should have a sharp notch to closely approximate the sharp crack conditions that exist in large complex welded structures such as welded ship hulls. Finally, the test specimen should be as large as practical because of the effect of constraint on the fracture behavior of structural steels.

After careful consideration of which of the various fracture test specimens (e.g., CVN, pre-cracked CVN, Crack-Opening Displacement-COD, DT, and K_{ID}) would be most applicable to the particular requirement for welded ship hulls, the 5/8-inch (15.9 mm) thick dynamic tear (DT) testspecimen[31] is recommended as the auxiliary test specimen.

For the ship hull steel application, the DT test specimen currently satisfies all of the above requirements better than any other test specimen. The DT test is an impact test (high-loading rate) that has a sharp pressed notch with residual tensile stresses (thus the strain concentration is larger than for machined notches). The beginning of the elastic-plastic transition occurs at NDT as shown in Figures 11, 12, and 13 for representative ABS-B, ABS-C, and A517 steels, respectively. Thus the DT test specimen results can be easily related to the NDT values for ship steels.

For the plate thicknesses normally used in ship hull construction (less than 2-inches (50.8 mm) thick), thickness has a second-order effect on the toughness behavior in the transition temperature region compared with the first-order effects of loading rate and notch acuity. Increasing the loading rate of notched steel specimens raises the transition temperature as shown in Fig. 8 and 9[32]. Increasing the notch acuity (from that in a machined CVN specimen to that in a pressed-notch DT specimen) also raises the beginning of the transition temperature range as shown in Fig. 11-13 and 26-29. The second-order effect of thickness (namely the very small change in transition behavior between 5/8 (15.9 mm) and 1 inch (25.4 mm) thick DT specimens) is shown in Figs. 11, 12, and 13. There are larger changes in transition temperature for much thicker plates (e.g., 3- to 12-inch (76 to 305 mm) thick plates used in thick-walled pressure vessels) but for the ship hull application (plates less than 2-inches (50.8 mm) thick), the effects of specimen thickness are second order and can be ignored.

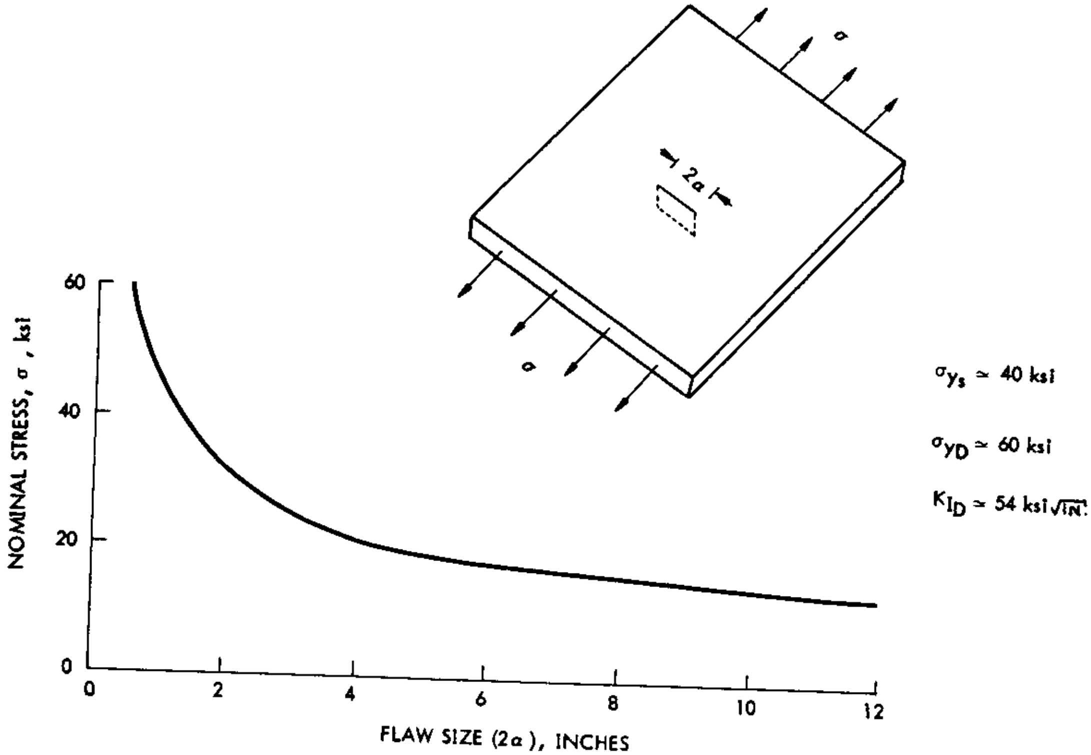

Fig. 10. Estimate of Stress-Flaw Size Relation for ABS Steel with $K_{ID}/\sigma yD \simeq 0.9$.

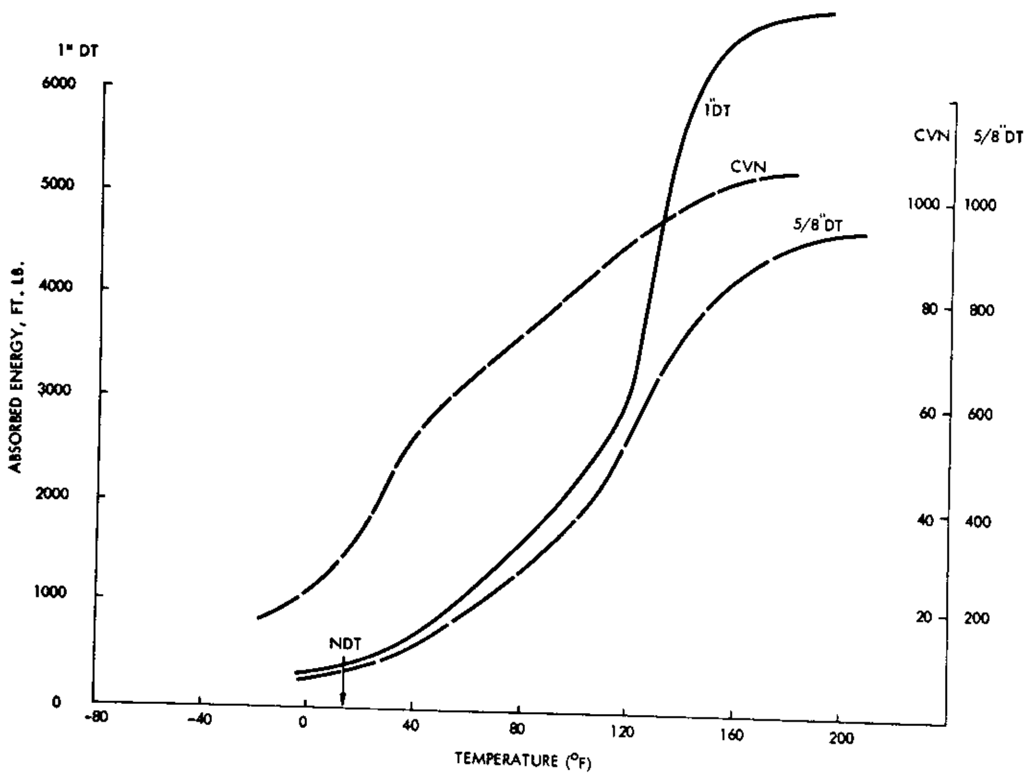

Fig. 11. Relation Between NDT, CVN, and DT Test Results for ABS-B Steel.

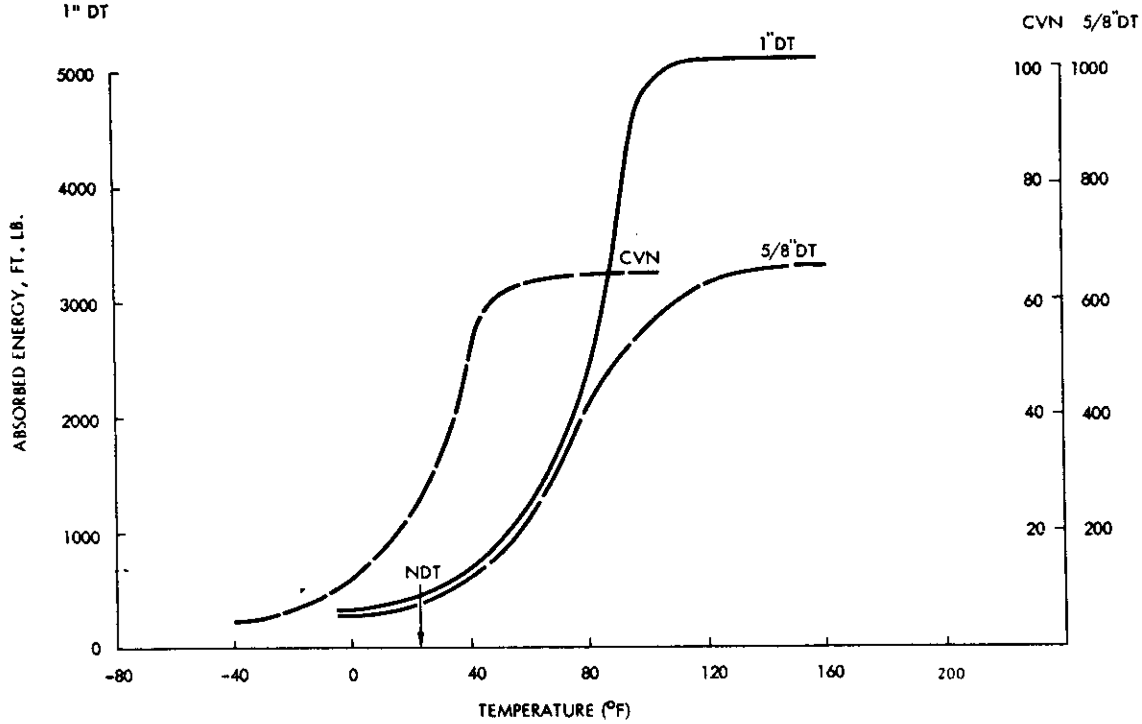

Fig. 12. Relation Between NDT, CVN, and DT Test Results for ABS-C Steel.

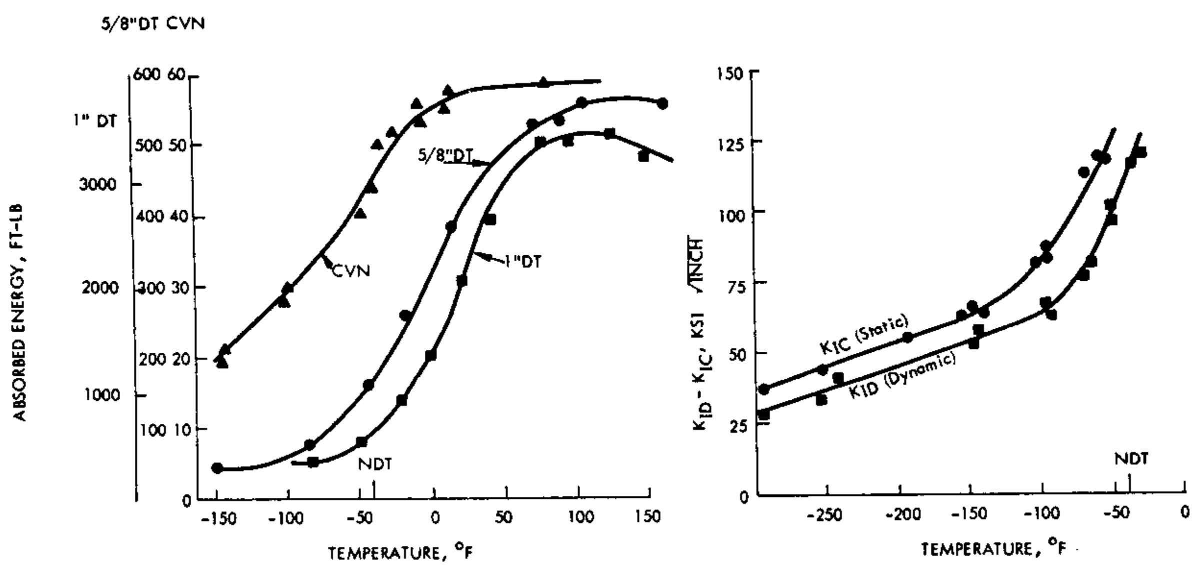

Fig. 13. Relation Between NDT, CVN, DT, K_{Ic}, and K_{ID} for A517 Steel.

Therefore, although it would be technically more desirable to use full-thickness DT specimens to specify the behavior of ship steels, only the 5/8-inch (15.9 mm) thick DT specimen is being recommended because the practical aspects of testing the 5/8-inch (15.9 mm) thick DT specimen far outweigh the disadvantage of having to use a less than full-plate thickness test specimen. The 5/8-inch (15.9 mm) DT specimen has recently been standardized (MIL Standard 1601[31]--also see Appendix C) and can be conducted in existing NDT type falling-weight test machines or in relatively small pendulum type machines.

For the above reasons, the DT test is recommended as the auxiliary test specimen to be used to insure that elastic-plastic behavior is actually being obtained in steels and weldments for welded ship hulls even though CVN impact test results currently are widely used as reference values for predicting the behavior of ship steels. Because of the wide-spread use of CVN test results, particularly in quality control, CVN values that are equivalent to DT test values are presented in Appendix E.

After having selected the DT test specimen as the auxiliary test specimen, the next step is to establish the DT value at 32°F (0°C) that will insure a K_{ID}/σ_{yD} ratio of 0.9 so that the desired level of elastic-plastic behavior is obtained for all steels and weldments. Because there are no direct theoretical solutions to establish the DT values corresponding to $K_{ID}/\sigma_{yD} = 0.9$, empirical considerations are used.

A review of available experimental test results indicates that at NDT, where $K_{ID}/\sigma_{yD} = 0.6$, the amount of absorbed energy for 5/8-inch (15.9 mm) thick DT specimens is approximately 100 ft lb (136 J). Thus at the specified value of $K_{ID}/\sigma_{yD} = 0.9$ at 32°F (0°C), the minimum absorbed energy for the DT specimens can be approximated by (0.9/0.6) times 100, or equal to 150 ft lb (203J). The general relation between K_I and energy in the elastic region would indicate that this ratio should be squared. However, in the elastic-plastic region, where the absorbed energy is increasing very rapidly with temperature, a linear relation may be more realistic. The value of 150 ft lb (203 J) is relatively small and, therefore, it is recommended that the DT test be conducted at 75°F (24°C) (room temperature) rather than 32°F (0°C) because it may be difficult to measure a significant change in resistance to fracture between 0°F (-18°C) (limit of plane-strain behavior) and 32°F (0°C) (a moderate level of elastic-plastic behavior). Although from a technical viewpoint it would be preferable to conduct the DT test at both 32°F (0°C) and 75°F (24°C), the practical considerations of the specification suggest that the DT test be conducted at +75°F (24°C) (room temperature).

If the test is conducted at 75°F (24°C), the minimum K_{ID}/σ_{yD} ratio should be 1.5 on the basis of a non-linear extrapolation from 0.9 at 32°F (0°C) as shown in Fig. 14. Thus, the nimimum DT value should be (1.5/0.9) times 150, or equal to 250 ft lb (339 J). Fig. 14 also shows a schematic representation of the lower-bound specification curve of required values (NDT = 0°F (-18°C) and $K_{ID}/\sigma_{yD} \simeq 1.5$ at 75°F (24°C) - actually 250 ft lbs (339 J) in a DT test) and the minimum desired values of $K_{ID}/\sigma_{yD} = 0.9$ at 32°F (0°C) compared with possible curves for ship steels that either do or do not meet the criterion. This figure shows that by meeting both of the toughness requirements at 0°F (-18°C) and 75°F (24°C) the desired behavior at 32°F (0°C)($K_{ID}/\sigma_{yD} \geq 0.9$) should be met.

Assuming that the dynamic yield strength is approximately 20 ksi (138 MN/m^2) higher than the static yield strength of a steel (Appendix B), the required DT values at 75°F (24°C) $K_{ID}/\sigma_{yD} \geq 1.5$) can be proportioned for strength level as shown in Table 1. This adjustment is necessary to insure that high strength steels have the same relative toughness levels as lower strength steels.

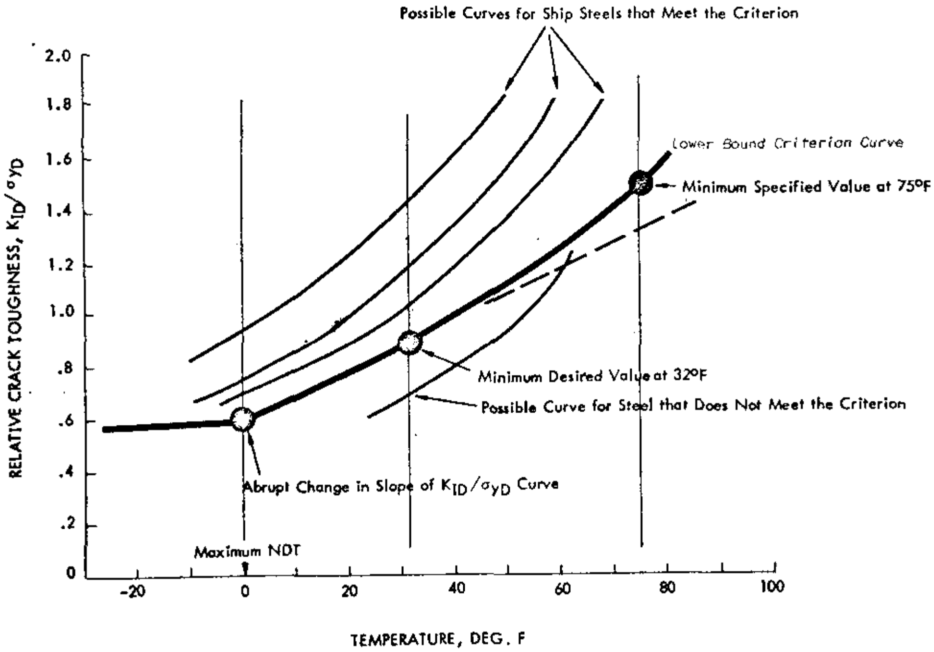

Fig. 14. Schematic Showing the Relation Between Proposed Toughness Criterion for Members in the Main-Stress Region and Behavior of Actual Ship Steels.

TABLE I

Dynamic Tear (DT) Requirements at +75°F (24°C) for Steels and Weldments in Main-Stress Regions for Primary Load-Carrying Members* of Ship Hulls

Actual Static Yield Strength σ_{ys}		Assumed Dynamic Yield Strength σ_{yD}		Proportionality factor for Strength Level	Absorbed Energy Requirements** for 5/8-inch (15.9 mm) thick specimens	
ksi	MN/m^2	ksi	MN/m^2		ft-lb	J
40	276	60	414	(60/60)	250	339
50	345	70	483	(70/60)	290	393
60	414	80	552	(80/60)	335	454
70	483	90	621	(90/60)	375	508
80	552	100	689	(100/60)	415	563
90	621	110	758	(110/60)	460	624
100	689	120	827	(120/60)	500	678

* These members must also meet the requirement of NDT $\leq$ 0°F (-18°C)

** Dynamic elastic-plastic behavior approximating $K_{ID}/\sigma_{yD} = 1.5$.

Thus, the auxiliary material specification in an overall fracture-control plan for welded steel ship hulls is that all steels and weldments used in primary load-carrying plate members in the main-stress regions of ships exhibit the levels of absorbed energy in a 5/8-inch (15.9 mm) dynamic tear (DT) specimen as presented in Table 1.

The values presented in Table 1 should be the minimum values of specimens oriented in the same direction as the primary stress level (notch oriented perpendicular to the direction of primary stress). In most cases, the specimens will be longitudinal to the rolling direction. However, if the transverse stress level becomes significant, then the test specimens should be oriented in the transverse direction. These and other details affecting the implementation of the proposed criteria are outlined in Appendix C.

It should be emphasized that the values presented in Table 1 are not fully plastic "shelf-level" values, but rather, are values that should insure the desired level of elastic-plastic behavior.

Development of Toughness Criterion for Secondary-Stress Regions

The toughness criteria developed thus far in this section are applicable to areas of maximum stress levels which include critical members in the main-stress regions of the hull. Primary load-carrying members within the secondary-stress region (central D/2 portion-Fig.4) will now be considered.

In this vicinity, nominal stresses can usually be expected to be less than one-half the maximum normal hull stress in the deck. Because low stresses (5 to 8 ksi (34 to 55 MN/m^2)) have been known to initiate brittle fractures in steels at temperatures less than NDT[5], and flaws are present in ships, it accordingly follows that a moderate notch-toughness criterion is required even in secondary-stress regions of primary load-carrying members.

Because the same size flaws can exist throughout the entire hull section, the toughness criterion for the secondary stress regions should result in the same required stress-intensity factor (K_{ID}) for both primary-and-secondary-stress regions. Thus, for the main-stress region, $K_{ID} \sim \sigma\sqrt{a_{cr}}$ and for the secondary-stress region, $K_{ID} \sim \frac{\sigma}{2}\sqrt{a_{cr}}$. A comparison of these relations shows that the required K_{ID} for the secondary-stress region is one-half that of the main-stress region. Accordingly, the required K_{ID}/σ_{yD} ratio is equal to 0.45 (K_{ID}/σ_{yD} is 0.9 for the main-stress regions). However, a history of welded steel fractures indicates that a design for this particular level of toughness (< NDT) would not be desirable because fractures have initiated from very small flaws when service temperatures are lower than NDT, even when the applied stresses were quite low[5].

Thus, even though a tolerable flaw size can be numerically computed for a K_{ID}/σ_{yD} ratio of 0.45, it would be very small (≃0.1 inch (2.5 mm)), and a minimum service temperature coincident with NDT (K_{ID}/σ_{yD} = 0.6) appears to be the lowest realistic design-toughness level. A graphical representation of this design-toughness level is presented in Figure 15.

A review of several hull cross sections indicates that primary load-carrying members in the secondary-stress regions usually have nominal-section thicknesses less than or equal to one inch (25.4 mm)[33]. This is due to the fact that the steel in these members is seldom a higher grade than ABS Grade B, which is restricted by ABS rules[25] to a one-inch (25.4 mm) thickness for this application. Thus a one-inch (25.4 mm) section thickness would appear to be the maximum thickness used. As mentioned previously, NDT essentially represents the upper limit of plane-strain behavior for this thickness.

Because the material-toughness requirement of K_{ID}/σ_{yD} = 0.6 at the minimum service temperature (32°F (0°C)) is coincident with the NDT temperature, it can be conveniently established by using the NDT test. Such a marginal toughness level does not require an auxiliary test to evaluate transition behavior. However, past experience with the NDT testing procedure indicates that a margin of at least 10°F (6°C) be allowed, particularly for a specification that is based solely on NDT. For all practical purposes, an NDT temperature of 20°F (-7°C) should be sufficient to assure that K_{ID}/σ_{yD} = 0.6 at 32°F (0°C).

Thus, all steels and weldments used in primary load-carrying plate members in the secondary-stress regions must satisfy a less stringent material-toughness requirement of NDT ≤ 20°F (-7°C).

As stated previously, the above material specifications for either the main-stress regions or the secondary-stress regions will not guarantee the complete absence of brittle fractures in welded ship hulls. Therefore, a fail-safe philosophy that incorporates properly designed crack arresters fabricated from steels with very high levels of notch toughness must be used in conjunction with the above material requirements. The next chapter on Crack-Arrester Performance Characteristics describes these requirements.

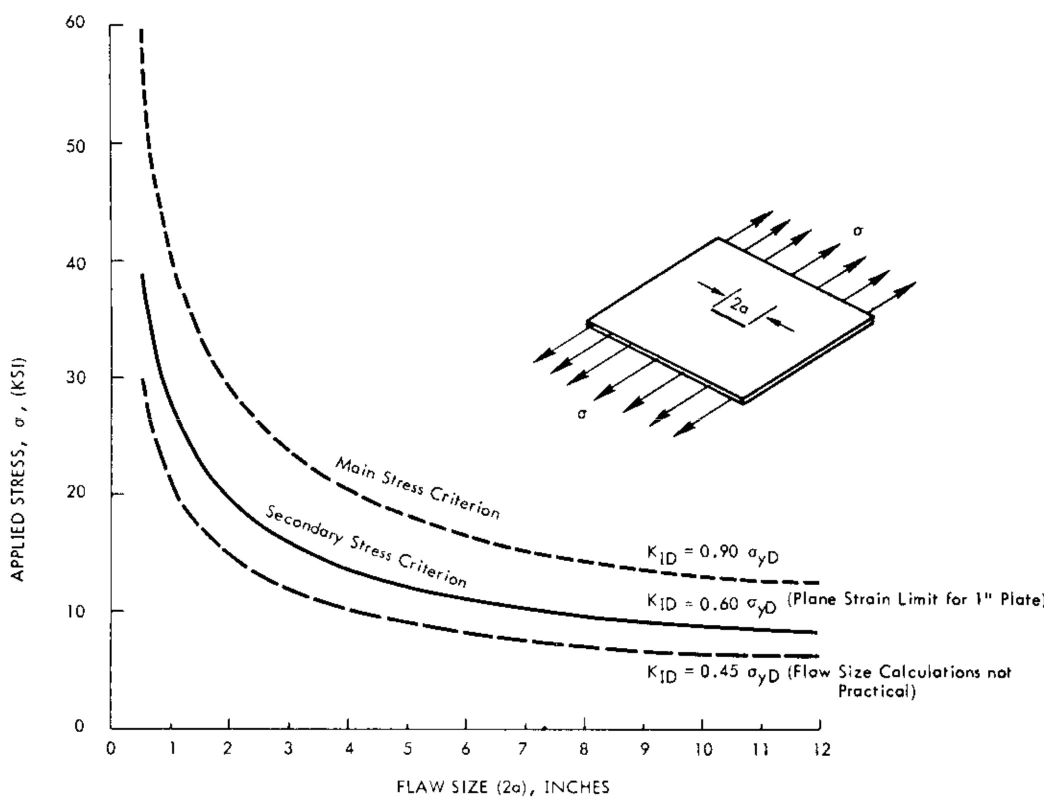

Fig. 15. Schematic Comparison of Main-Stress and Secondary-Stress Criterion

V. CRACK-ARRESTER PERFORMANCE CHARACTERISTICS

Conformance to the fracture-toughness criteria described in the previous section (NDT = 0°F (-18°C) and $K_{ID} \geq 0.9$ at 32°F (0°C)) does not guarantee the complete absence of brittle fractures in ships. If these criteria are followed, there is a very large probability that brittle fractures will not occur. However, the possibility still exists that a crack may propagate in a ship hull even if the materials satisfy these criteria. Therefore, to provide a fail-safe design, a properly designed crack-arrest system must be used in the hull structure. Such a system must satisfy three basic requirements as follows:

1) Proper material

2) Proper local geometry of crack arrester

3) Proper location of crack arrester within the cross-section of the hull

The proposed criteria and rationale for the design of crack arresters in welded ship hulls is described with respect to each of these categories.

Arrester Material

To be effective in a fail-safe design, crack arresters must exhibit a plastic level of performance (Figure 5) under conditions of dynamic loading at the service temperature. Thus the single toughness requirement for steels and weldments used in crack arresters is that these materials be subjected to DT tests at 32°F (0°C) and exhibit a high level of fracture resistance. The definition of this high level of fracture resistance is developed as follows:

1) At 32°F (0°C), the steels and weldments used as primary load-carrying members in the central 0.4L of a welded ship hull are required to exhibit $K_{ID}/\sigma_{yD} \geq 0.9$ (previous section).

2) The DT value at 32°F (0°C) of steels with a static yield strength of 40 ksi (276 MN/m^2) (σ_{yD} = 60 ksi (414 MN/m^2)) and a K_{ID}/σ_{yD} value of 0.9 is approximately 150 ft lb (203J) for the 5/8-inch (15.9 mm) thick specimen.

3) At 32°F (0°C), the steels and weldments used in crack arresters should exhibit levels of toughness <u>considerably greater</u> than those in primary load-carrying members to be effective. For 40 ksi (276 MN/m^2) yield strength steels a factor of about 4 appears to be realistic.

4) Therefore, steels and weldments used as crack arresters should exhibit approximately four times the DT value of 150 ft lbs (203J) described in item 2. Thus, the required DT value at 32°F (0°C) would be 600 ft lb (813J) in a 5/8-inch (15.9 mm) DT test specimen. Because crack-arrester plates have the particular function in a ship of arresting transverse cracks, the specified values should be for longitudinal specimens.

5) Adjusting these required DT values for yield strength (in the same manner as was done for the primary hull steels and weldments, Table 1) would indicate that for a yield strength of 100 ksi (689 MN/m^2), the required DT value should be 1200 ft lbs (1627J). Experimental results of steels that should be completely satisfactory as crack arrester steels (e.g., HY-80 and HY-100 steels) indicate that this value of 1200 ft lb (1627J) is excessive. Therefore, the required values are scaled down to conform with engineering experience.

6) Accordingly, the proposed DT value for 100 ksi (689 MN/m^2) yield strength steels is 800 ft lb (1085 J) for the 5/8-inch (15.9 mm) thick DT specimen.

7) Required DT values for steels having yield strengths from 40 to 100 ksi (276 to 689 MN/m^2) are linearly proportioned between 600 and 800 ft lb (813 and 1085 J) for the 5/8-inch (15.9 mm) thick specimen as shown in Table II.

In summary, the material test requirement for steels and weldments used in crack arresters is that a dynamic tear (DT) test be conducted at 32°F (0°C) (minimum service temperature) and that the materials exhibit the minimum levels of absorbed energy presented in Table II. Basically, these values represent fully plastic behavior for high-strength steels, and high levels of plastic behavior for low-strength steels, Figure 5.

Crack-Arrester Geometry

At present, the most common types of crack arresters are 1) riveted seams in the primary hull structure, 2) welded strakes of tough material which are an integral strength-carrying member of the hull cross section (in-plane arresters), and 3) welded stiffeners, beams, or other rigid members attached perpendicular to the primary hull plating (out-of-plane arresters). Each of these three types of arresters will be described as to their practical applicability in welded ship structures.

Riveted Crack Arresters

Early crack arresters consisted of overlayed riveted straps near gunwales and hatch openings that formed discontinuous seams in the hull structure, Figure 16. Studies by Boyd[7)] and Mosborg[34)] indicate that such arresters have been successful in arresting cracks because of the definite mechanical discontinuity. Thus riveted crack arresters appear to be satisfactory from a technical viewpoint and are allowed as an alternate to certain special application material requirements in the ABS Rules [27)], subject to special consideration. They do not appear to be as widely used in recent years, however, because the use of riveted construction in combination with welding may result in a longer construction period and the overall decline of riveted construction in recent years has lowered the availability of riveters.

Welded (In-Plane) Arresters

Welded (in-plane) arresters currently are used in welded steel ship hulls as shown in Figure 17 and are referred to as special application steels[27)]. These special application steels are designed as integral strength-carrying components in conjunction with the primary structure, and hence the primary design of the hull controls the nominal thickness of the in-plane arrester. The arresters are usually made of materials with very good notch toughness. Because the thickness is controlled by the design of the primary hull structure, the width of the arresters is the only remaining design variable.

Laboratory test studies [35)] have confirmed the expectation that the ability of tough strakes to arrest propagating cracks is proportional to the width of the strakes. Thus, there is definitely a minimum width that should be specified for a proper fail-safe design and a 6-ft. (1.8 m) plate width is suggested. However, very little is known regarding the loads and energies involved or the basic mechanism of crack arrest and the minimum required width of in-plane crack arresters should be a subject of future research.

Welded (Out-of-Plane) Arresters

An alternate form of welded crack arresters consisting of plates welded perpendicular to the primary plating has been studied in the laboratory[36)]. Figure 18 illustrates the geometry of

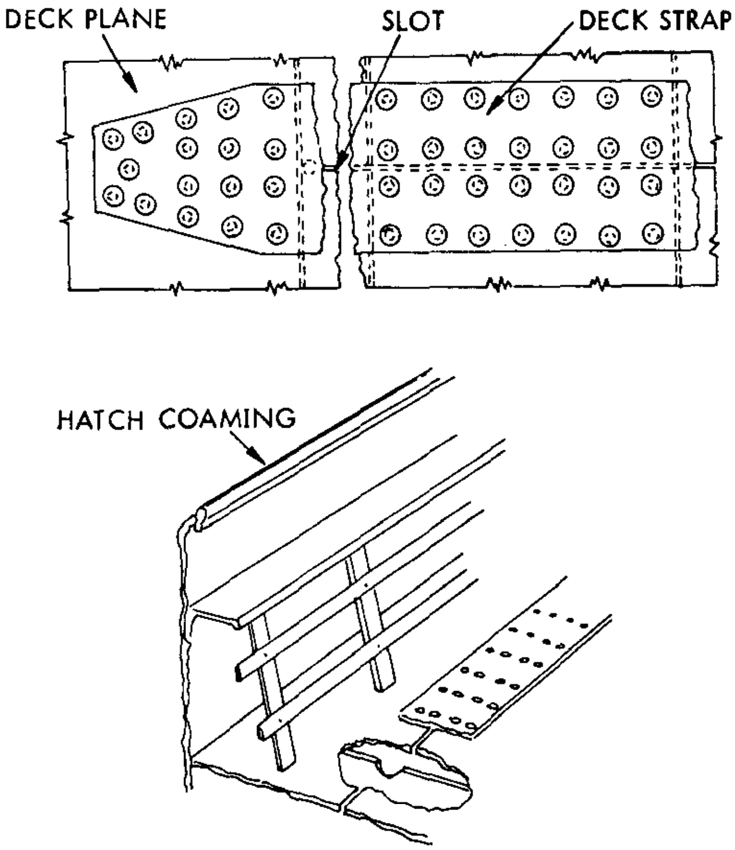

Fig. 16. Typical Geometry of Riveted Crack Arrester

TABLE II

Dynamic Tear (DT) Requirements at 32°F (0°C) for Steels and Weldments Used as Crack Arresters

Static Yield Strength		Assumed Dynamic Yield Strength		Absorbed Energy Requirements* for 5/8 inch (15.9 mm) thick DT Specimens	
ksi	MN/m^2	ksi	MN/m^2	ft-lb	J
40	276	60	414	600	813
50	345	70	483	635	861
60	414	80	552	670	908
70	483	90	621	700	949
80	552	100	689	735	997
90	621	110	758	770	1044
100	689	120	827	800	1085

* Dynamic Plastic Behavior

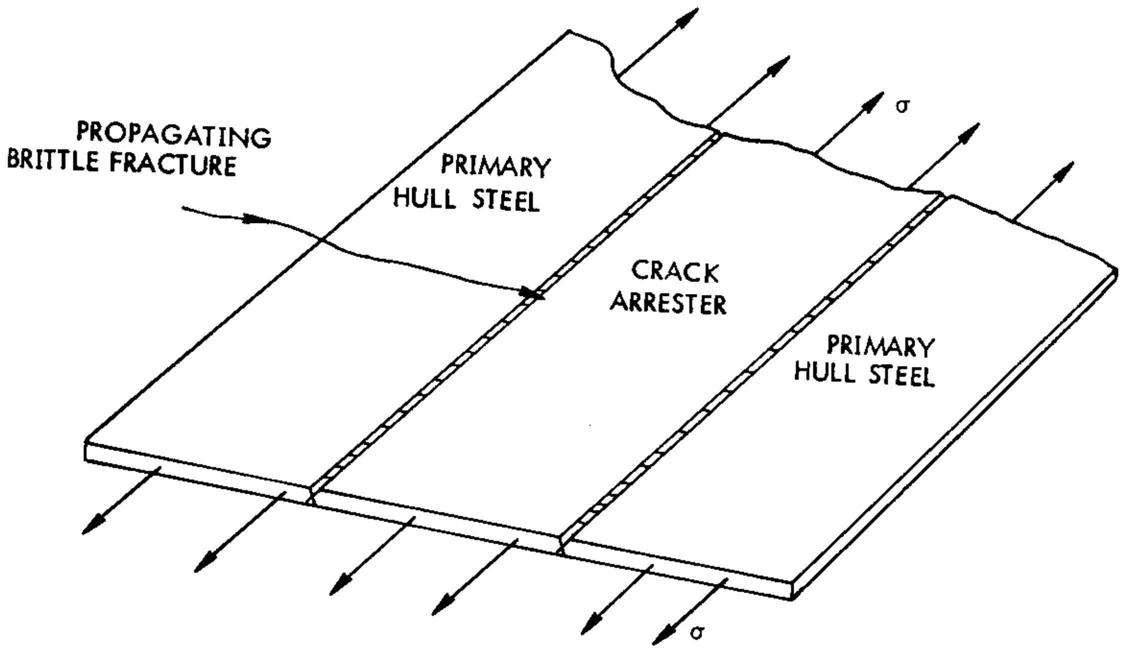

Fig. 17. Typical Geometry of In-Plane Crack Arrester

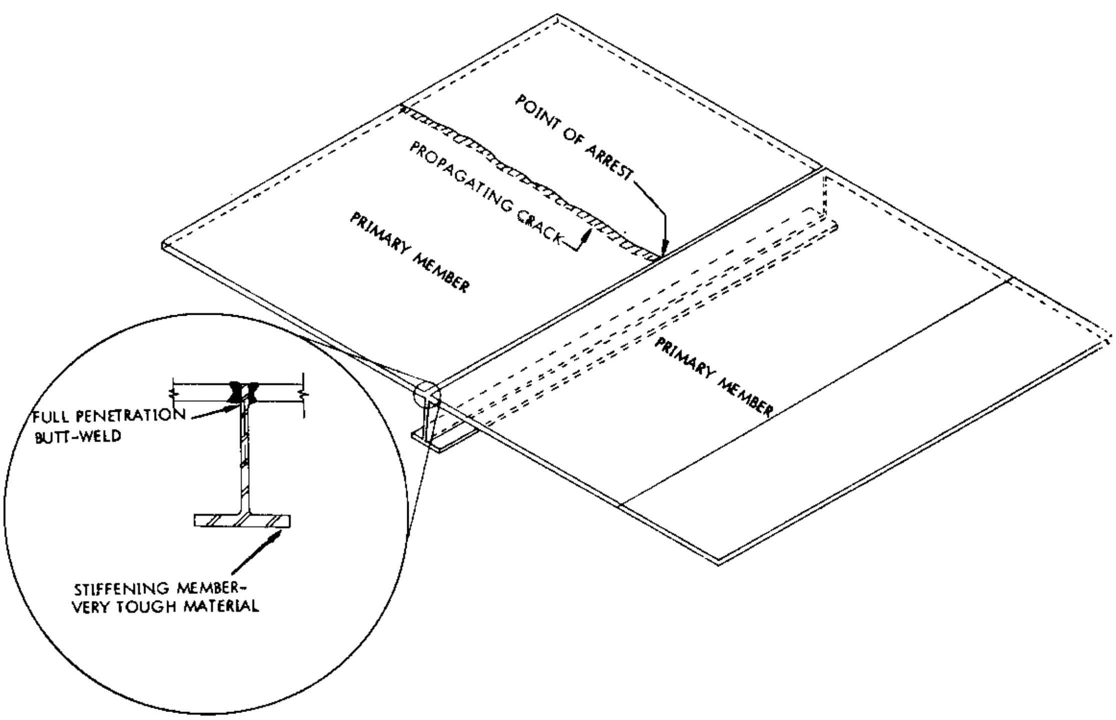

Fig. 18. Schematic Showing Out-of Plane Crack Arrester

out-of-plane arresters and how they arrest a propagating crack. Although this method apparently has not been used in the construction of welded ship hulls, preliminary laboratory test results[36] indicate that these out-of-plane arresters may be very effective.

Out-of-plane arresters also may be very practical because their configuration resembles the girders and stiffening members commonly employed in the hull structure. Thus, members such as the longitudinal bulkheads, large center-of-hull wide-flange girders, stiffeners, bilge keels, etc. may be used as crack arresters provided they meet the other requirements for crack arresters given in this section. These arresters could be considered in place of in-plane arresters if additional studies show they are as effective as in-plane crack arresters.

Because out-of-plane arresters may be subjected to through-thickness stresses (resulting from transverse loading stresses) it is imperative that plate laminations which may lead to lamellar tearing during normal service loading be eliminated. Thus, this system should not be used until the advantages and disadvantages are studied.

Arrester Location

For normal ship applications, steels that act as crack arresters are used within the critical midship 0.4L portion of the hull according to current provisions of ABS Section 43.3.8-b, Special Applications[27]. These special application steels usually are located at critical points such as sheerstrakes and lower turns of the bilge. Special application steels also are located around the perimeters of hatch openings because these areas are often subjected to high-stress concentration and therefore represent critical areas in the hull cross-section. Thus there is considerable rationale behind the current use of special application steels as crack arresters even though these steels are not specifically referred to as crack arresters. Accordingly the following discussion of the philosophy of crack-arrester location is not an attempt to replace current practice, but to supplement it.

The primary area of a ship in which the location of crack arresters may need to be modified is the upper load-carrying deck in the central 0.4L portion of a ship for the following reasons:

1) Members in this region are subjected to relatively high values of tensile stress.

2) This region generally has a considerable amount of non-structural welds, openings, etc. which make it more susceptible to fracture.

3) The upper deck region has been the dominant source of catastrophic failures in ship hulls.

Therefore, in this particular vicinity between the two gunwales, it is recommended that additional welded "in-plane" crack arresters be used. Furthermore, these "in-plane" arrester strakes should run continuously through the center 0.4L portion of the deck. Obviously, additional crack arresters in the bottom shell would be desirable from an overall fracture-control viewpoint as accounted for in the 1973 ABS Rules[27] where "strakes of special material in the deck and bottom shell" are required for vessels 800 feet (244 m) long intended to carry oil in bulk, Section 22.33. For a fail-safe design, it is recommended that additional crack arresters be located in both the deck and the bottom shell.

Some form of transverse spacing restriction on crack arresters that would limit the potential crack propagation length seems desirable. For instance, if a fatigue crack in the primary steel grew to a critical size and initiated a fast propagating crack in each direction, the propagation would most likely continue until it encountered crack arresters. Obviously, the further the arresters are spaced apart, the greater the amount of hull section that would be lost in the event of a brittle fracture.

In order that the maximum transverse distance between crack arresters be held to a reasonable length, it is recommended that at least two additional arresters be placed in vessels with a beam of 120 feet (37 m) or less and at least three additional arresters be used for widths greater than 120 feet (37 m). Examples of this application are shown in Figures 19 and 20. In general, it is recommended that the crack arresters be placed directly above the longitudinal bulkheads because the welded connections at longitudinal bulkheads represent areas that are more highly susceptible to the presence of flaws and crack initiation because of the constraint at these connections. Crack arresters at this location should greatly reduce the susceptibility to crack initiation.

Because of the various locations of the longitudinal bulkheads in the transverse hull sections, it is not feasible to specify precise spacing requirements for crack arresters. It is assumed, however, that they usually will be situated so that the general conditions shown in Figures 19 and 20 are followed. In the event the designer feels that there are no areas particularly susceptible to fracture initiation in the upper deck, he may elect to space the arresters more evenly than those shown in Figures 19 and 20.

It should be emphasized that the above comments on arrester geometry and location are guidelines only, and that a more detailed study of the overall mechanism of crack arrest, including location and geometry is recommended. This study should also include the structural aspects of how large the arrested fracture can be before the overall structural integrity of the ship is jeopardized.

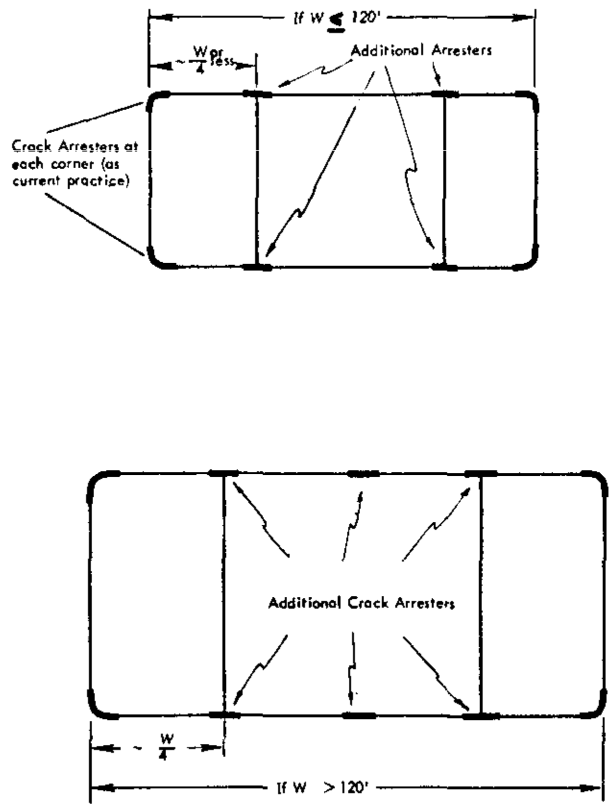

Fig. 19. General Guidelines For Spacing of Crack Arresters in Hull Section

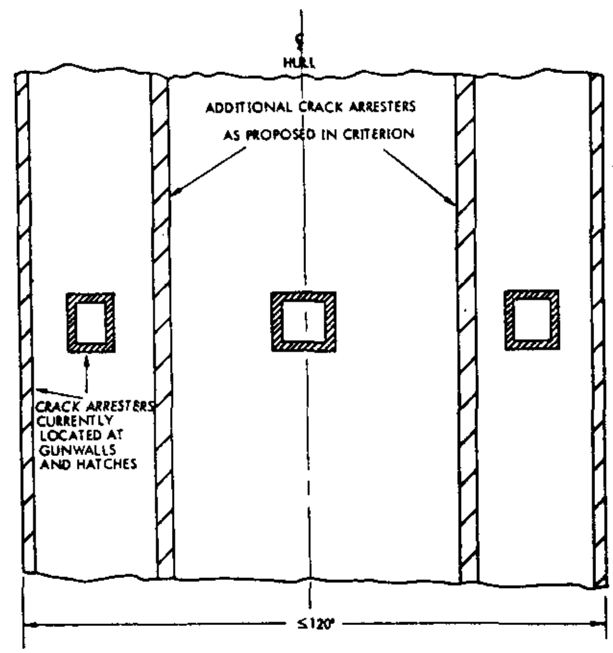

Fig. 20. Plan View of Upper Deck Showing Proposed Location of Additional Crack Arresters

VI. TECHNICAL ABILITY TO MEET CRITERION

Ordinary Strength

Most ship hulls are fabricated using existing grades of ABS steels (also designated ASTM A-131[37]). These steels have a wide range of toughness levels as measured by CVN impact and NDT tests, Figure 21. The results in Figure 21 show that the average NDT values for various grades of ABS steels range from -70°F (-57°C) to +10°F (-12°C). Accordingly, there obviously are steels available that will easily meet the NDT requirement of 0°F (-18°C) for welded ship hulls. The question of whether or not these steels will also meet the DT requirement is not as easily answered because of the lack of available DT data.

Limited test results available are analyzed in this section to give a preliminary indication regarding the availability of existing ship hull steels that will meet the criterion. Figures 11, 12, and 22 show test results of ordinary-strength ship hull steels used in primary load-carrying members (ABS-B and ABS-C) for which CVN, NDT, and DT test results have been obtained. In all of these cases, the results show that the DT requirement of 75°F (24°C), Table 1, is barely met and that the NDT requirements are almost met. Accordingly, it is assumed that any other heats of these grades of steels that have similar CVN test results (where DT results are unavailable) would also meet the NDT and DT criteria. Thus, these CVN impact curves can be compared with the CVN impact test results of Figure 21 that showed the wide range of values obtained for numerous heats of various grades of ABS steels.

A detailed comparison is made in Figures 23 and 24 for ABS-B and ABS-C steels and shows that slightly more than one-half of the ABS-B steels and about two-thirds of ABS-C steels as currently produced would satisfy the proposed toughness criterion. It would be expected that a greater percentage of ABS-C steels should meet the criterion because of the slightly better characteristics of this steel compared with ABS-Grade B. Superimposing these same CVN results of ABS-B and ABS-C steels that essentially meet both the NDT and DT criteria on the average results of ABS-C normalized, CS, D, and E steels (as well as higher strength grades DHN and EH) in Figure 25, shows that these higher-quality grades of ABS steels should easily meet the proposed toughness criterion. Thus, from a technical veiwpoint, existing ABS-Grades of steel (both ordinary strength and higher strength) are capable of meeting the proposed criterion. However, two of the ABS Grades most widely used in primary load-carrying members, namely Grades B and C, may not meet the main-stress-region criterion (NDT ≤ 0°F (-18°C)) consistently, although they should meet the secondary-stress-region criterion (NDT ≤ 20°F (-7°C).

High-Strength Steels

Of the two toughness criteria for welded ship hull steels, the NDT requirement is easily met. This fact would be expected because NDT usually is considerably lower for the high-strength heat-treated steels compared with the lower strength ABS grades of hot-rolled steels. A limited number of DT test results on high-strength steels with yield strengths ranging from 50 to 100 ksi (345 to 689 MN/m^2), given in Figures 13 and 26-29, indicate that the DT requirements (Table 1) likewise can be met. However, the margin between the required DT toughness values and the actual values is less than that for the lower strength steels. This behavior also would be expected, because at the same time that the actual DT shelf levels are decreasing (with increasing strength level), the required DT toughness levels are increasing. Figure 30 shows this general trend between actual and required DT values as a function of yield strength level. However, there appears to be sufficient margin between actual and required values so that the criterion can be met consistently by existing high-strength steels.

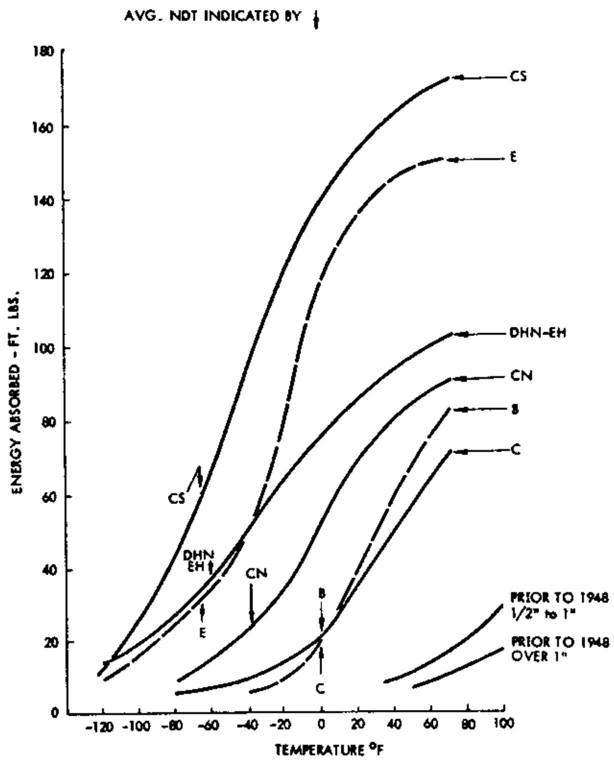

Fig. 21. Average CVN Impact Results for ABS Grades of Steel

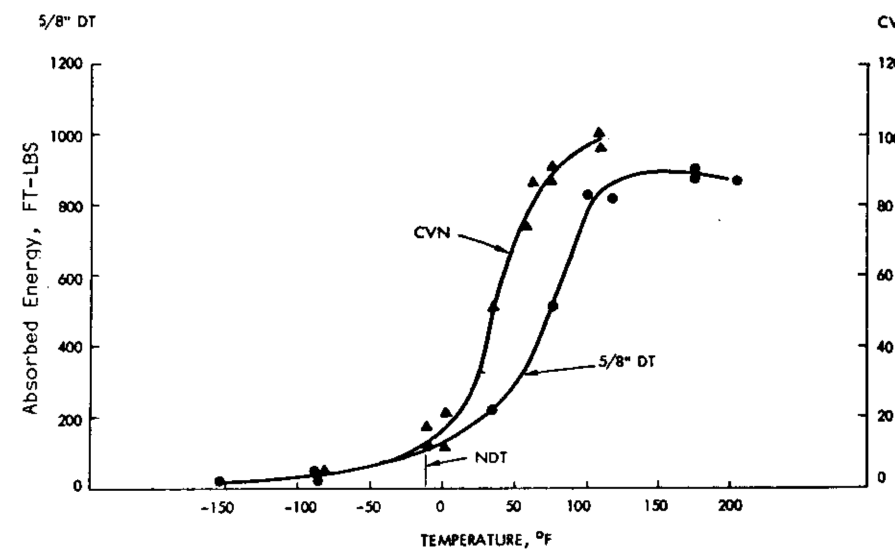

Fig. 22. CVN, DT, and NDT Test Results for ABS-C Steel

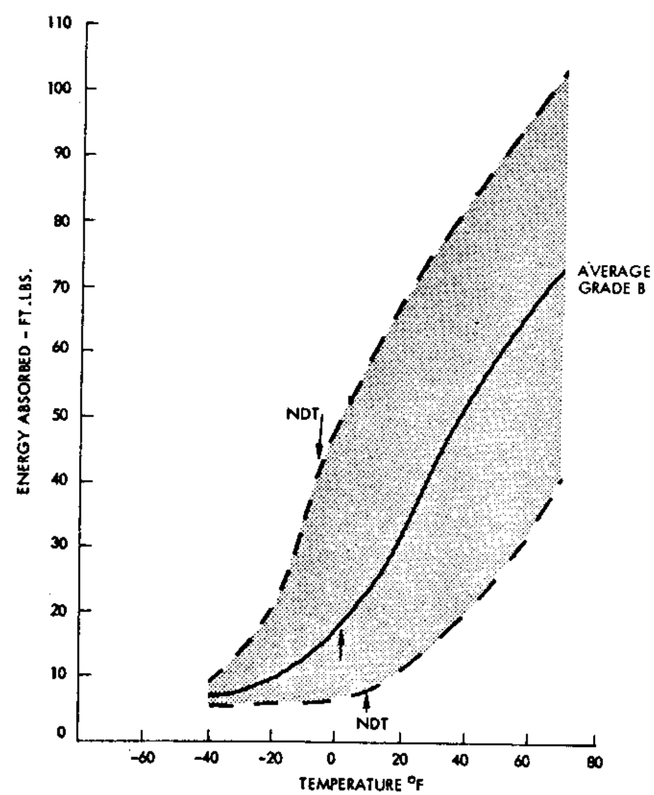

Fig. 23. Comparison of Average ABS-B Steel Toughness Level With Range of Toughness Values

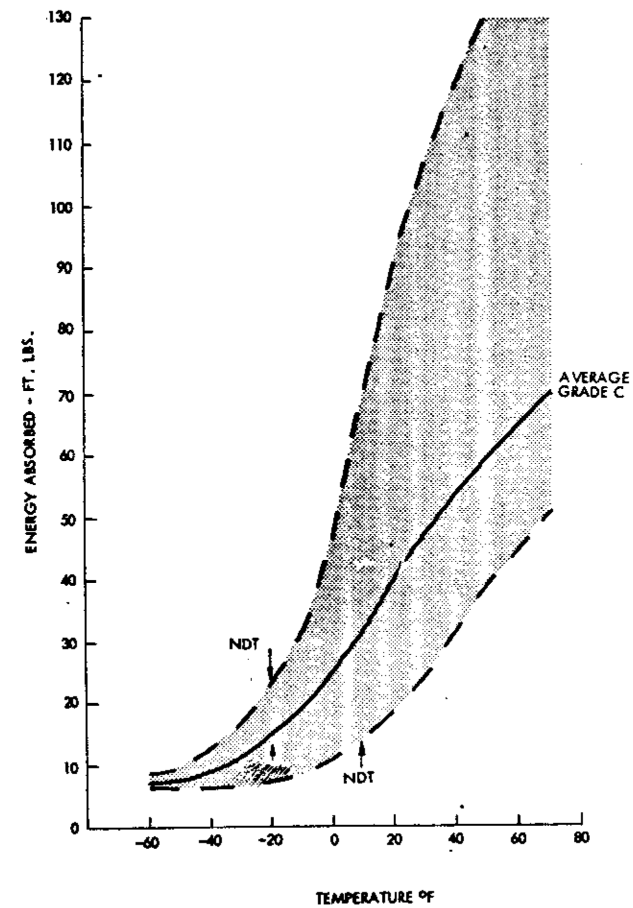

Fig. 24. Comparison of Average ABS-C Steel Toughness Level With Range of Toughness Values

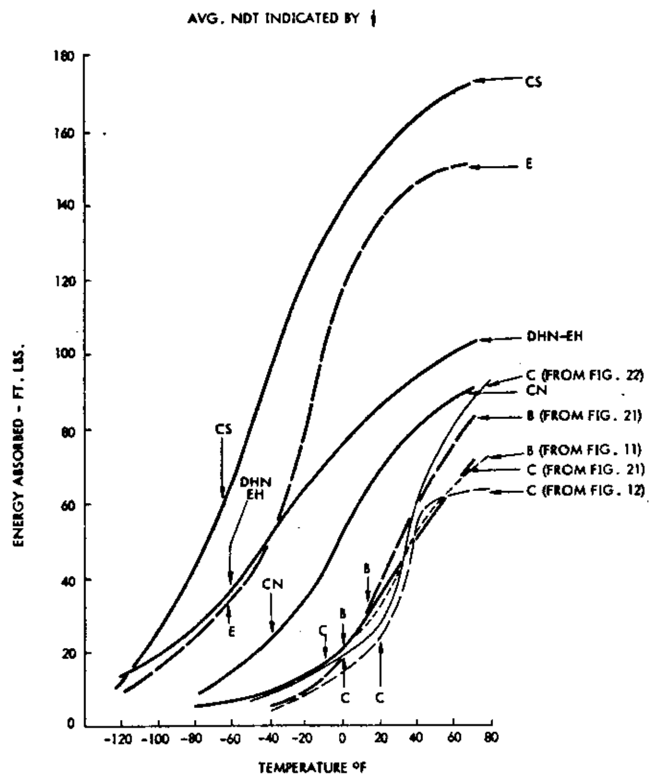

Fig. 25. Comparison of Toughness Levels of ABS-B and C Grades of Steel With C-N, DHN, EH, E, and CS Grades

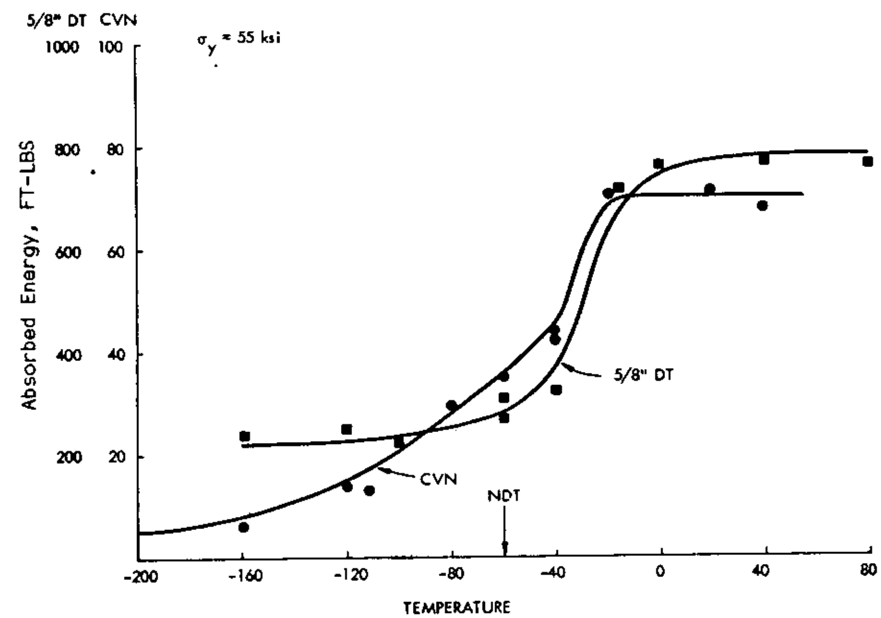

Fig. 26. DT and CVN Test Results for 537A Steel -σy = 55 ksi (379 MN/m²)

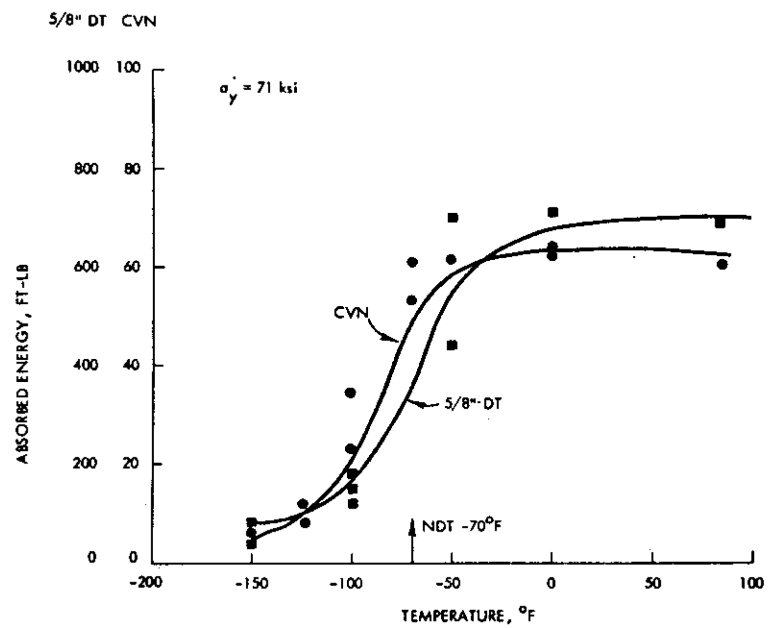

Fig. 27. DT and CVN Test Results for A537B Steel -σy = 71 ksi (490 MN/m^2)

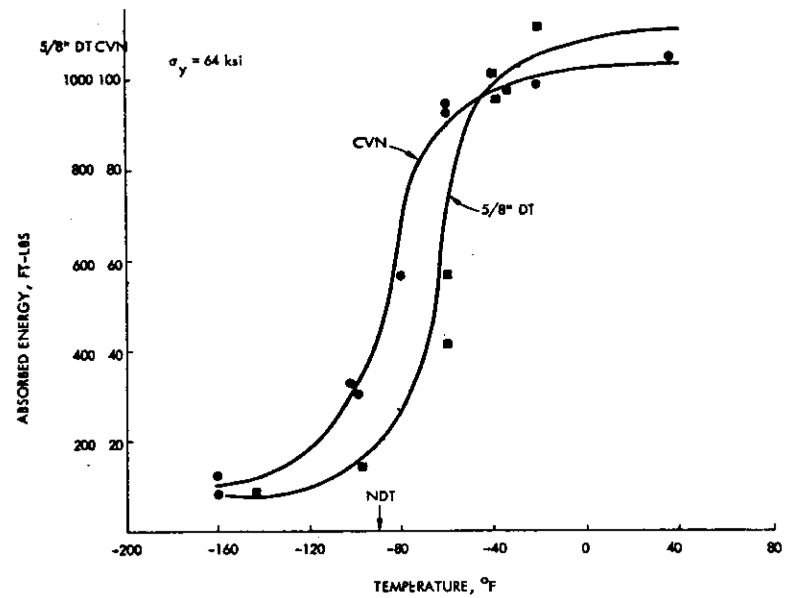

Fig. 28. DT and CVN Test Results for A537B Steel -σy = 64 ksi (441 MN/m^2)

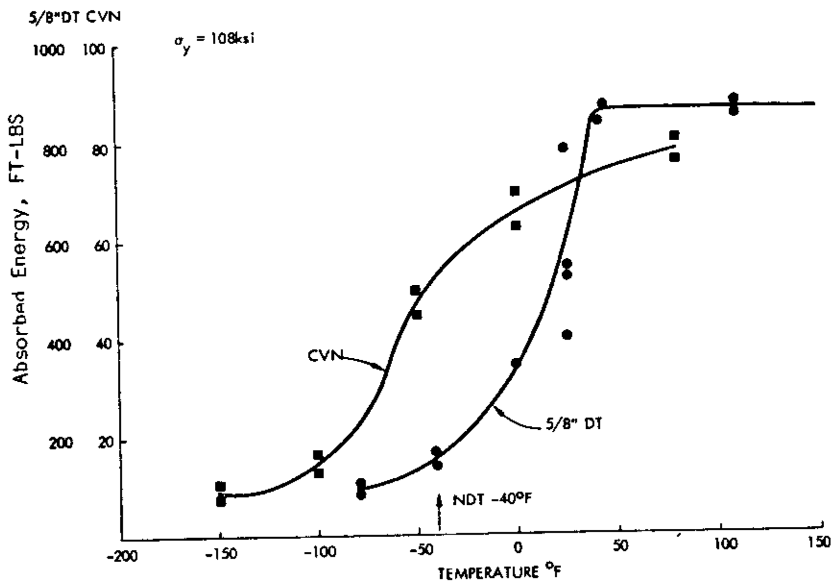

Fig. 29. DT and CVN Test Results for A517 Steel -σy = 108 ksi (745 MN/m²)

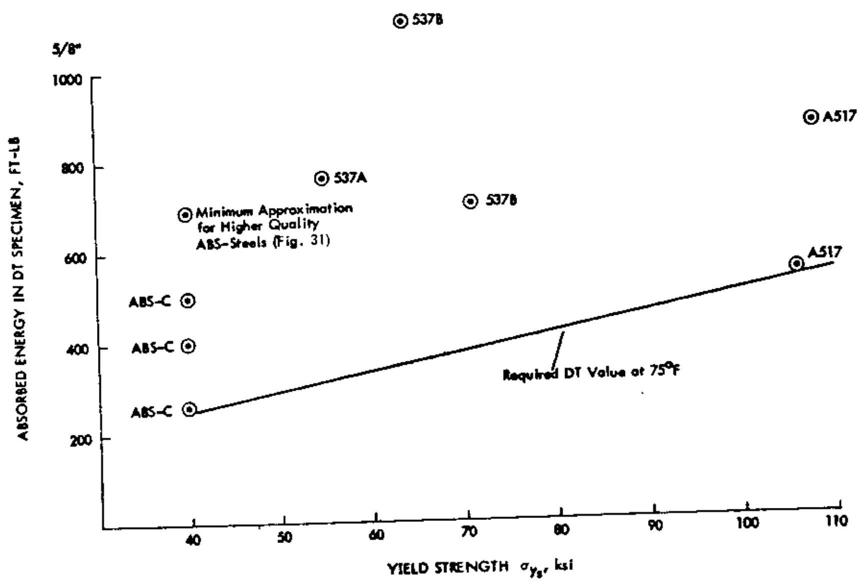

Fig. 30. Comparison of Actual Required DT Values at 75°F (24°C) for Primary Hull Steels

Crack Arresters

As discussed previously, the toughness requirements for crack arresters, Table II, are (and should be) considerably higher than the requirements for primary load-carrying members, Table I. Because of the lack of DT test results on steels that might be used as crack arresters, an indirect comparison using CVN impact test results must be made for the higher quality ABS Grades of steel. Figure 21 shows that the difference in NDT temperature between ABS-Grades B or C steel and the average of ABS-Grades DHN, EH, E, and CS is approximately 80°F (45°C). In addition, the difference in transition temperature at the middle portion of the CVN curves for these same two groups of steels is also about 80°F (45°C). Therefore, it seems very likely that a conservative DT curve for DHN-EH, E, and CS steels may be approximated by shifting the DT curves for the ABS Grades B or C steels 80°F (45°C) lower on the temperature scale. Figure 31 shows the construction of this conservative approximation of the DT curves for these steels. The shifted DT curves imply that these steels meet the crack arrester criterion in that they exhibit about 650 ft lbs (881 J) at 75°F (24°C). Although the required values of 5/8-inch (15.9 mm) thick specimens are close to the actual values, it must be kept in mind that the shifted curve probably does not exhibit as much notch toughness as would actual DT values for these steels because these steels actually exhibit higher CVN shelf values. In summation, it would seem that ABS grades E, CS, DHN, and EH, as currently produced, would be satisfactory crack-arrester steels at the ordinary-and higher-strength levels.

The crack-arrester criterion for high-strength steels, Table II, is more difficult to meet, especially at the 100 ksi (689 MN/m^2) yield strength level. The DT results for steels having yield strengths ranging from 60 to 100 ksi (414 to 689 MN/m^2) that might also be considered for crack arresters indicate that the required DT values for crack arresters can be met but by a relatively narrow margin in some cases. The crack-arrester requirements can be met more easily by either HY-80, A537B, or HY-100 steels, as shown in a general comparison of actual DT values versus required DT values for crack arresters, Figure 32.

In summary, structural steels at all strength levels are available to meet the proposed criterion for both primary hull steel and crack arresters. The toughness requirements are such that not all heats of B and C Grade steel as currently produced will be usable in the primary load-carrying plate members in the main-stress regions of ships. For crack arresters, ABS-C and C-normalized steels do not appear to be adequate. The applicability of the higher quality grades of ABS steels as either primary hull steels or crack-arrester steels should remain satisfactory. The cost of meeting the proposed toughness criterion appears to be a very small percentage of the total cost of any particular ship as described in Appendix D.

The proposed criterion should produce no change in current practice of high-strength steel application in the primary hull. It most likely will, however, cause some changes in the steels and weldments used for crack arresters, particularly for the highest strength level steels. It should be noted, however, that the actual number of crack arresters required in the overall ship is a small percentage of the total steel used.

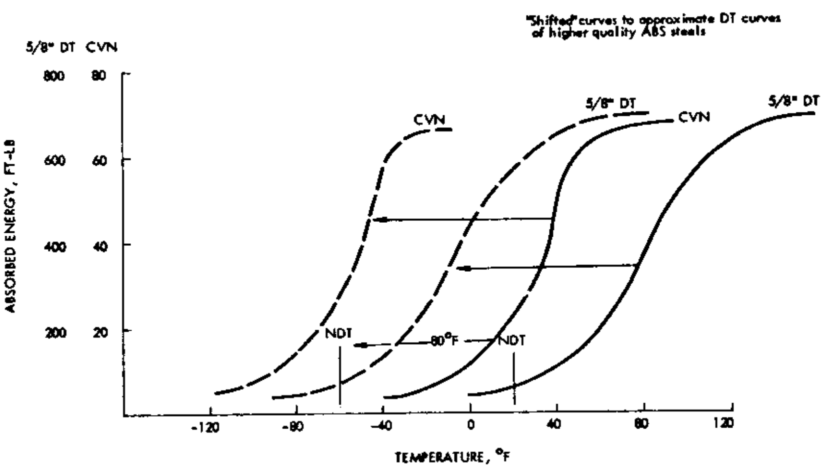

Fig. 31. Construction of "Shifted" ABS-C Curve To Approximate DT Curve of Higher Quality ABS Steel

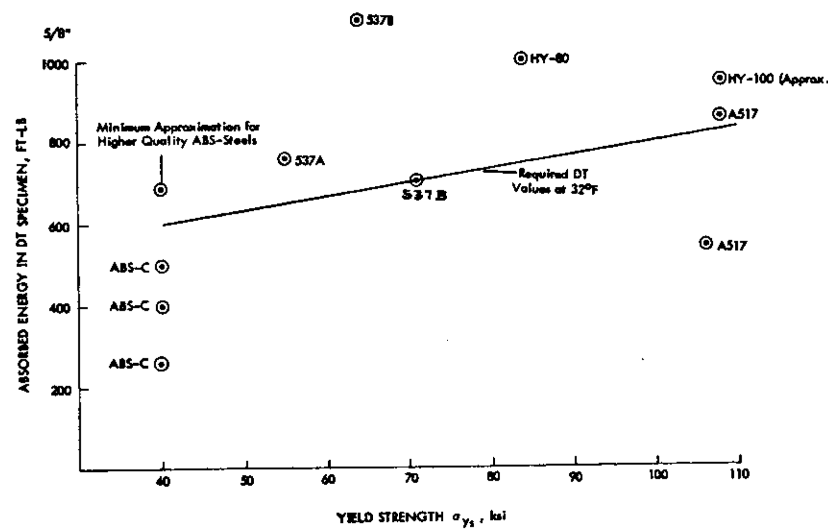

Fig. 32. Comparison of Actual and Required DT Values At 32°F (0°C) for Arrester Steels

VII. COMPARISON OF PROPOSED CRITERION WITH EXISTING TOUGHNESS SPECIFICATIONS

General

Although concepts of fracture mechanics were used to develop the proposed toughness criterion, existing fracture-mechanics tests cannot be used to specify material properties because non-plane-strain behavior is specified. Thus, as described in Section IV, it is necessary to use some test other than a fracture test for a specification test to insure against low-energy shear and, therefore, the proposed criterion is established in terms of DT test results. However, as described in Appendix A, existing material-toughness requirements for ship hull steels are in terms of CVN impact test results. Therefore, to compare the proposed criterion with existing specifications, it is necessary to approximate the required DT values shown in Table 1 (which actually are meant to insure a K_{ID}/σ_{yD} value of 0.9 at 32°F [0°C]), by CVN values, using empirical relations. Several empirical relations exist between K_{ID} and CVN and one of these is used in Appendix E to approximate the proposed DT requirements with equivalent CVN values. These equivalent CVN values will be compared with the Unified Requirements (Appendix A) as well as other toughness specifications for welded ship hulls to establish the relationship between existing toughness requirements and the proposed toughness requirements.

Comparison with Unified Requirements

The toughness requirements for ABS Grades of steel have been unified with other classification societies throughout the world as described in Appendix A. Grades widely used, namely A, B, C, and CS, currently do not have any specific material-toughness requirements in terms of toughness tests. As shown in Appendix E, the CVN value equivalent to a K_{ID}/σ_{yD} of 0.9 at 32°F (0°C) for 40 ksi (276 MN/m²) yield strength steels (ABS Grades) is estimated to be 20 ft lb (27 J). Thus, for most of the ABS steels currently used in the primary hull members, the proposed toughness criterion would be equivalent to a CVN impact value of 20 ft lb (27 J) at 32°F (0°C). In view of the early history of a 15 ft lb (20 J) requirement resulting from an analysis of the World War II ship failures and the fact that ships are becoming much larger in size with heavier loadings, the equivalent requirement of 20 ft lb (27 J) at the minimum service temperature (32°F [0°C]) appears to be very realistic.

ABS Grades D and E are generally used for crack arresters in the United States and they do have toughness requirements of 35 ft lb (47 J) at 32°F (0°C), and 45 ft lb (61 J) at 14°F (10°C), respectively. The proposed equivalent required CVN value at 32°F (0°C) for crack arresters, Appendix E, is 54 ft lb (73 J). Thus the proposed toughness requirements are only slightly higher than the existing unified toughness requirements for the ordinary strength ABS-Grades of steel.

For the higher-strength ABS Grades of steels there are toughness requirements for the DH and EH steels of 25 ft lb (34 J) at -4°F (-20°C), and 25 ft lb (34 J) at -40°F (-40°C), respectively. Note that these requirements specify a lower impact value at a lower temperature compared with the requirements for D and E steels. Although higher strength steels generally have a lower transition temperature than ordinary strength steels, this should not serve as a basis for specifying a lower testing temperature (or a lower impact value) for a steel subjected to the same service conditions. It is true that by specifying a lower testing temperature, the impact value at the service temperature may well be higher than that for ordinary strength level steels. However, low-energy shear behavior is sometimes observed in high-strength steels. Furthermore, this level of energy may be such that the steel is not suitable for use in primary load-carrying members. Obviously then, lower energy requirements at lower temperatures do not necessarily eliminate the possibility of the steel exhibiting low energy at service temperatures. Therefore, it would seem that a more reliable approach to developing toughness requirements for higher strength steels compared with ordinary strengths steels would be to specify a high-toughness value at the same testing temperature. Thus it is more difficult to compare the existing unified specifications for high-strength steels with the toughness criteria proposed in this study. However, it would appear that the desired result of both the existing and proposed criteria is the same, namely obtaining a higher toughness value at the service temperature (32°F [0°C]) for the higher strength steels compared with the ordinary strength steels.

Lloyd's Requirement

In 1958, Hodgson and Boyd[25)] analyzed numerous brittle fracture failures in various types of ships. On the basis of their detailed investigation, they proposed a 35 ft-lb (47 J) CVN impact criterion coupled with a 30% fibrous-fracture appearance at 32°F (0°C) for steels used in welded ship hulls. In Fig. 33, their criterion is compared with the results of numerous ship failures. Their definition of success, failure, or borderline plates is as follows:

1) "Success" plates are those which fractured in a ductile manner, or those in which a brittle fracture originating outside the plate was arrested.

2) "Failure" plates are those which were completely traversed by a brittle fracture.

3) "Borderline" plates are those which cannot be classified in either of the above groups.

The results of their analysis showed that only two plates which met both the 35 ft-lb (47 J) and 30% fibrous-fracture-appearance criterion, Quadrent II, Fig. 33, could be classified as failure plates. Thus their criterion appeared to be very satisfactory and was proposed to Lloyds. The 35 ft-lb (47 J) requirement was accepted (for ABS Grade D steels) but the 30% fibrous was not, although the percent fibrous fracture is recorded for information.

The 30% fibrous-fracture requirement (which insures the presence of some shear) does have significance in that the requirement would imply that the material is performing at a temperature somewhat above that at which it is normally 100% brittle. In this regard, it is consistent with the requirement of the proposed criterion that NDT be 32°F (18°C) below the minimum service temperature. Because fibrous-fracture appearance is difficult to judge accurately particularly with higher strength steels, such requirements have never been widely accepted. Thus specifying that NDT be 32°F (18°C) below the service temperature is an indirect means of insuring some level of fibrous fracture and appears to be a more feasible criterion.

Boyd's Method I

Based on considerable experience with large structures such as welded ships, bridges, storage tanks, etc., Boyd[11)] has developed a generalized toughness criterion that accounts for the following factors:

1) Service temperature
2) Plate thickness
3) Stress level
4) Quality of design and fabrication
5) Required safety level
6) Type of loading
7) Thermal stress relief

Using various adjustments, he develops the minimum service temperature at which a particular steel (limited to 35-55 ksi (241 to 379 MN/m^2) yield strength levels) can be used.

Using his approach, a specific criterion was developed for welded ship hulls subjected to dynamic loading at 32°F (0°C), which requires that the ft lb values be 20 ft lb (27 J) at a yield strength of 40 ksi (276 MN/m^2) and 30 ft lb (41J) at a yield strength of 50 ksi (345 MN/m^2). Although it appears that these requirements are the same as those proposed in the present investigation, the testing temperature for Boyd's Method I is 4°F (-16°C) (approximately equal to the NDT temperature required by the new criterion). Therefore, Boyd's 20 ft lb (27 J) requirement at 4°F (-16°C) is actually slightly more severe than the proposed criterion which implies an equivalent CVN value of 20 ft lb (27 J) at 32°F (0°C).

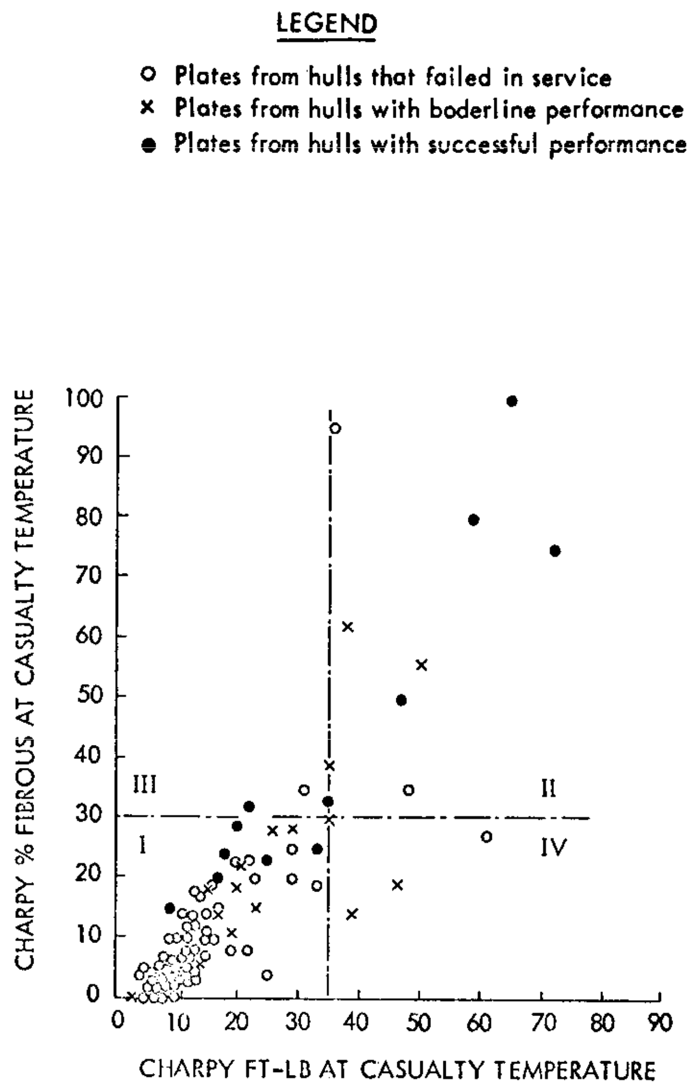

Fig. 33. Comparison of Boyd's (Lloyd's) 35 ft lb (47 J) and 30% Fibrous-Fracture-Appearance Criteria with Test Results from Actual Ship Failures (Ref. 25)

VIII. CONCLUSIONS AND RECOMMENDATIONS

The results of this study of fracture-control guidelines for welded ship hulls, and the development of a comprehensive material-toughness criterion that can be used for ship steels of all strength levels in the range 40 to 100 ksi (276 to 689 MN/m^2) may be summarized as follows:

1) In spite of considerable research on the problem of brittle fractures in welded ship hulls, brittle fractures still occur and fracture-control guidelines for welded ship hulls are necessary.

2) *Although concepts of fracture mechanics have shown that proper design and fabrication are very important in the control of brittle fractures in welded ship hulls, some minimum level of material toughness is necessary because of the complex loadings to which welded ship hulls are subjected.*

3) A fail-safe philosophy that combines a reasonable level of notch toughness with properly designed crack arresters is recommended as an optimum solution to minimizing the probability of brittle fractures in welded steel ship hulls consistent with economic realities.

4) Because of the dynamic aspect of loading encountered by ships, fracture-mechanics concepts were used to develop desired levels of dynamic K_{ID} / σ_{yD} behavior for steels and weldments used in ship hulls.

5) Translating these concepts into actual specification test requirements, the primary material specification in an overall fracture-control plan for welded steel ship hulls is *that all steels and weldments used in primary load-carrying plates members in the main-stress regions of ships have a maximum NDT of 0°F (-18°C) as measured by ASTM Test Method E-208-69.*

6) Although necessary, this primary NDT requirement is not sufficient and an auxiliary dynamic tear (DT) test is to be conducted at +75°F (24°C) to insure that the desired elastic-plastic behavior is obtained.

7) The required values of absorbed energy as measured in the DT test are proportioned for yield strength using concepts of fracture mechanics, Table I.

8) All steels and weldments used in primary load-carrying plate members in the secondary-stress regions of ships must satisfy a less stringent material-toughness requirement of NDT $\leq$ 20°F (-7°C).

9) To implement the fail-safe philosophy described in this report, properly designed crack arresters fabricated from steels with very high levels of notch toughness *must* be used. The high levels of notch toughness are essentially full-shear behavior, Table II.

10) The material and design considerations presented in this report recognize the fact that in an overall fracture-control plan for welded ship hulls, the designer generally *does not have absolute control over the fabrication of a welded ship hull*. Thus, he should establish material and design controls that are adequate to prevent the complete failure of welded ship hulls. Hence, the emphasis in this fracture-control plan is on the choice of proper materials (toughness specifications for steels and weldments) and <u>design</u>

(proper use of crack arresters), even though quality fabrication and inspection of welds are extremely important.

11) An estimate of the possible economic consequences of meeting the proposed toughness criterion indicates that the total cost of a ship should not increase more than about 1.5% because of these toughness requirements.

In general, the results of this investigation have developed material-toughness requirements for ship steels of all strength levels which, in combination with properly designed crack arresters, should result in rational fracture-control guidelines that will minimize the probability of brittle fractures in welded ship hulls consistent with economic realities.

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APPENDIX A

UNIFIED HULL STEEL REQUIREMENTS OF SEVEN CLASSIFICATION SOCIETIES

General

Prior to the initial widespread adoption of arc welding, which was influenced heavily by the emergency shipbuilding programs of World War II, the occurrence of failures by brittle fracture in the predominately riveted ship hulls had been very rare. As a result, no attempt had been made among the various classification societies of the world to control the manufacture or performance of ship steels with regard to resistance to brittle fracture. Instead, it was accepted practice to control only the traditional material properties such as tensile strength. However, during World War II, the American industry introduced the first large-scale production of welded ship hulls, and as a result became the first country to significantly encounter the problem of brittle fractures in welded steel hulls. Accordingly, the American Bureau of Shipping (ABS) in cooperation with various industries, governmental agencies, and technical societies moved toward immediate solutions involving all aspects of shipbuilding [A-1,A-2]. Design changes involving rounding and strengthening of the hatch corners, removing square cutouts in the sheerstrake , and adding riveted crack arresters in various locations led to immediate reductions in the incidence of failures [A-3,A-4].

In 1948, the ABS revised their material specifications to include three "classes" of mild steel, namely: Classes A, B, and C. Moving from Class A to C increased the quality of steel and resistance to brittle fracture. Recognizing the effect of thickness on overall material performance, these steels were limited to applications for which their quality appeared to be suitable [A-5] as follows:

Class A - Plate thickness 1/2" (12.7 mm)
Class B - Plate thickness 1/2" to 1" (12.7 to 25.4 mm)
Class C - Plate thickness 1" to 2" (25.4 to 50.8 mm)

Although the revision marked a considerable improvement over the specifications existing during World War II, ships built to similar specifications by other countries were still encountering brittle fractures. Thus, it seemed that the 1948 rules were not sufficiently stringent, and improvements were needed. Throughout the 1950's, the ABS continued to improve the specified quality of their steel [A-6]. Their overall policy of controlling notch toughness included manufacture control (which also led to improved weldability) and limitations on plate thicknesses for each class of steel (which led to decreased constraint). Examples of improvements are as follows:

A. In 1953, Class C (as normally produced) was limited to 1-3/8 inches (34.9 mm) in thickness. Thicker plates were subject to special approval, which often implied that Class C with normalized heat treatment was required.

B. In 1956, Class B was revised, requiring a greater manganese/carbon ratio.

Before the ABS revision of 1948, societies outside the United States had limited experience with welded hull construction. They felt that their shipbuilding steel was superior to that of America's wartime production, and thus were initially reluctant to adopt special controls on steel manufacture [A-2]. Nonetheless, as welded ship construction outside the United States increased, so did the incidence of serious fractures. Thus, the various societies began to recognize the merit in the toughness-control measures taken by the ABS in 1948. For instance, Lloyd's Register of Shipping (LR) introduced three amendments to their steel specifications in 1949:

A. Limits were set on sulphur and phosphorus contents (similar to ABS).

B. A minimum ratio of manganese to carbon was set (similar to ABS).

C. Special approval was required for welded plates greater than 1 inch (25.4 mm) thick. . . .later referred to as "Lloyd's Clause 13". This item represented the first implication of a toughness-test requirement for shipbuilding steels.

In 1952, Det Norske Veritas (DNV) introduced requirements similar to Lloyd's and in addition, proposed the use of notched impact tests. It was felt that the quality of steel was too sensitive to fabrication to rely solely on material property specifications in controlling notch toughness [A-5]. Thus, in 1954, DNV became the first ship classification society to introduce a toughness-test requirement to steel specifications. This was the conventional Charpy V-notch (CVN) impact test. Shortly thereafter, the Japanese and several European societies added CVN requirements also.

Throughout the 1950's, all societies continued to revise their specifications to improve the quality of steel. The general approach to toughness control was based on control of the steel during manufacturing, restrictions on plate thickness, and an increasing use of notch-toughness tests. Although their specifications were similar in several aspects, the various societies worked independently to reduce the susceptibility of their ships to brittle fracture. A fundamental problem was that the mechanics of fracture was not well understood (or agreed upon) by either metallurgists or designers, and thus some of the specification changes resulted in significant divergences among the societies. This divergence presented an especially perplexing problem when two or more societies were in collaboration with regard to a particular ship.

Considerable discussion was held among the various members of the classification societies regarding the possible unification of material specifications. As a result, these societies began holding informal conferences in 1952 which continued until June 27, 1957, when a formal meeting was held in which all seven classification societies participated (American Bureau of Shipping, Bureau Veritas, Germanischer Lloyd, Lloyd's Register of Shipping, Nippon Kaiji Kyokai, Det Norske Veritas, and Registro Italianno Navale). At that time it was agreed to establish a committee to examine the various existing requirements of that time, make comparisons, and formulate new unified rules for manufacture and quality of shipbuilding steel.

At the beginning of the project the committee recognized that the basic approach to the specification of structural steels could take one of two forms: 1) The definition of a certain number of grades of steel, each of which represents some relative level of material quality, or 2) The definition of various structural circumstances (applications) within the ship hull. There seemed to be a general consensus that a specification related to a particular application would be the ideal choice, but the subject of brittle fracture was not considered to be well enough understood at that time to take this approach. Thus, the decision was made to define a certain number of grades of steel and leave the matter of specific application to the individual societies.

After establishing specific grades of steel, the committee acknowledged two basic alternatives to quality control with regard to notch toughness as follows: 1) Specification of the manufacturing process and material metallurgy so that the steel maker has more certainty of what is to be produced, or 2) Specification of mechanical tests on the finished steel product so that the designer can be more assured of adequate material performance. It was only natural that those feeling responsible for steelmaking argued in favor of the former principle, while those more concerned with the design of ship hulls favored the latter principle in the various discussions[A-5]. Nevertheless, in consideration of the extreme sensitivity in relations among manufacture, toughness testing, and final material performance in structures, as well as the need to control chemistry for adequate weldability, it was recognized that the two methods of material control were inseparable. Thus, an agreement was reached to utilize both principles in the specifications.

There was considerable debate regarding the selection of which mechanical test should be used to judge the fracture toughness of the finished steel product. Although the standard CVN impact test had been widely used to measure the toughness of ship steels, the members of the committee apparently were not eager to accept it as the criterion basis. The feeling was expressed that the CVN impact was not as reliable an index of notch toughness as certain other tests. Nonetheless, the goal at that time was to unify classification societies, and the CVN impact test was the only test available with sufficient standardization to be acceptable on a worldwide basis. Thus, the CVN impact test was finally accepted as the material acceptance test, but provisions were also made to allow for other tests to replace or supplement the CVN impact test upon verification of their technical adequacy. Continual studies of the material requirements for steels used in merchant shipbuilding have been made by ABS and future trends are described in a recent paper by Crum[A-7].

The Unified Requirements

Because almost all ships were built from mild-strength steels at that time, the specification only included steels with tensile strengths of 58 to 71 ksi (400 to 490 MN/m^2) and an approximate yield strength of 32 ksi (221 MN/m^2). In conjunction with the agreed basic approach to specification design, 5 grades of steel with varying quality and control were defined as Grades A, B, C, D, and E. These grades generally increase in quality of production, notch toughness, and therefore unit cost. Although the matter of application was left to the individual societies, there is a general trend among the societies to use Grade A in areas where plate thicknesses are small and tensile stresses are very low, Grades B, C, and D as primary load-carrying members, and Grade E in selected areas of high-stress concentration (crack arresters). The various grade specifications of the Unified Requirements are presented in Table A-1[A-5].

Although there was considerable discussion concerning the applicability of the CVN impact test to each of the various grades, it was decided not to incorporate impact requirements for the lower quality grades. Ultimately, Grades D and E became the only two grades of steel to which an impact criterion was applied. The criterion for Grade D (primary steel) was a carryover of Lloyd's 1957 rule requiring 35 ft lbs (47 J) at 32°F (0°C)[A-8]. Lloyd's original rule also stipulated a minimum of 30 per cent fibrous-fracture appearance, although this portion was not adopted for Unification. This same 35 ft lb (47 J) requirement (as well as the fracture-appearance requirement) was presented by Boyd as a comparatively good requirement in relation to actual ship plates which have failed in service (see Section VI of this report and Fig. 33). The criterion for crack arresters (Grade E) was more severe, requiring 45 ft lbs (61 J) at 14°F (-10°C).

The decision not to incorporate impact requirements for Grades B and C was not well accepted by some of the societies, and it resulted in several compromises wherein each society placed emphasis on additional controls over manufacture. It was agreed that Grade C was to be normalized for thicknesses over 1-1/4 inches (31.8 mm) in the unification, and further reservations were made by individual societies in regard to chemical requirements and/or normalization and impact testing requirements.

TABLE A-I

The Unified Requirements of 1961

(Reference A-5)

GRADE	A	B	C	D	E
Method of Manufacture			Process to be specially approved	Process to be specially approved	Process to be specially approved
Deoxidation	Killed or semi-killed (Note 1)	Killed or semi-killed	Fully killed, fine grain practice (Aluminum treated)	Any method except rimmed steel	Fully killed, fine grain practice (Aluminum treated)
Austenitic grain size (McQuaid-Ebn method) ASTM scale (See ASTM E112-58T)			5 or finer To be determined on each charge (See note 4)		5 or finer To be determined on each charge
Chemical composition		See Notes 3 & 5	Note 5	Note 5	Note 5
Carbon	See Note 2	0.21% max	0.23% max	0.21% max	0.18% max
Manganese	See Note 2	0.80% min	0.60% - 1.40%	0.60% - 1.40%	0.70% - 1.50%
Silicon			0.15% - 0.30%	0.35% max	0.10% - 0.35%
Sulphur	0.05% max	0.05% max	0.05% max	0.05% max	0.05% max
Phosphorus	0.05% max	0.05% max	0.05% max	0.05% max	0.05% max
Tensile test: Tensile strength Elongation	41 to 50 kg/sq mm, or 26 to 32 tons/sq. in., or 58,000 to 71,000 lbs/zq. in. for all grades				
Impact test Temperature Energy				0°C 35 ft/lbs min or 4.84 kgm. min	-10°C 45 ft/lbs min or 6.22 kgm. min Every plate to be tested
Heat treatment			Normalized over 1½ in. (33mm) thick		Normalized

Note 1 – For Grade A rimming steel may be accepted subject to limitations by special agreement with the Society

Note 2 – For Grade A in thicknesses over ½ in (12.2 mm) the manganese content shall not be less than 2.5 times the carbon content.

Note 3 – For Grade B when the silicon content is 0.15 per cent or more (killed steel) the minimum manganese content may be reduced to 0.60 percent.

Note 4 – For Grade C the determination of grain size may be alternatively substituted by a suitable impact test agreed between the Society and the Steelmaker.

Note 5 – For Grades B, C, D, and E, the sum of carbon content plus 1/6 of the manganese content shall not exceed 0.40 per cent

Individual Requirements of the Seven Unified Societies

As mentioned previously, each society reserved the right to make minor alterations in the Unified Requirements to suit their own needs, and in this respect the Unified Requirements only serve as a guide for each society to follow. Examples of some of the more significant changes that have been adopted by individual societies since the unification are as follows:

1) American Bureau of Shipping - In regard to impact energy requirements, provisions have been made to test specimens oriented transverse to the rolling direction as an alternative to longitudinal specimens. A Grade CS that has a relatively high Mn/C ratio, and generally greater toughness, has been added.

2) Lloyd's Register of Shipping - Provides reduced impact energy requirements for subsize test pieces.

3) Bureau Veritas - Does not use Grade B.

4) Registro Italianale - Has increased the energy requirements to: 43 ft lb (58 J) at 32°F (0°C) for Grade D, and 54 ft lb (73 J) at 14°F (-10°C) or 25 ft lb (34 J) at -31°F (-35°C) for Grade E.

5) Det Norske Veritas - Still retains "NVW" grades of steel.

6) Nippon Kaiji Kyokai - No significant changes.

7) Germanischer Lloyd - No information available.

These and other minor alterations have been adopted by the societies at their own discretion.

Since the time of unification, the possibility of using higher strength steels in ship hull structures has been recognized by each society. Therefore, provisions have been made in the specifications for the manufacture, control, and product inspection of such steels. As is the case for mild steels, specific grades are designated within respective levels of yield strength as to quality and control of manufacture.

The CVN impact test is used in all applicable cases to control notch toughness and there is a general trend among the societies to specify both lower energy requirements and lower test temperatures for these steels than are maintained by the Unified Requirements. The significance of these requirements is that they parallel the typical reduction in both transition temperature and CVN energy which generally accompany the higher strength steels. However, as discussed in Section IV, toughness requirements should increase with increasing strength level.

Fig. A-1 presents the various CVN impact requirements of all societies on a temperature gradient chart. They have been grouped and surrounded in perimetric fashion to show the general trends that have developed, particularly in regard to the toughness requirements for higher strength steels. That is, the trend developed by RI, NV & ABS to lower both the testing temperature and the impact energy requirements for higher strength steels, as shown on Fig. A-1.

There are two societies, Lloyd's Register and Bureau Veritas, who maintain the same testing temperatures for higher strength steels that were adopted for the Unified Requirements. Bureau Veritas maintains the same impact energy requirements while Lloyd's proportions the requirements with yield strength. The strength proportioned requirements of Lloyd's represent the same basic approach utilized in developing the DT toughness requirements proposed in this report.

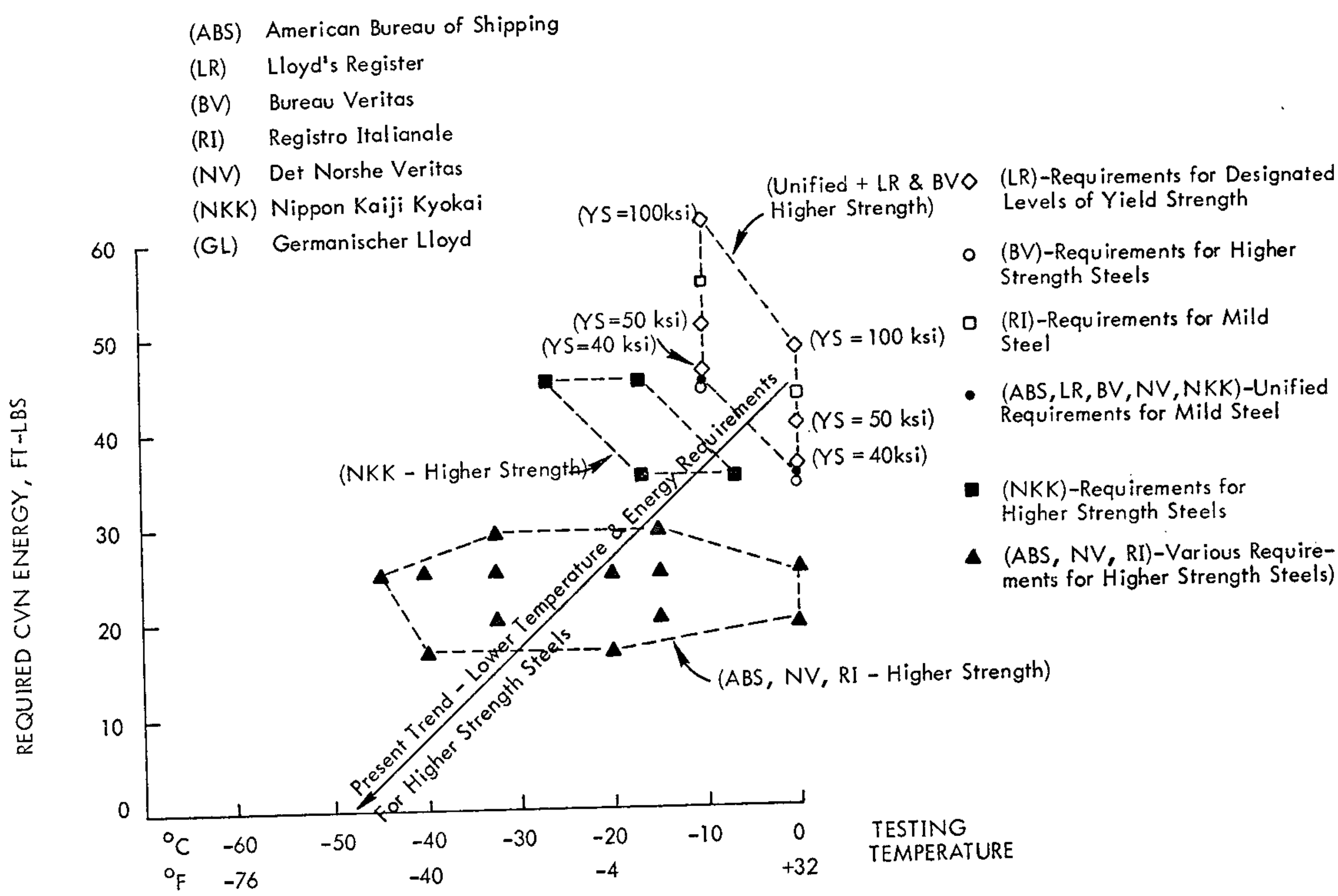

Fig. A-1. CVN Impact Requirements of World Unified Ship Classification Societies

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APPENDIX B

INTRODUCTION TO CONCEPTS OF FRACTURE MECHANICS

Fracture mechanics is a method of characterizing fracture or fatigue behavior in terms of structural parameters familiar to the engineer, namely, stress and flaw size. Fracture mechanics is based on stress analysis and thus does not depend on the use of empirical correlations to translate laboratory results into practical design information as long as the engineer can properly analyze the stresses in a specific structural application and knows the size of the flaws present in the structure. Therefore, the development of fracture mechanics offers considerable promise in solving the problem of designing to prevent brittle fractures in large complex welded structures

The fundamental principle of fracture mechanics is that the stress field ahead of a sharp crack can be characterized in terms of a single parameter K_I, the stress intensity factor, having units of ksi $\sqrt{\text{inch}}$ ($MN/m^{3/2}$). The equations that describe the elastic-stress field in the vicinity of a crack tip in a body subjected to tensile stresses normal to the plane of the crack are presented in Figure B-1. These stress-field equations show that the distribution of the elastic-stress field in the vicinity of the crack tip is invarient in all structural components that are subjected to deformations of this type (designated as Mode I because the applied stress is normal to the crack surface). Furthermore, the magnitude of the elastic-stress field can be described by a single parameter, K_I. Consequently, the applied stress, the crack shape and size, and the structural configuration associated with structural components subjected to this type of deformation affect the value of the stress-intensity factor (K_I) but do not alter the stress-field distribution ahead of the crack. Thus this analysis can be used for different structural configurations as shown in Figure B-2. Other crack geometries have been analyzed for different structural configurations and are published elsewhere. In all cases, K_I is a function of the nominal stress and the square root of flaw size.

The material properties that are a measure of the fracture resistance likewise have units of ksi $\sqrt{\text{inch}}$ ($MN/m^{3/2}$) but depend on the particular material, loading rate, and constraint as follows:

K_c = Critical stress-intensity factor for static loading and plane-stress conditions of variable constraint. Thus, this value depends on specimen thickness.

K_{Ic} = Critical stress-intensity factor for static loading and plane-strain conditions of maximum constraint. Thus, this value is a minimum value for thick plates.

K_{ID} = Critical stress-intensity factor for dynamic (impact) loading and plain-strain conditions of maximum constraint.

Each of these values are also a function of temperature for those steels exhibiting a transition from brittle to ductile behavior. For a given temperature, generally $K_{ID} < K_{IC} < K_c$.

By knowing the critical value of K_I at failure (K_c, K_{Ic}, or K_{ID}) for a given steel of a particular thickness and at a specific temperature and loading rate, the designer can determine flaw sizes that can be tolerated in structural members for a given design stress level. Conversel he can determine the design stress level that can be safely used for a flaw size that may be present in a structure.

As a general example, consider the equation relating K_I to the applied stress and flaw size for a through-thickness crack in a wide plate, that is $K_I = \sigma\sqrt{\pi a}$. Assume that laboratory

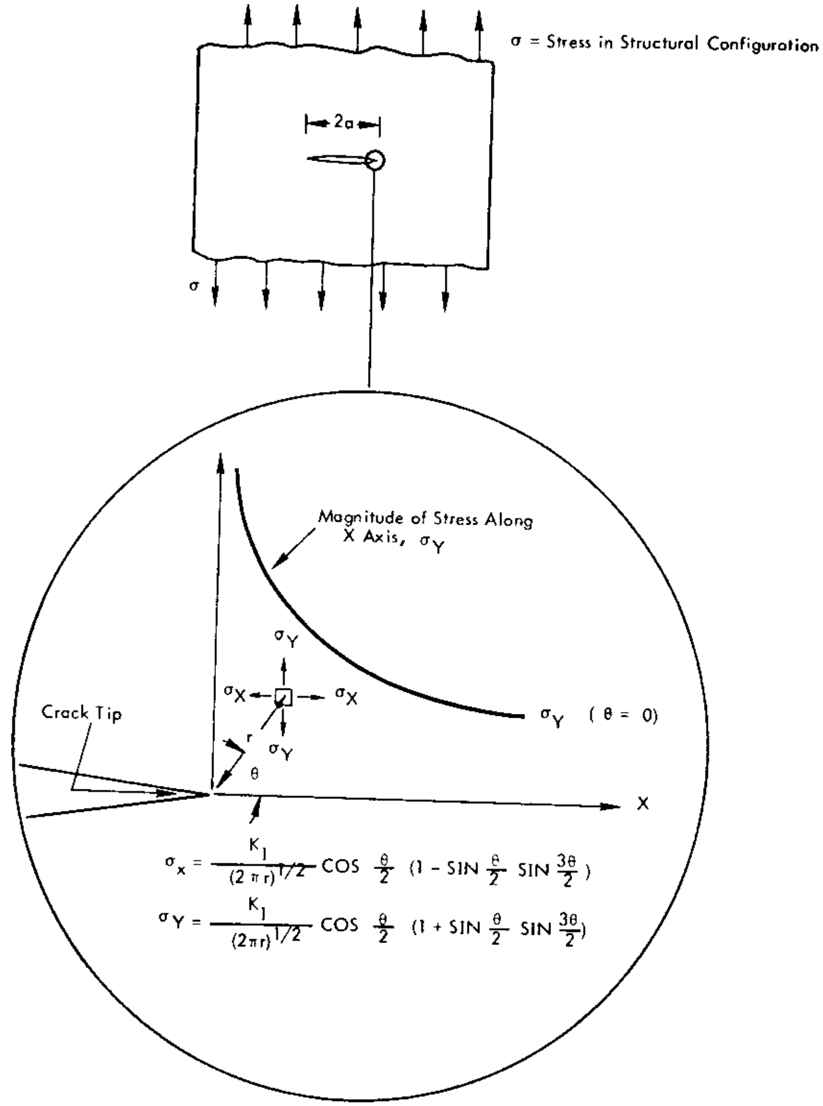

Fig. B-1. Elastic-Stress-Field Distribution Ahead of a Crack

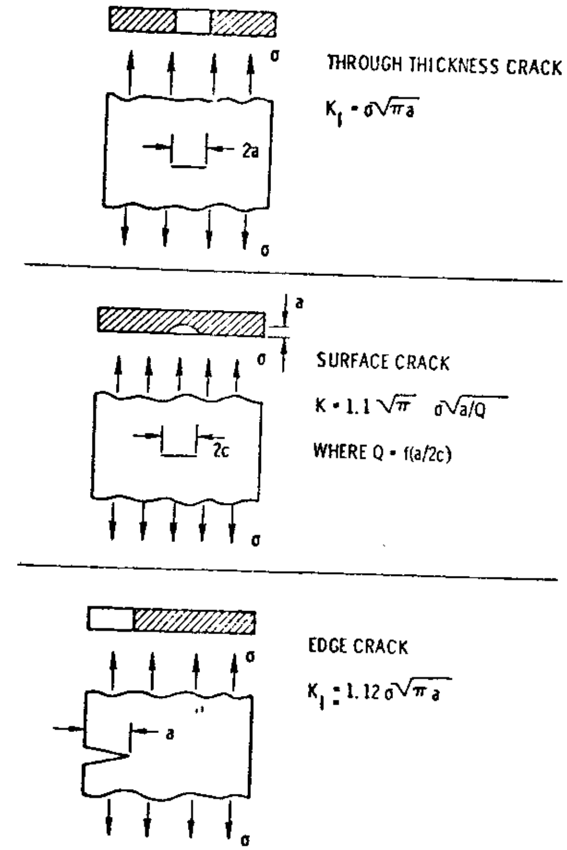

Fig. B-2. K_I Values for Various Crack Geometries test results show that for a particular structural steel with a yield strength of 80 ksi (552 MN/m^2) the K_c is 60 ksi $\sqrt{inch}$ (66 $MN/m^{3/2}$) at the service temperature, loading rate, and plate thickness used. Also assume that the design stress is 20 ksi (138 MN/m^2). Substituting $K_I = K_c$ = 60 ksi $\sqrt{inch}$ (66 $MN/m^{3/2}$) into the appropriate equation in Figure B-3, 2a = 5.7 inches (145 mm). Thus for these conditions the tolerable flaw size would be about 5.7 inches (145 mm). For a design stress of 45 ksi (310 MN/m^2), the same material could only tolerate a flaw size, 2a, of about 1.1 inches (27.9 mm). If residual stresses such as may be due to welding are present so that the total stress in the vicinity of a crack is 80 ksi (552 MN/m^2), the tolerable flaw size is reduced considerably. Note from Figure B-3 that if a tougher steel is used, for example, one with a K_c of 120 ksi $\sqrt{inch}$ (132 $MN/m^{3/2}$) the tolerable flaw sizes at all stress levels are significantly increased. If the toughness of a steel is sufficiently high, brittle fractures will not occur and failures under tensile loading can occur only by general plastic yielding, similar to the failure of a tension test specimen. Fortunately, most ship steels have this high level of toughness.

A useful analogy for the designer is the relation between applied load (P), nominal stress (σ), and yield stress (σ_y) in an unflawed structural member, and between applied load (P), stress intensity (K_I), and critical stress intensity for fracture (K_c, K_{Ic}, or K_{ID}) in a structural member with a flaw. In an unflawed structural member, as the load is increased, the nominal stress increases until an instability (yielding at σ_y) occurs. As the load is increased in a structural member with a flaw (or as the size of the flaw grows by fatigue), the stress intensity, K_I, increases until an instability (fracture at K_c, K_{Ic}, K_{ID}) occurs. Thus the K_I level in a structure should always be kept below the appropriate K_c value in the same manner that the nominal design stress (σ) is kept below the yield strength (σ_y).

Another analogy that may be useful in understanding the fundamental aspects of fracture mechanics is the comparison with the Euler column instability. The stress level required to cause instability in a column (buckling) descreases as the L/r ratio increases. Similarly, the stress level required to cause instability (fracture) in a flawed tension member decreases as the flaw size (a) increases. As the stress level in either case approaches the yield strength, both the Euler analysis and the K_c analysis are invalidated because of yielding. To prevent buckling, the actual stress and (L/r) values must be below the Euler curve. To prevent fracture, the actual stress and flaw size, a, must be below the K_c line shown in Figure B-3. Obviously, using a material with a high level of notch toughness (e.g. a K_c level of 120 ksi $\sqrt{inch}$ (132 $MN/m^{3/2}$) compared with 60 ksi $\sqrt{inch}$ (66 $MN/m^{3/2}$) in Figure B-3) will increase the possible combinations of design stress and flaw size that a structure can tolerate without fracturing.

The critical stress-intensity at fracture (K_c, K_{Ic}, or K_{ID} depending on plate thickness) of a particular material for a given temperature and loading rate is related to the nominal stress and flaw size as follows:

$$K_c, K_{Ic}, \text{ or } K_{ID} = C\sigma\sqrt{a}$$

where K_c, K_{Ic}, or K_{ID} = material toughness, ksi $\sqrt{inch}$ ($MN/m^{3/2}$) at a particular temperature, loading rate, and plate thickness

C = constant, function of crack geometry

σ = nominal stress, ksi (MN/m^2)

a = flaw size, inches (mm)

Thus, the maximum flaw size a structural member can tolerate at a particular stress level is:

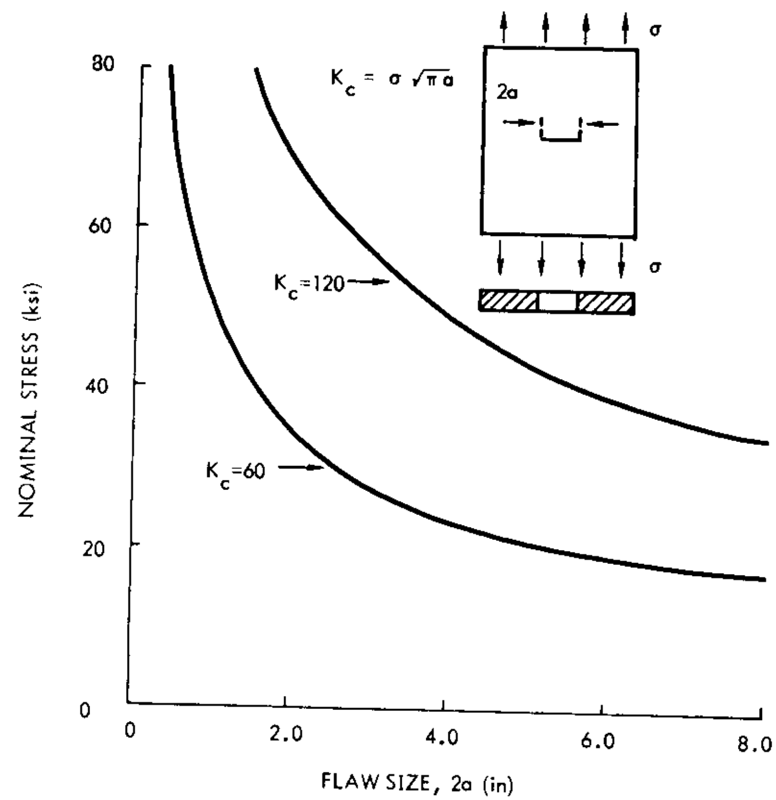

Fig. B-3. Stress-Flaw Size Relation for Through Thickness Crack

$$a = \left(\frac{K_c, K_{Ic}, \text{ or } K_{ID}}{C\sigma}\right)^2$$

By knowing the particular relation between K_C, K_{Ic}, or K_{ID}, σ, and flaw size, a, for a given structure (the most widely used relations are shown in Figure B-2) the engineer can analyze the safety of a structure against fracture in the following manner:

1) Obtain the values of K_c, K_{Ic}, or K_{ID} and σ_y at the service temperature and loading rate for the materials being used in the structure. Note that for a complete analysis of welded structures, values for the base metal, weld metal and heat-affected zone should be obtained. As noted in the main report, most ship steels have toughness values greater than can be measured by existing ASTM test methods and thus auxiliary test methods must be used to estimate K_{ID} values. Although this is a very desirable condition because it means most ship steels are not brittle at service temperatures, the determination of the critical toughness values is quite difficult.

2) Select the type of flaw that will most likely exist in the member being analyzed and the corresponding K_I equation. Figure B-2 shows the fracture mechanics models that describe the most common types of flaws occurring in structural members. Complex shape flaws can often be approximated by one of these models. Additional equations to analyze other crack geometries are given in reference 16 of the text.

3) Plot the stress-flaw-size relation using the appropriate K_I expression.

An example of this relation between stress, flaw size, and material toughness is presented in Figure B-3. The results of this stress-flaw size curve can be used to establish design stress levels and inspection requirements. The following important conclusions should be noted:

1) In regions of high residual stress, where the actual stress can equal the yield stress over a small region, the critical crack size has to be computed for σ_y instead of the design stress, σ. If the material (steel and weld metal) is sufficiently tough, the critical crack size at full yield stress loading should be satisfactory. Under fatigue loading, the residual stresses should decrease and the critical crack size becomes the value at the design stress. Note that the "critical crack size" in a structure is a function of the stress level and is not a single value for a particular material.

2) If the level of toughness of the material is sufficiently high, any crack which does initiate from a weld in the presence of residual stresses should arrest quickly as soon as the crack propagates out of the region of high residual stress. However, the initial flaw size for any subsequent fatigue crack growth will be fairly large.

3) For design stress levels, check the calculated critical crack size. If it is larger than the plate thickness, crack growth (by fatigue) should lead to relaxation of the constraint ahead of the crack, i.e., plane-stress behavior. For this case, the K_c (critical plane-stress stress-intensity factor) will be greater than K_{Ic} or K_{ID} which is an additional degree of conservatism.

4) For steels with low-toughness values and high design stress levels, e.g., design stress of 60 ksi (414 MN/m^2) and a K_c of 60 ksi $\sqrt{\text{inch}}$ (66 $MN/m^{3/2}$), Figure B-3, the steel could still be used if the design stress is reduced significantly. However, use of structural steels with low-toughness levels requires precise levels of total inspection of the structure and is not considered possible.

EFFECT OF TEMPERATURE, LOADING RATE, AND THICKNESS ON K_c, K_{Ic}, or K_{ID}

General

In principle, the application of fracture mechanics in analysis of flawed members is straightforward, as shown in the previous examples. In reality, however, the application of fracture mechanics to analyze flawed members depends on the engineer having specific information in the following areas:

1) Stress Analysis of Cracks

   The stress-intensity factor, K_I, has been established for various crack geometries, and can be approximated for other geometries . Thus the application of fracture mechanics generally is not hampered by the availability of stress-intensity factors for various shape cracks. The most commonly used stress-intensity factors were shown in Figure B-2.

2) Actual Flaw Sizes

   The actual flaw size in a structure is very difficult to determine. Such factors as quality of inspection, skill of the inspector, available equipment, etc., make the determination of actual flaw sizes in a structure extremely difficult. From an engineering viewpoint, the designer must assume that the largest possible reasonable size flaw can be present in regions of maximum stress unless he has specific knowledge to the contrary.

3) Crack-Toughness Values for Particular Materials

   As is well known, the inherent crack toughness of most structural steels decreases with decreasing temperature and/or increasing loading rate. In addition the notch toughness also decreases with increasing plate thicknesses up to the limiting value of plane strain, K_{Ic} or K_{ID}. Thus, before the engineer can predict the fracture behavior of a particular structural member, using concepts of fracture mechanics, he must know the K_c value for the particular service temperature and loading rate, as well as member thickness. Very little quantitative information on the crack toughness of ship steels currently exists, although that which does exist indicates that the toughness levels of these steels are higher than can be measured using existing ASTM Standardized Test Methods. Thus auxiliary test methods are necessary to estimate the crack-toughness levels of ship steels.

Thickness Effects

Ahead of a sharp crack, the lateral constraint is such that through-thickness stresses are present. Because these stresses must be zero at each surface of a plate, the through-thickness stresses are less for thin plates compared with thick plates. For very thick plates, a triaxial state-of-stress occurs which reduces the apparent ductility of the steel and the notch toughness is reduced. This decrease in notch toughness is controlled by the thickness of the plate, even though the inherent metallurgical properties of the material are unchanged. Thus the notch toughness (K_c) decreases for thick plates compared with thinner plates of the same material. This behavior is shown in Figure B-4, for a high strength maraging steel. For thicknesses greater than some value related to the toughness and strength of individual steels, maximum constraint occurs and plane strain (K_{Ic}) behavior results. Conversely, as the thickness of the plate is decreased (even though the inherent metallurgical characteristics of the steel are not changed), the notch-toughness increases and plane-stress (K_c) behavior exists.

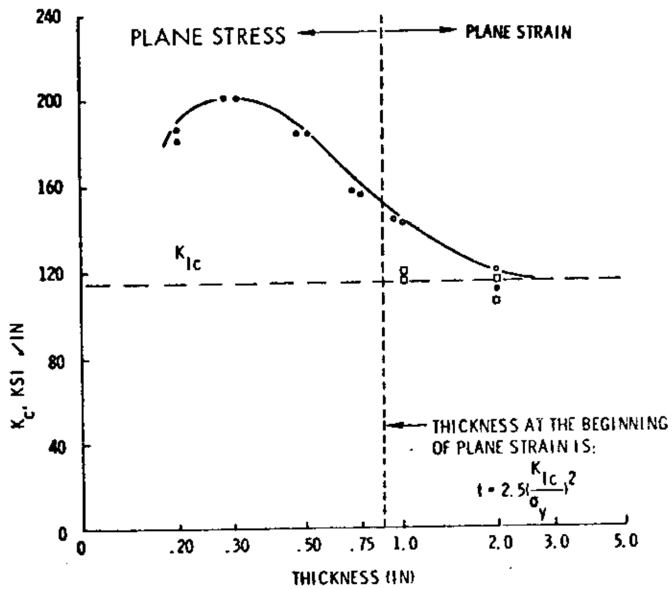

Fig. B-4. Effect of Thickness on K_c Behavior

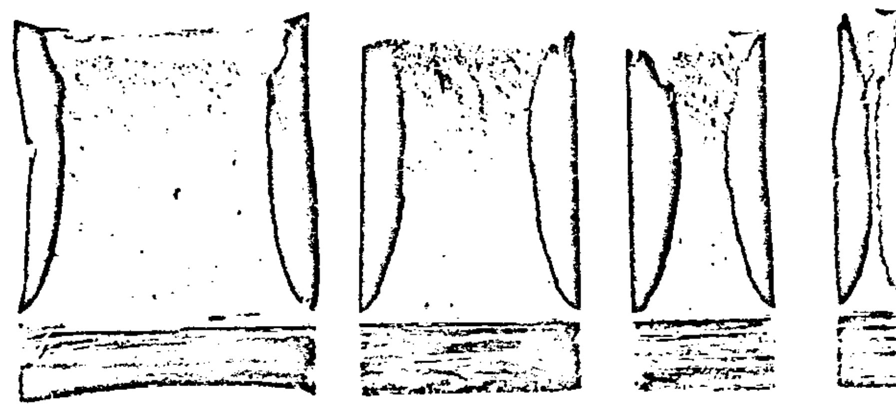

Fig. B-5. Effect of Specimen Thickness (2-, 1 1/2-, 1-, and 1/2- inches) on Toughness as Determined by Size of Shear Lips

Figure B-5 shows the shear lips on the surface of fracture test specimens having different plate thicknesses. The percentage of shear lips as compared with the total fracture surface is a qualitative indication of notch toughness. A small percentage of shear lip area indicates a relative brittle behavior. A comparison of the fracture surfaces in Figure B-5 shows that thinner plates are more resistant to brittle fracture than thick plates. This fact is not new to engineers, but the fact that a quantitative fracture mechanics analysis of the phenomena can now be made is new.

Temperature and Loading Rate

In general, the crack toughness of most steels decreases with decreasing temperature and increasing loading rate. Loading rate refers to the time it takes to reach maximum load and for most structures can vary from very slow (essentially static for K_{Ic}) to dynamic (usually impact loading rates for K_{ID}). Examples of this type behavior for two ship steels, ABS-C and A517, were presented in Figures 8 and 13. Note that the same general behavior exists for the K_{Ic}, CVN, and DT test results (Figure 13) but that the rapid increase in values occurs at different temperatures because the tests are conducted at different loading rates. The actual loading rates for most structures are generally between the limits of "static" loading (strain rate approximately 10^{-5} sec^{-1}) and dynamic or impact (strain rate approximately 10 sec^{-1}). If specific information on the loading rates of actual structures can be obtained, an intermediate loading rate (Figure 5) can be used to analyze the fracture behavior. However intermediate loading-rate tests are extremely expensive to conduct.

The salient features of the results presented in Figures 8, 13, and B-4 may be summarized as follows:

1) Increasing test temperature increases the K_c, K_{Ic}, or K_{ID} value at a particular loading rate for most structural steels.

2) Increasing the loading rate decreases the critical K_c or K_{Ic} value to a K_{ID} value at a particular temperature for most structural steels.

3) Increasing the thickness of the plate of steel being investigated decreases the K_c value to a lower bound K_{Ic} value, Figure B-4.

STATIC VERSUS DYNAMIC CONDITIONS

Current methods of design and fabrication are such that engineers expect structures to be able to tolerate yield stress loading in tension without failing. The maximum allowable flaw size in a member can be related to the notch toughness and yield strength as follows:

$$a = \left(\frac{K_c,\ K_{Ic},\ \text{or}\ K_{ID}}{C\sigma_y} \right)^2$$

For conditions of maximum constraint (plane strain), such as would occur in thick plates or in regions of high constraint, the flaw size becomes proportional to $(K_{Ic}/\sigma_y)^2$, where both K_{Ic} and σ_y should be measured at the service temperature and loading rate of the structure.

Thus the K_{Ic}/σ_y ratio (or K_{ID}/σ_{yD}) becomes a good index for measuring the relative toughness of structural material. Because for most structural applications it is desirable that the structure tolerate large flaws without fracturing, the use of materials with high K_{Ic}/σ_y ratios is a desirable condition.

The question becomes, how high must the K_{Ic} / σ_y ratio for a structural material be to insure satisfactory performance in complex welded structures such as ships, where complete initial inspection for cracks and continuous monitoring of crack growth throughout the life of a structure are not always possible, practical, or economical.

No simple answer exists because the engineer must take into account such factors as the design life of the structures, consequences of a failure in a structural member, redundancy of load path, probability of overloads and fabrication and material cost. However, as described in the main report, fracture mechanics can provide an engineering approach to rationally evaluate this question. Basic assumptions are that flaws do exist in structures, yield stress loading is probably in some critical parts of a structure, and plane-strain conditions can exist (although the use of thin plates tends to minimize the possibility of plane-strain behavior). Therefore, the K_{Ic} / σ_y ratio for materials used in particular structure is one of the primary controlling parameters that defines the relative safety of a structure against brittle fracture.

If a structure is loaded "slowly" (~ 10^{-4} in/in/second), the K_{Ic} / σ_{ys} ratio is the controlling toughness parameter. If, however, the structure is loaded "rapidly" (~ 10' in/in/second or impact loading), the K_{ID} / σ_{yD} ratio is the controlling parameter. Definitions and test conditions for each of these ratios is as follows:

1) K_{Ic} - critical plane-strain stress-intensity factor under conditions of static loading as described in ASTM Test Method E-399 - Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials.

2) σ_{ys} - Static tensile yield strength obtained in "slow" tension test as described in ASTM Test Method E-8 - Standard Methods of Tension Testing of Metallic Materials.

3) K_{ID} - Critical plane-strain stress-intensity factor as measured by "dynamic" or "impact" tests. The test specimen is similar to a K_{Ic} test specimen, but is loaded rapidly. There is no standardized test procedure but the general test method is described elsewhere.

4) σ_{yD} - Dynamic tensile yield strength obtained in "rapid" tension test at loading rates comparable to those obtained in K_{ID} tests. Although extremely difficult to obtain, a good engineering approximation based on experimental results of structural steels is:

$$\sigma_{yD} = {}_{ys} + 20 \text{ ksi}$$

As discussed in the main report, the toughness of ship hull steels should be analyzed using K_{ID} / σ_{yD} values, because ships can be subjected to dynamic loadings. If ships are loaded at somewhat lower loading rates, the use of K_{ID} / σ_{yD} parameters to establish required toughness levels is conservative.

SUBCRITICAL CRACK GROWTH

The above analysis pertains to conditions at fracture. For most structural steels, the tolerable flaw sizes are much larger than any initial undetected flaws. However, for structures subjected to fatigue loading (or stress-corrosion cracking), these initial cracks can grow throughout the life of the structure. Fracture mechanics provides a means to analyze the subcritical crack-growth behavior of structures using the same general equations and flaw geometries (Figure B-2) used to analyze conditions at fracture. Thus, an overall approach to preventing fracture or fatigue failures in large welded structures assumes that a small flaw of certain geometry exists after fabrication and that this flaw can either cause brittle fracture or grow by fatigue to the critical size. To insure that the structure does not fail by fracture, the calculated critical crack size, a_{cr}, at design load must be sufficiently large, and the number of cycles of loading required to grow a small crack to a critical crack must be greater than the design life of the structure.

Thus, although S-N curves have been widely used to analyze the fatigue behavior of steels and weldments, closer inspection of the overall fatigue process in complex welded structures indicates that a more rational analysis of fatigue behavior is possible by using concepts of fracture mechanics. Specifically, small (possibly large) fabrication flaws are invariably present in welded structures, even though the structure has been inspected. Accordingly, a realistic approach to designing to prevent fatigue failure would be to assume the presence of an initial flaw and analyze the fatigue crack growth behavior of the structural member. The size of initial flaw is obviously highly dependent upon the quality of fabrication and inspection.

A schematic diagram showing the general relation between fatigue crack initiation and propagation is shown in Figure B-6. The question of when does a crack "initiate" to become a "propagating" crack is somewhat philosophical and depends on the level of observation of a crack, i.e., crystal imperfection, dislocation, microcrack, lack of penetration, etc. An engineering approach to fatigue would be to assume an initial flaw size on the basis of the quality of inspection used, and then to calculate the number of cycles it would take for this crack to grow to a size critical for brittle fracture. It is of interest to note that the fracture mechanics approach has been found to be compatible with existing S-N fatigue data of welded members.

The procedure to analyze the crack-growth behavior in steels and weld metals using fracture-mechanics concepts is as follows:

1) On the basis of quality of inspection estimate the maximum initial flaw size, a_o, present in the structure and the associated K_I relation, Figure B-2, for the member being analyzed.

2) Knowing K_c or K_{Ic} and the nominal maximum design stress, calculate the critical flaw size, a_{cr}, that would cause failure by brittle fracture.

3) Obtain an expression relating the fatigue crack growth rate of the steel or weld metal being analyzed. The following conservative estimates of the fatigue-crack growth per cycle of loading, da/dN, have been determined for martensitic steels (for example, A514/517) as well as ferrite-pearlite steels (for example, A36) in a room temperature air environment.

   Martensitic Steels

   $da/dN = 0.66 \times 10^{-8} (\Delta K_I)^{2.25}$

   Ferrite-Pearlite Steels

   $da/dN = 3.6 \times 10^{-10} (\Delta K_I)^3$

   where

   da/dN - fatigue crack growth per cycle of loading, inches/cycle

   K_I = stress-intensity factor range, ksi $\sqrt{\text{inch}}$ ($MN/m^{3/2}$)

4) Determine K_I using the appropriate expression for K_I, the estimated initial flaw size, a_o, and the range of live-load stress, $\Delta\sigma$ (cycle fatigue stress).

5) Integrate the crack-growth rate expression between the limits of a_o (at the initial K_I) and a_{cr} (at K_{Ic}) to obtain the life of the structure prior to failure.

A numerical example of this procedure is as follows:

1) Assume the following conditions:
   a) A514 steel, σ_y = 100 ksi (689 MN/m^2)
   b) K_{Ic} = 150 ksi $\sqrt{inch}$ (165 $MN/m^{3/2}$)
   c) a_o = 0.3 inches (7.6 mm), edge crack in tension, Figure B-2
   d) σ_{max} = 45 ksi (310 MN/m^2)

      σ_{min} = 25 ksi (172 MN/m^2)

      $\Delta\sigma$ = 20 ksi (138 MN/m^2) (live-load stress range)
   e) $K_I = 1.12 \sqrt{\pi}\ \sigma\sqrt{a}$, edge crack in tension, Figure B-2

2) Calculate a_{cr} at σ = 45 ksi (310 MN/m^2)

$$a_{cr} = \left(\frac{K_{Ic}}{1.12 \sqrt{\pi}\ \sigma_{max}}\right)^2 = \left(\frac{150}{1.12\ (1.77)\ (45)}\right)^2$$

$$a_{cr} = 2.8 \text{ inches (71.1 mm)}$$

3) Assume an increment of crack growth, Δa. In this case assume $\Delta a = 0.1$ inch (2.5 mm). If smaller increments of crack growth were assumed, the accuracy woul be increased slightly.

4) Determine expression for ΔK_I, where a_{avg} represents the average crack size betwe the two crack increments a_i and a_j.

$$\Delta K_I = 1.12 \sqrt{\pi}\ \Delta\sigma \sqrt{a_{avg}}$$

$$\Delta K_I = 1.98\ (20)\ \sqrt{a_{avg}}$$

5) Using the appropriate expression for crack-growth rate,

   $da/dN = 0.66 \times 10^{-8} (\Delta K_I)^{2.25}$

   Solve for ΔN for each increment of crack growth replacing da/dN by $\Delta a/\Delta N$

$$\Delta N = \frac{\Delta a}{.66 \times 10^{-8}\ (1.98\ (20)\ \sqrt{a_{avg}})^{2.25}}$$

$$\Delta N = 12{,}500 \text{ cycles}$$

6) Repeat for a = .4 to .5 inches (10.2 to 12.7 mm), etc., by numerical integration as shown in Table B-I. The flaw size - life results for this example are presented in Figure B-7. If only the desired total life is required, the expression for ΔN ca

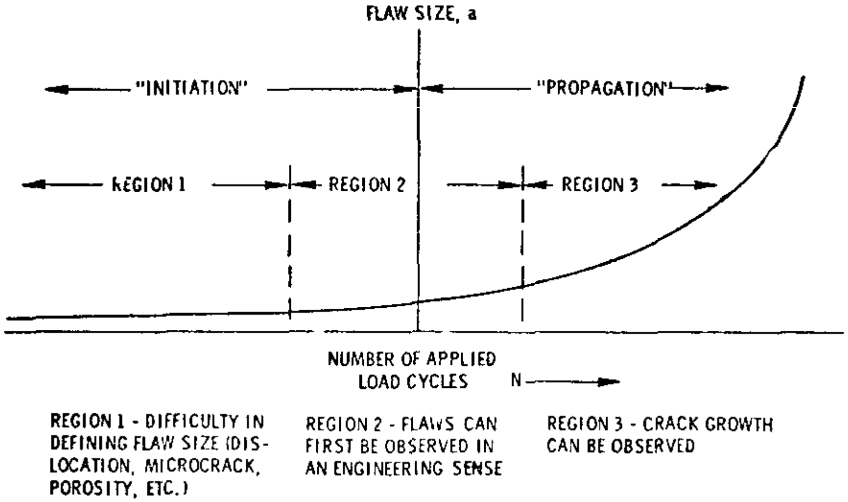

Fig. B-6 . Schematic Showing Relation Between "Initiation" Life And "Propagation" Life

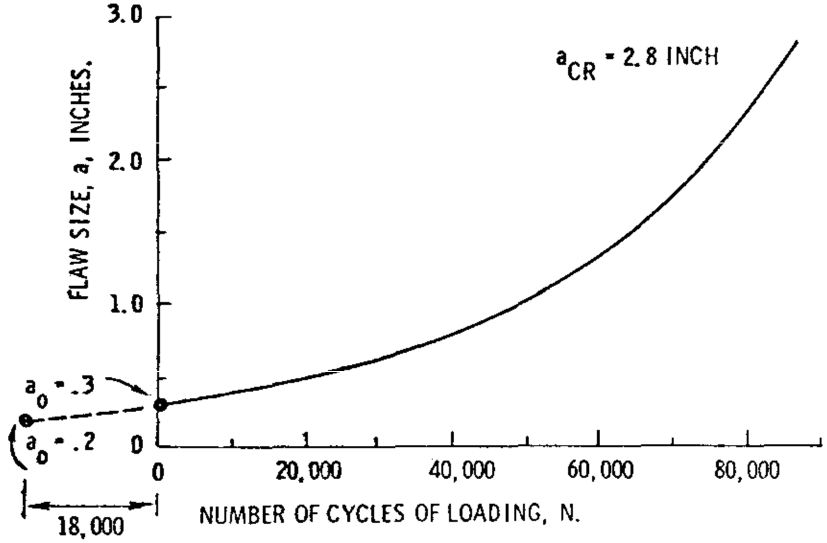

Fig. B-7. Fatigue Crack Growth Curve

be integrated directly. In this example, direct integration yielded a life of 87,600 cycles while the numerical technique gave a life of 86,700 cycles.

Note that the total life to propagate a crack from 0.3 to 2.8 inches (7.6 to 71.1 mm) in this example is 86,700 cycles. If the required life is 100,000 cycles, then this design would be inadequate and one or more of the following changes should be made:

1) Increase the critical crack size at failure (a_{cr} = 2.8 inches (71.1 mm)) by using a material with a higher K_{Ic} value.

2) Lower the design stress σ_{max}, to increase the critical crack size at failure.

3) Lower the stress range ($\Delta\sigma$) to decrease the rate of crack growth, thereby increasing the number of cycles required for the crack to grow to the critical size. Note that because the rate of crack growth is a power function of $\Delta\sigma$, or actually ΔK, lowering the stress range slightly has a significant effect on the life.

4) Improve the fabrication quality and inspection capability so that the initial flaw size (a_o) is reduced. It is clear from Table B-I and Figure B-7 that most of the life is taken up in the early stages of crack propagation. In fact, to double the initial crack size during the early stages of propagation requires almost half the total number of cycles. Therefore, any decrease in initial flaw size has a very significant effect on the fatigue life of a structural member.

In this example, if a_o were only 0.2 inches (5.1 mm) the design would be satisfactory. That is, the number of cycles to grow a crack 0.2 to 0.3 inches (5.1 to 7.6 mm) is about 18,000 cycles as indicated in Figure B-7, which (added to the 86,700 cycles required to grow the crack from .3 to 2.8 inches (7.6 to 71.1 mm)) would make the total life equal to 104,700 cycles. It should be noted that for steels with high-toughness levels the state-of-stress ahead of large cracks may be plane stress and thus larger cracks could be tolerated than are calculated on the basis of plane-strain behavior. However, because the crack-growth rate is increasing rapidly for large cracks as illustrated in Figure B-7, the life may not be increased significantly.

At present, this fracture-mechanics analysis has the same limitation that the conventional S-N analysis has, in that variable amplitude loading is not considered. However, preliminary results of various research programs indicate that random-load crack propagation analyses are feasible.

TABLE B-I

FATIGUE CRACK GROWTH CALCULATIONS

$$\Delta N = \frac{\Delta a}{.66 \times 10^{-8} \left(1.98 \; (\Delta\sigma) \sqrt{a_{avg}}\right)^{2.25}}$$

WHERE Δa = 0.10 inch (2.54 mm)

$\Delta\sigma$ = 20 ksi (138 MN/m^2)

a_o, Inch	a_f, Inch	a_{avg}, Inch	ΔK ksi $\sqrt{\text{inch}}$	ΔN Cycles	ΣN Cycles
.3	.4	.35	23.5	12,500	12,500
.4	.5	.45	26.7	9,750	22,250
.5	.6	.55	29.4	7,550	29,800
.6	.7	.65	32.2	6,150	35,950
.7	.8	.75	34.6	5,200	41,150
.8	.9	.85	36.6	4,600	45,750
.9	1.0	.95	38.8	4,100	49,850
1.0	1.1	1.05	40.5	3,700	53,550
1.1	1.2	1.15	42.5	3,300	56,850
1.2	1.3	1.25	44.5	2,950	59,800
1.3	1.4	1.35	46.1	2,700	62,500
1.4	1.5	1.45	47.7	2,550	65,050
1.5	1.6	1.55	49.3	2,350	67,400
1.6	1.7	1.65	51.0	2,200	69,600
1.7	1.8	1.75	52.5	2,050	71,650
1.8	1.9	1.85	54.0	1,900	73,550
1.9	2.0	1.95	55.6	1,800	75,350
2.0	2.1	2.05	56.8	1,700	77,050
2.1	2.2	2.15	58.5	1,600	78,650
2.2	2.3	2.25	59.6	1,500	80,150
2.3	2.4	2.35	60.8	1,450	81,600
2.4	2.5	2.45	62.5	1,400	83,000
2.5	2.6	2.55	63.5	1,350	84,350
2.6	2.7	2.65	64.8	1,200	85,550
2.7	2.8	2.75	66.0	1,150	86,700

1 inch = 25.4 mm

1 ksi$\sqrt{\text{inch}}$ = 1.1 MN/m$^{3/2}$

APPENDIX C

TECHNICAL FACTORS AFFECTING THE IMPLEMENTATION OF CRITERIA

The specific material-toughness criteria developed in this report are as follows:

1) All steels and weldments used in primary load-carrying plate members in the main-stress regions of ships have a maximum NDT of 0°F (-18°C) as measured by ASTM Test Method E-208-69.
2) All steels and weldments used in primary load-carrying plate members in the main-stress regions exhibit the levels of absorbed energy in a 5/8-inch (15.9 mm) thick dynamic-tear (DT) specimen as presented in Table I.
3) All steels and weldments used in primary load-carrying plate members in the secondary-stress regions of ships must satisfy a less stringent material-toughness requirement of NDT ≤ 20°F (-7°C).
4) Crack-arrester steels must exhibit very high levels of DT notch toughness (essentially fully plastic) as presented in Table II.

Although the above criteria provide the general guidelines for fracture control in welded ship hulls, there are several very important factors to be considered in the implementation of these criteria. These factors are as follows:

1) Specific Strength Levels: Ordinary-strength ship steels have yield strengths as low as 32 ksi (221 MN/m^2), although the actual values of these steels are closer to the 40 ksi (276 MN/m^2) level shown in Table I.

   For specification use, however, the particular ABS (or ASTM) steels that fall into the various strength levels must be established.

2) Definition of Load-Carrying Members: Each of the different types of primary load-carrying members (main-stress and secondary-stress) should be identified specifically in terms of their allowable design stress levels.
3) Longitudinal vs Transverse Specimen Orientation: The DT test specimens should be oriented so that the specimens are parallel to the direction of significant stress. In most cases, this will be longitudinal. However, there may be cases where the transverse stress can be significant and therefore the toughness transverse to the rolling direction must be adequate. Thus, specimen orientation becomes an important feature from a structural viewpoint as well as the more familiar one of amount of cross-rolling.
4) Existing Rules and Specifications: For ordinary-strength level steels, the existing ABS Rules and Specifications have been developed over the years on the basis of considerable experience and appear to be satisfactory.

   If the proposed material-toughness requirements are added to the ABS Rules currently in existence, the reliability of ships will be improved. How the proposed criteria should be incorporated into existing Rules, and how the rules should be modified for high-strength steels will require careful consideration of the scope of existing specifications.

5) Plates Less than 5/8-inch (15.9 mm) Thick: Generally thin plates are less susceptible to brittle fractures compared with thicker plates. Thus, primary load-carrying members that are smaller than the thickness of the standard 5/8 inch (15.9 mm) DT specimen should be satisfactory. However, the use of sub-thickness DT specimens (with a corresponding reduction in required energy) is recommended.

6) Plates Greater than 2-inches (50.8 mm) Thick: In the range 5/8-2 inches (15.9 to 50.8 mm), thickness has a second-order effect on the toughness of ship steels compared with notch acuity and loading rate. However, if plates 2 inches (50.8 mm) or thicker are used, either a larger thickness DT specimen should be specified or the required energy should be increased above that required in Tables I or II.

7) Shipyard Testing Facilities: A consideration of the details of shipyard testing procedures should be made. These would include the number of specimens to be tested, use of falling weight or pendulum-type testing machines, and simplified procedures for measuring absorbed energy such as adjusting the initial potential energy to be equal to the energy the specimen is required to absorb.

To facilitate the implementation of both the NDT and DT testing procedures, copies of ASTM Test Method E 208-69 "Standard Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels" and MIL Standard 1601 (ships), "DT Test Procedures" are included in this appendix.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

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Standard Method for

CONDUCTING DROP-WEIGHT TEST TO DETERMINE NIL-DUCTILITY TRANSITION TEMPERATURE OF FERRITIC STEELS[1]

ASTM Designation: E 208 – 69

This Standard of the American Society for Testing and Materials is issued under the fixed designation E 208; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval.

INTRODUCTION

This drop-weight test was developed at the Naval Research Laboratory in 1952 and has been used extensively to investigate the conditions required for initiation of brittle fractures in structural steels. Drop-weight test facilities have been established at several Naval activities, research institutions, and industrial organizations in this country and abroad. The method is used for specification purposes by industrial organizations and is referenced in several ASTM specifications and the ASME Boiler and Pressure Vessel Code. This procedure was prepared to ensure that tests conducted at all locations would have a common meaning.

1. Scope

1.1 This method covers the determination of the nil-ductility transition (NDT) temperature of ferritic steels, $\frac{5}{8}$-in. and thicker.

1.2 This method may be used whenever the inquiry, contract, order, or specification states that the steels are subject to fracture toughness requirements as determined by the drop-weight test.

2. Summary of Method

2.1 The drop-weight test employs simple beam specimens specially prepared to create a material crack in their tensile surfaces at an early time interval of the test. The test is conducted by subjecting each of a series (generally four to eight) of specimens of a given material to a single impact load at a sequence of selected temperatures to determine the maximum temperature at which a specimen breaks. The impact load is provided by a guided, free-falling weight with an energy of 250 to 1200 ft-lb, depending on the yield strength of

[1] Under the standardization procedure of the Society, this method is under the jurisdiction of the ASTM-ASME Joint Committee on Effect of Temperature on the Properties of Metals. A list of members may be found in the ASTM Year Book.

Current edition effective May 30, 1969. Originally issued 1963. Replaces E 208 – 66 T.

the steel to be tested. The specimens are prevented by a stop from deflecting more than a few tenths of an inch.

2.2 The usual test sequence is as follows: After the preparation and temperature conditioning of the specimen, the initial drop-weight test is conducted at a test temperature estimated to be near the NDT temperature. Depending upon the results of the first test, tests of the other specimens are conducted at suitable temperature intervals to establish the limits within 10 F (5 C) for break and no-break performance. A duplicate test at the lowest no-break temperature of the series is conducted to confirm no-break performance at this temperature.

3. Significance

3.1 The fracture strength transitions of ferritic steels used in the notched condition are markedly affected by temperature. For a given "low" temperature, the size and acuity of the flaw (notch) determines the stress level required for initiation of brittle fracture. The significance of this test method is related to establishing that temperature, defined herein as the NDT temperature, at which the "small flaw" initiation curve, Fig. 1, falls to nominal yield strength stress levels with decreasing temperature, that is, the point marked NDT in Fig. 1.

3.2 Interpretations to other conditions required for fracture initiation may be made by the use of the generalized flaw-size, stress - temperature diagram shown in Fig. 1. The diagram was derived from a wide variety of tests, both fracture initiation and fracture arrest tests, as correlated with the NDT temperature established by the drop-weight test. Validation of the NDT concept has been documented by correlations with numerous service failures encountered in ship, pressure vessel, machinery component, forged, and cast steel applications.

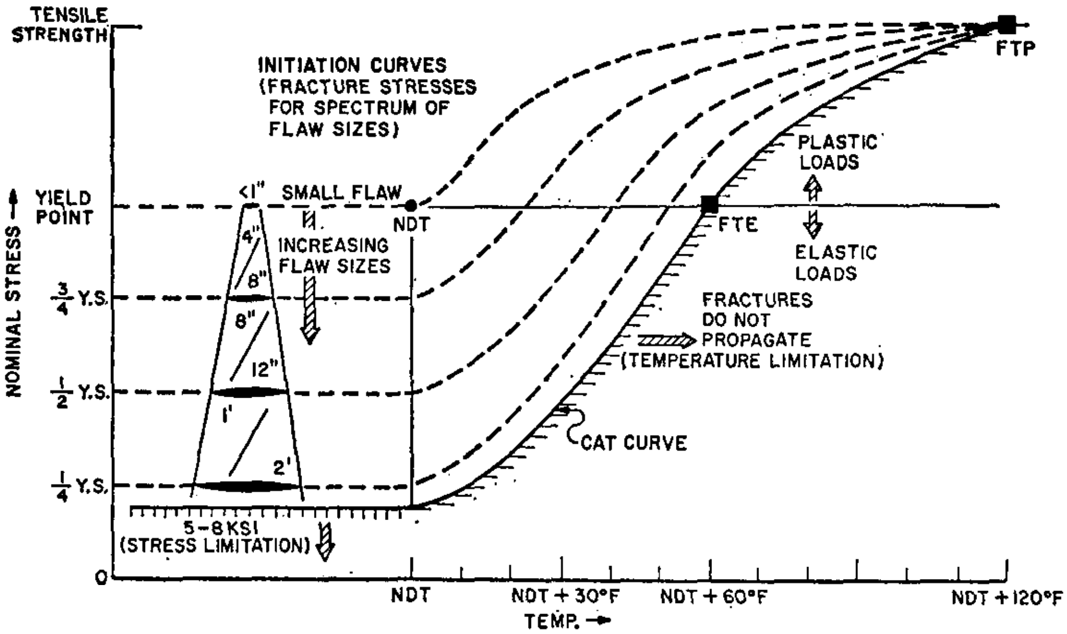
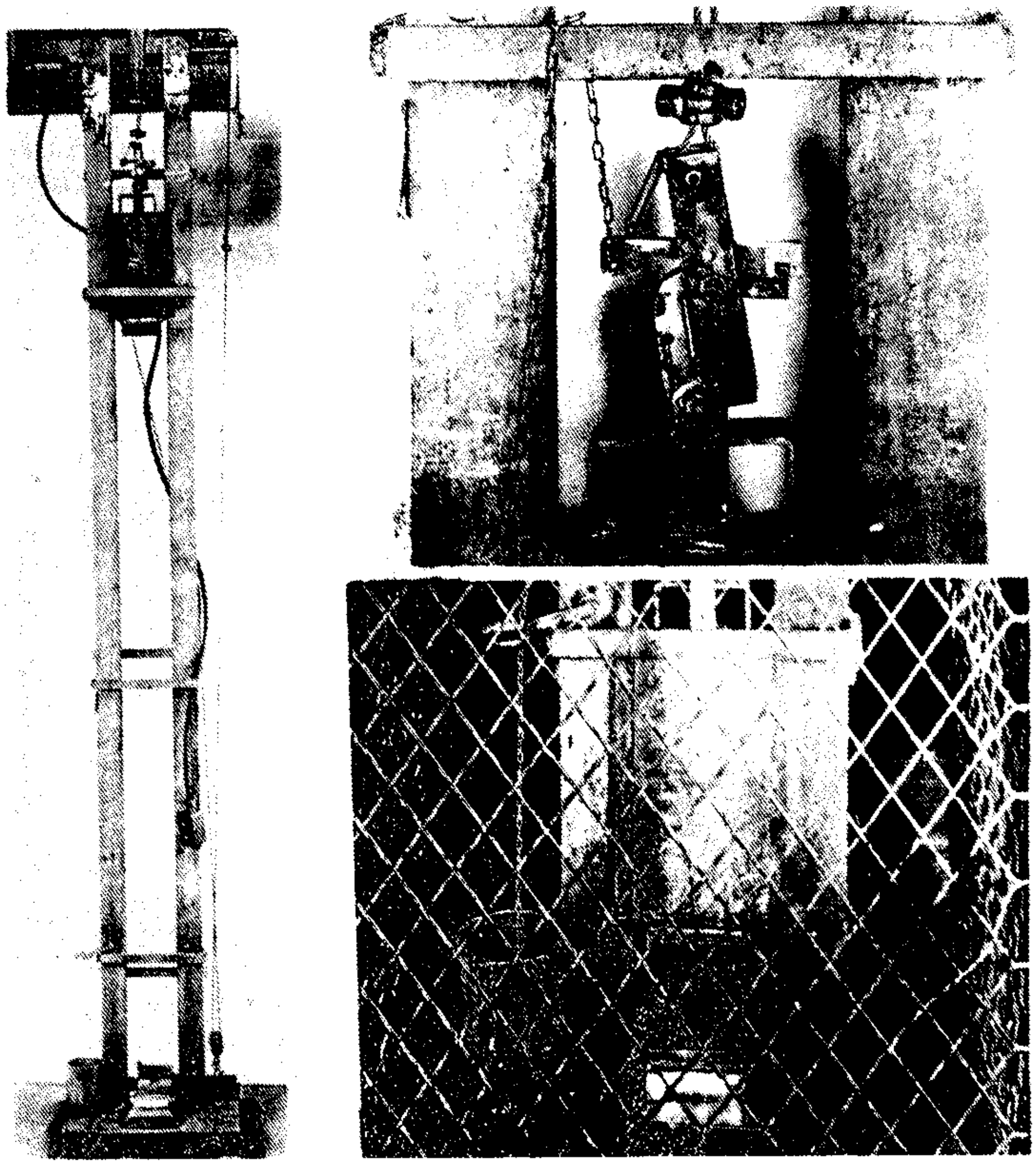


FIG. 1—Generalized Fracture Analysis Diagram Indicating the Approximate Range of Flaw Sizes Required for Fracture Initiation at Various Levels of Nominal Stress, as Referenced by the NDT Temperature (see References (1) and (2)).



(*a*) *Left*—Complete Assembly
(*b*) *Upper Right*—Quick-Release Mechanism
(*c*) *Lower Right*—Guard Screen
Fig. 2—Drop-Weight Test Apparatus.

4. Definition

4.1 *Nil-Ductility Transition (NDT) Temperature*—The maximum temperature where a standard drop-weight specimen breaks when tested according to the provisions of this method.

5. Precautions

5.1 The drop-weight test was devised for measuring fracture initiation characteristics of $\frac{5}{8}$-in. and thicker structural materials. This test is not recommended for steels less than $\frac{5}{8}$ in. thick.

5.2 This method establishes standard specimens and conditions to determine the NDT temperature of a given steel. The use of standard specimens with nonstandard test conditions or the use of nonstandard specimens shall not be allowed for specification purposes.

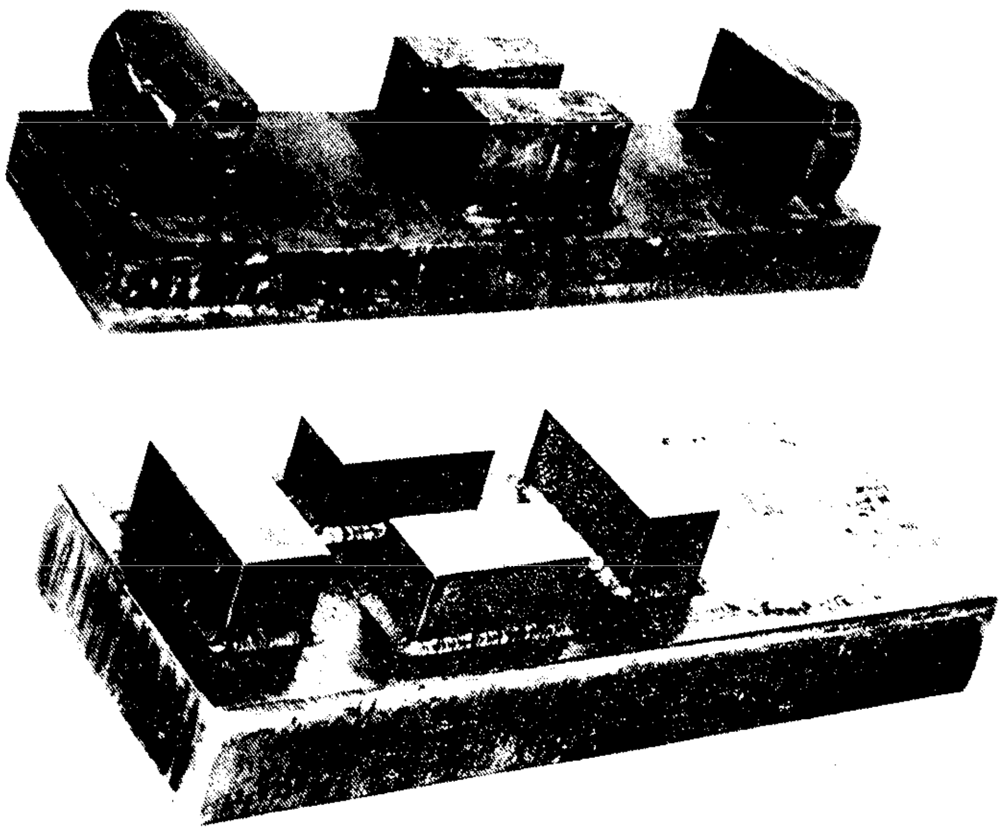
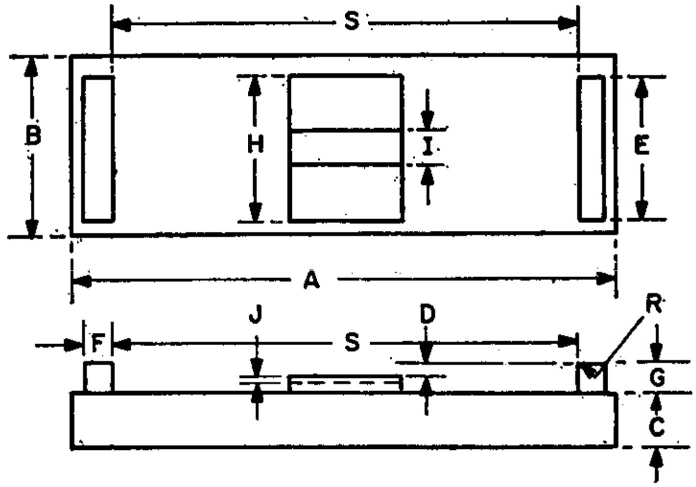


FIG. 3—General Appearance of the Anvils Required for Drop-Weight NDT Tests.

5.3 This method employs a small weld bead deposited on the specimen surface, whose sole purpose is to provide a brittle material for the initiation of a small, cleavage crack-flaw in the specimen base material during the test. Anomalous behavior may be expected for materials where the heat-affected zone created by deposition of the crack-starter weld is made more fracture resistant than the unaffected plate. This condition is developed for quenched and tempered steels of high hardness obtained by tempering at low temperatures. The problem may be avoided by placing the crack-starter weld on these steels before conducting the quenching and tempering heat treatment. Except for other cases which may be readily rationalized in metallurgical terms (for example, it is possible to recrystallize heavily cold-worked steels in the heat-affected zone and develop a region of improved ductility), the heat-affected zone problem is not encountered with conventional structural grade steels of a pearlitic microstructure or quenched and tempered steels tempered at high temperatures to develop maximum fracture toughness.



Anvil Dimension	Units	Specimen Type			Tolerance
		P-1	P-2	P-3	
S, Span	in.	12.0	4.0	4.0	±0.05
	mm	305	100	100	±1.5
D, Deflection stop	in.	0.30	0.060	0.075	±0.002
	mm	7.60	1.50	1.90	±0.05
A, Anvil length	← not critical →				
B, Anvil width	← not critical →				
C, Anvil thickness	in	1.5 min	1.5 min	1.5 min	
	mm	38 min	38 min	38 min	
E, Support length	in.	3.5 min	2.0 min	2.0 min	
	mm	90 min	50 min	50 min	
F, Support width	← not less than *G* →				
G, Support height	in.	2.0	2.0	2.0	±1
	mm	50	50	50	±25
R, Support radius	in.	0.075	0.075	0.075	±0.025
	mm	1.0	1.0	1.0	±0.1
H, Stop width	in.	3.5 min	2.0 min	2.0 min	±2
	mm	90 min	50 min	50 min	±50
I, Weld clearance	in.	0.9	0.9	0.9	±0.1
	mm	22	22	22	±3
J, Weld clearance depth	in.	0.4 min	0.4 min	0.4 min	
	mm	10 min	10 min	10 min	

FIG. 4—Anvil Dimensions.

6. Apparatus

6.1 The drop-weight machine is of simple design based on the use of readily available structural steel products.[2] The principal components of a drop-weight machine are a vertically-guided, free-falling weight, and a rigidly supported anvil which provides for the loading of a rectangular plate specimen as a simple beam under the falling weight. Figure 2(*a*) illustrates a typical drop-weight machine built of standard structural shapes.

6.2 A rail, or rails, rigidly held in a vertical position and in a fixed relationship to the base shall be provided to guide the weight. The weight shall be

[2] Detail drawings for the construction of this machine are available from ASTM Headquarters at a nominal charge.

provided with suitable devices which engage the rail, or rails, and ensure that it will drop freely in a single, vertical plane. The weight may be raised by any convenient means. A weight-release mechanism, functioning similarly to that shown in Fig. 2(*b*), shall be provided to release the weight quickly without affecting its free fall. The weight shall be made in one piece, or if made of several pieces, its construction shall be rigid to ensure that it acts as a unit when it strikes the specimen. The striking tup of the weight shall be a steel cylindrical surface with a radius of 1 in. and a minimum hardness of Rc 50 throughout the section. The weight shall be between 50 and 300 lb. The rails and hoisting device shall permit raising the weight various fixed distances to obtain potential energies of 250 to 1200 ft-lb.

6.3 A horizontal base, located under the guide rails, shall be provided to hold and position precisely the several styles of anvils required for the standard specimens. The anvil guides shall position the anvil with the centerline of the deflection stops under the centerline of the striking tup of the weight. In general, the base will also support the guide rails, but this is not a requirement. The base shall rest on a rigid foundation. The base-foundation system shall be sufficiently rigid to allow the normal drop-weight energy (Table 1) to deflect a standard specimen to the stop at temperatures above the NDT. The base shall not jump or shift during the test, and shall be secured to the foundation if necessary to prevent motion.

TABLE 1—STANDARD DROP-WEIGHT TEST CONDITIONS.

Type of Specimen	Specimen Size, in.	Span, in.	Deflection Stop, in.	Yield Strength Level, ksi	Drop-Weight Energy for Given Yield Strength Level[a]	
					ft-lb	kg-m
P-1............	1 by 3½ by 14	12.0	0.3	30 to 50	600	83
				50 to 70	800	110
				70 to 90	1000	140
				90 to 110	1200	165
P-2............	¾ by 2 by 5	4.0	0.06	30 to 60	250	34
				60 to 90	300	41
				90 to 120	350	48
				120 to 150	400	65
P-3............	⅝ by 2 by 5	4.0	0.075	30 to 60	250	34
				60 to 90	300	41
				90 to 120	350	48
				120 to 150	400	55

[a] Initial tests of a given strength level steel shall be conducted with the drop-weight energy stated in this column. In the event that insufficient deflection is developed (no-test performance) an increased drop-weight energy shall be employed for other specimens of the given steel.

6.4 A guard screen, similar to that shown in Fig. 2(*c*), is recommended to stop broken specimen halves of the very brittle steels which break into two pieces with both halves being ejected forcefully from the machine.

6.5 The general characteristics of two of the anvils required are illustrated in Fig. 3. The anvils shall be made in accordance with the dimensions shown in Fig. 4. The anvil supports and deflection stops shall be steel-hardened to a minimum hardness of RC 50 throughout their cross section. The space be-

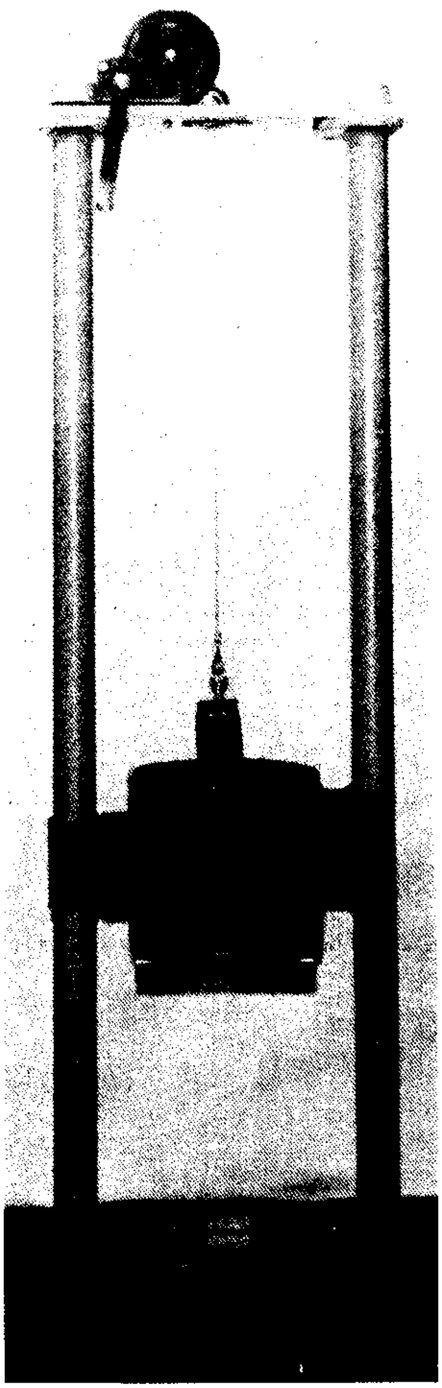


FIG. 5—Portable Drop-Weight Test Machine Used for Tests at Different Fabrication Sites.

tween the two stops is provided as clearance for the crack-starter weld on the specimen. The deflection stops may be made in two separate pieces, if desired. The anvil-base system shall be sufficiently rigid to allow the normal drop-weight energy (Table 1) to deflect the specimen to the stop at temperatures well above the NDT.

6.6 A measuring system shall be provided to assure that the weight is released from the desired height for each test, within the limits of +10, −0 per cent.

6.7 Modifications of the equipment or assembly details of the drop-weight machine shown in Fig. 2 are permitted provided that the modified machine is functionally equivalent. Figure 5 illustrates a portable machine design used by an industrial concern for drop-weight tests of materials used for pressure vessel components at different fabrication sites.

7. Test Specimens

7.1 *Identification of Material*—All sample material and specimens removed from a given plate, shape, forging, or casting product shall be marked to identify their particular source (heat number, slab number, etc.). A simple identification system shall be used which can be employed in conjunction with an itemized table to obtain all the pertinent information.

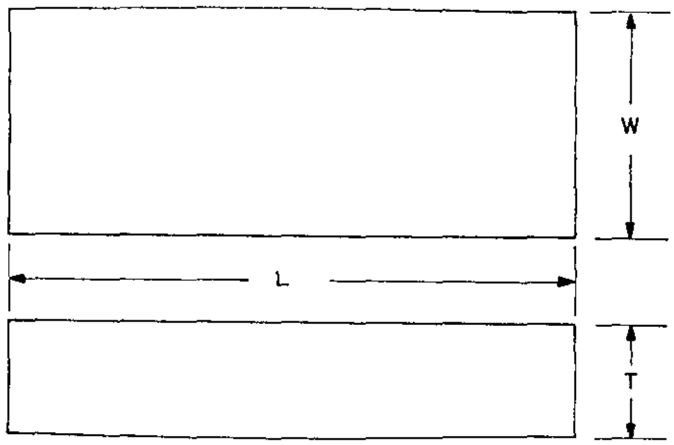
7.2 *Orientation*—The drop-weight test is insensitive to specimen orientation with respect to rolling or forging direction. However, unless otherwise agreed to, all specimens specified by the purchaser shall be of the same orientation and it shall be noted in the test report.

7.3 *Relation to Other Specimens*—Unless otherwise specified by the purchaser, the specimens shall be removed from the material at positions adjacent to the location of other type test specimens (for example, mechanical test specimens) required for evaluation of other material properties.

7.4 *Special Conditions for Forgings and Castings*—Where drop-weight testing of cast or forged material is specified, the size and location of integrally attached pad projections or prolongations to be used for specimen fabrication shall be agreed to in advance by the purchaser. If the design of the casting or forging does not allow an attached test-material coupon, the following requirements shall apply:

7.4.1 Drop-weight specimens cast or forged separately to the dimensions required for testing shall be allowed only where the product dimensions are equivalent and the purchaser agrees.

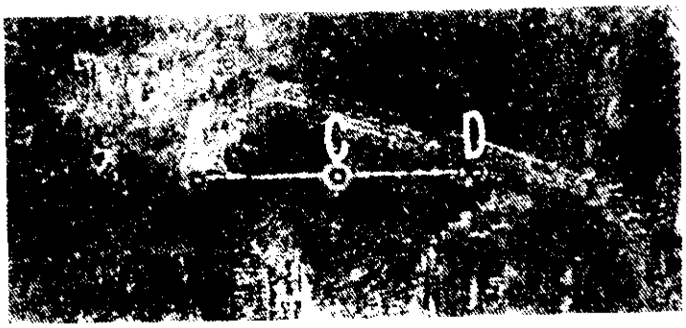
7.4.2 Specimens may be taken from a separately produced test-material coupon if the supplier can demonstrate that it is equivalent to the product with respect to chemical composition, soundness, and metallurgical condition. The material shall be from the same heat and shall have been fabricated under identical conditions as the product. The specimens shall be machine-cut from locations agreed to in advance by the purchaser.



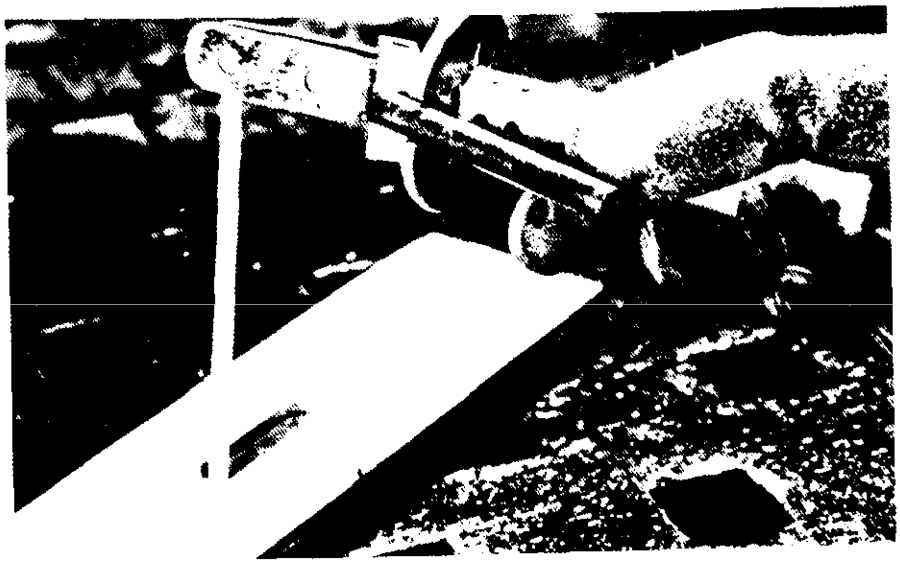
Dimension	Units	Specimen Type					
		P-1		P-2		P-3	
		Dimension	Tolerance	Dimension	Tolerance	Dimension	Tolerance
T, Thickness	in.	1.0	±0.12	0.75	±0.04	0.62	±0.02
	mm	25	±2.5	19	±1.0	16	±0.5
L, Length	in.	14.0	±0.5	5.0	±0.5	5.0	±0.5
	mm	360	±10	130	±10	130	±10
W, Width	in.	3.5	±0.1	2.0	±0.04	2.0	±0.04
	mm	90	±2.0	50	±1.0	50	±1.0

FIG. 6—Standard Drop-Weight Specimen Dimensions.

7.4.3 Specifically, in the case of casting requiring X-ray quality standards, the separate test-material coupon shall be cast separately but simultaneously with the product. Chills shall not be used. The test-material coupon shall be sound. The size of the test coupon shall be in proportion to the thickness, *T*, in the cast product, where *T* is the diameter of the largest circle that can be inscribed in any cross section of the casting, or



(*a*) Punch Marks



(*b*) Copper Template

(*c*) Crack-Starter Weld

FIG. 7—Methods of Locating the Weld Deposit Properly on the Test Specimen.

where T is defined in advance by the purchaser as the nominal design thickness, as follows:

Thickness, T, in.	Separately Cast, Nonchilled, Test-Coupon Size
½ and less	None required
⅝ to 2	When several small castings are poured from one heat, one casting shall be used to provide test specimens, if adaptable
⅝ to 1	T by 2 by 5 in. for irregularly shaped castings
>1 to 3	T by $4.5T$ by $4.5T$
>3 to 5	T by $3T$ by $3T$
Over 5	T by $3T$ by $3T$ for castings that are representative of cast plates
Over 5	T by T by $6\sqrt{T}$ for castings that are representative of cast bars

7.4.4 Specimens showing casting or metallurgical faults on broken fracture surfaces shall be "No-Test."

7.5 *Size of Blank*—Dimensions of the blank size required for standard test specimens are shown in Fig. 6. Equally significant NDT temperatures, within ±10 F (±5 C), are determined for a given steel with tests using any of the standard specimens. As may be convenient for the particular thickness of material, any of the standard specimens shown in Fig. 6 and prepared as described in 7. Test Specimens, may be chosen for this method. The results obtained with standard test conditions shall comply with the requirements of this method for determining the NDT temperature.

7.6 *Specimen Cutting*—The specimen sample material and the specimen ends may be flame-cut. The specimen sides shall be saw-cut or machined, using adequate coolant to prevent specimen overheating, and shall be a minimum of 1 in. from any flame-cut surface. Products thicker than the standard specimen thickness shall be machine-cut to standard thickness from one side, preserving an as-fabricated surface unless otherwise specified, or agreed to, in advance by the purchaser. The as-fabricated surface so preserved shall be the welded (tension) surface of the specimen during testing.

7.7 *Crack-Starter Weld*—The crack-starter weld, which is a centrally located weld bead, approximately 2½ in. long and ½ in. wide, shall be deposited on the as-fabricated tension surface of the drop-weight specimen.[3] To assist the welding operator in centering the weld deposit properly on the test piece, three punch marks as shown in Fig. 7(*a*) or a copper template containing a 1 by 3-in. centrally positioned slot, Fig. 7(*b*), shall be used.[4] In either case, Points *A* and *D*, each of which are 1¼ in. from the center point *C*, are weld start locations; the terminal point for each half of the weld bead is Point *C*. The bead appearance is determined by the amperage, arc voltage, and speed of travel used. A current of 180 to 200 amp, a medium arc length, and a travel speed that will result in a moderately high-crowned bead have been found to be suitable conditions. An oscillating or weaving motion is unnecessary when the noted[3] electrode is used since it naturally deposits a bead having a width of from ½ to ⅝ in. The weld height at the center of the bead should be approximately equal to the height of the bead crown, but any deficiency observed after cleaning the weld can be corrected by adding more metal to the crater-depression. An enlarged view of an as-deposited crack-starter weld is shown in Fig. 7(*c*).

[3] Murex Hardex-N electrodes, available from Metal and Thermit Corp., Rahway, N. J., have been found satisfactory for the crack-starter weld. However, each new lot of these electrodes shall be checked for suitability in accordance with requirements of 7.10.

[4] The copper template is especially recommended for the Type P-2 and P-3 specimens since it eliminates weld spatter which may interfere with proper seating of the specimen during test.

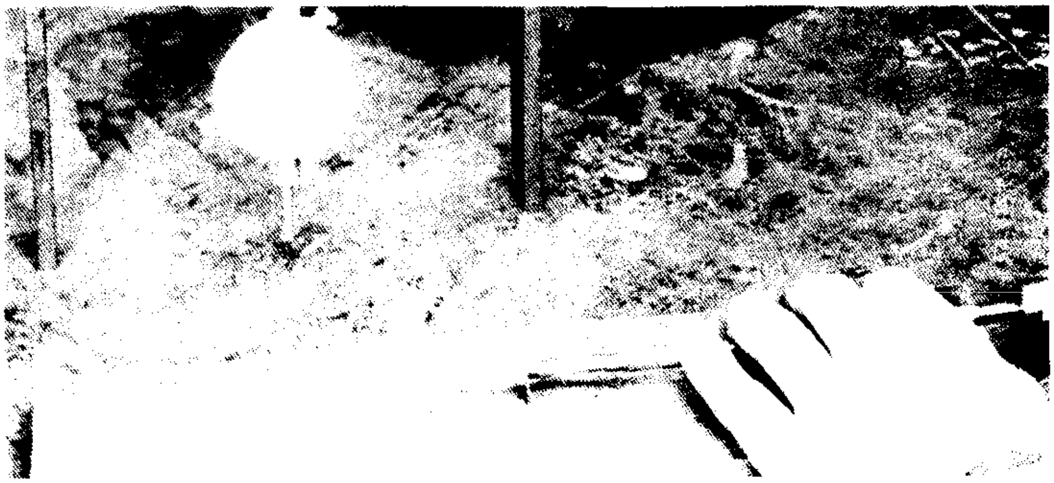


FIG. 8—Notching of Crack-Starter Weld Deposit.

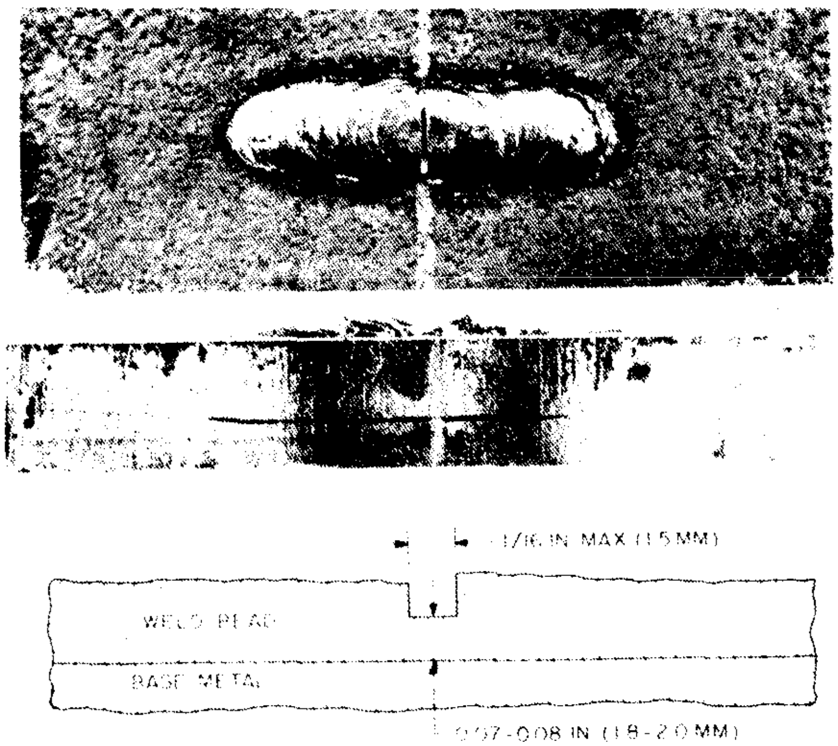


FIG. 9—Weld-Notch Details and Example of a Notched Weld.

7.8 *Weld Notch*—The final preparation of the specimen consists of notching the deposited weld at the center of the bead length. Care shall be taken to ensure that only the weld deposit is notched and that the cutting tools do not contact the specimen surface. The notch may be cut with thin abrasive disks, as shown in Fig. 8, or other convenient cutting tools such as mechanical saws, hack

53—45

saws, etc. The weld-notch details and a representative example of a notched weld is given in Fig 9.

7.9 *Measuring Weld-Notch Depth*—The depth of the notch from the crown of the weld will vary with expected variations in weld crown dimensions. The depth of the notch is not measured, since it is the thickness of the weld remaining above the specimen and under the bottom of the notch that has been standardized, as shown in Fig. 9. This weld thickness above the specimen shall be maintained across as much of the weld width as permitted by the bead contour. Figure 10 illustrates a device for measuring the thickness of weld metal at the bottom of the notch. The adjustable dial indicator with bridge support is set at zero while in position on the specimen with the indicator tip contacting the specimen surface immediately adjacent to the notch. The bridge is then placed over the weld with the indicator tip resting on the bottom of the notch to measure the weld metal thickness directly. Weld beads notched too deeply may be repaired by the deposition of more weld metal after grinding of the notched area without contacting the surface of the specimen. With experience in the preparation of a few specimens, the instrument need be used only in the final checking of the finished notch.

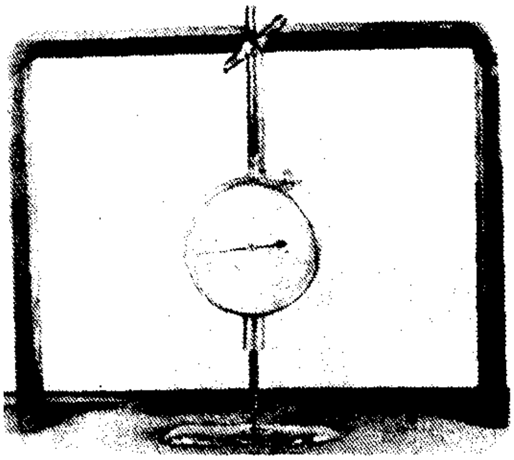
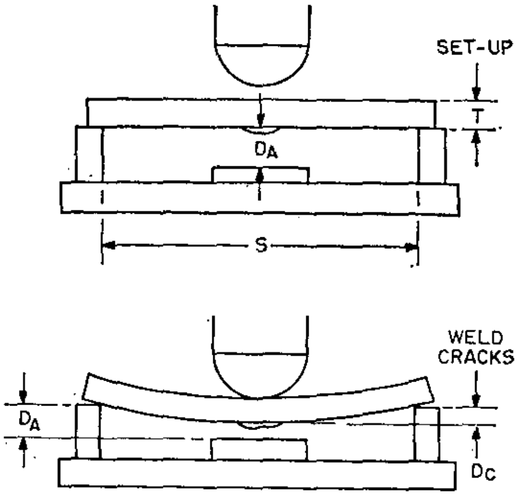


FIG. 10—Method for Measuring Weld Metal Thickness at the Bottom of the Notch.

7.10 *Other Crack-Starter Welds*—The satisfactory completion of drop-weight tests is dependent upon the "crack-starting" conditions developed by the notched weld. As shown schematically in Fig. 11, the specimen deflection, D_C, that cracks the weld, is significantly less than the allowable anvil stop deflection, D_A, for all standard thickness, T, specimens tested on the proper span, S. The carefully prepared and specially handled electrode (described in 7.7[3]) has been proved successful for crack-starting purposes for all temperatures up to approximately 400 F (200 C). Other weld materials shall be considered to perform satisfactorily as crack-starters if they also develop cleavage cracks at suitably high test temperatures at or near the instant that yielding occurs in the surface fibers of the test specimen. Weld materials, other than those described in 7.7, may be used for the crack-starter bead pro-



YIELD POINT LOADING IN PRESENCE OF SMALL CRACK IS TERMINATED BY CONTACT WITH STOP

FIG. 11—Drop-Weight Test Method.

vided the following requirements are met:

7.10.1 Using standard conditions as specified in Table 1, three standard Type P-2 specimens ($\frac{3}{4}$ by 2 by 5 in.) shall be drop-weight tested at a temperature 100 F (55 C) or more above the NDT temperatures of the plate material.

7.10.2 If the three tests demonstrate that the weld notch is always cracked upon deflection of the specimen tension surface to the maximum amount permitted by the proper anvil stop, the other crack-starter weld shall be authorized and considered to conform to the requirements of this method.

7.10.3 Welding procedures or crack-starter weld dimensions other than those described in 7.7 shall also be considered to perform satisfactorily as crack-starters if they are demonstrated to develop cleavage cracks at suitably high test temperatures at or near the instant that yielding occurs in the surface fibers of the test specimens. For example, a $\frac{3}{4}$ to 1-in. long crack-starter weld deposited in one direction only with the welding conditions and the electrodes described in 7.7 has been used successfully as a crack-starter weld for the Type P-3 specimen. The shorter weld reduces the total heat input into the specimen and is considered less likely to cause metallurgical changes in the specimen base materials of the low-alloy, high-tensile strength pressure vessel steels. For the Type P-1 specimen, the shorter weld does not provide the reproducibility or consistency for crack-starting purposes obtained with the standard crack-starter weld described in 7.7. Other welding procedures or crack-starter weld dimensions than those described in 7.7 may be used as the crack-starter bead for a given standard type (P-1, P-2, or P-3) specimen provided that three specimens are tested in accordance with 7.10.1 and results obtained in accordance with 7.10.2.

8. Procedure—General

8.1 Some care and thought are necessary to make a successful drop-weight determination of the NDT temperature. Adequate auxiliary equipment and a definite procedure will aid in making the test. The following sections will define in detail and in orderly fashion the equipment and procedure requirements:

8.2 Conduct the test by placing a specimen in a heating or cooling device until it is at the desired temperature. Then place it with minimum loss of time (see 12.4) on the anvil and align where it will be struck squarely by the weight. Allow the weight to drop from a known preselected height on the specimen. Examine the specimen after the strike to determine its condition as defined by the requirements of this method. Repeat this process until the NDT temperature has been determined.

8.3 The number of specimens required to determine the NDT temperature is a function of the experience of the operator with the material and of the use of an adequate procedure. A skilled operator working with known material can determine the NDT temperature with as few as three specimens. Generally, six to eight specimens are required.

9. Specimen—Anvil Alignment

9.1 *Anvil Requirements*—Test each type of drop-weight specimen only on the anvil designated for that type specimen in accordance with Table 1.

9.2 *Specimen - Anvil Alignment*—In order to obtain a valid test properly align the specimen on the anvil. Align the specimen, anvil, and weight so the specimen is struck under the following conditions:

9.2.1 The specimen shall be horizontal

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FIG. 12—Method for Alignment of Specimen.

(a) (b) (c)

(a) Wax Pencil Line Scribed on Tension Side of a Specimen
(b) Application of Masking Tape to Anvil Stop Surfaces
(c) Transfer of Wax Lines to the Tape When the Specimen Hits the Stop

FIG. 13—Method Employed to Indicate Contact of the Specimen with the Anvil Stop.

and the ends shall rest on the anvil supports.

9.2.2 The striking tup of the weight shall strike within ±0.1 in. (±2.5 mm) of a line on the compression side of the specimen, normal to a long edge and directly opposite the notch in the crack-starter weld.

9.2.3 No part of the crack-starter weld will touch the deflection stops at any time during the test.

9.2.4 The specimen sides and ends shall be free from any interference during the test.

9.3 *Alignment Tool*—The technique shown in Fig. 12 has been used successfully to achieve longitudinal and angular specimen alignment of the specimen. Draw a wax-pencil line on the compression surface of the specimen normal to a long edge and directly opposite the notch. Place the specimen on the anvil so this line coincides with the edge of a removable guide bar. Place the bar against the machine rails so that its edge defines the striking line of the tup on the weight.

10. Selection of Test Energy

10.1 Strike the specimen by a free-falling weight having adequate energy to deflect the specimen sufficiently to crack the weld deposit and to make the tension surface contact the anvil stop. The design of the machine permits the use of various impact energies to accommodate the different strength levels of the various materials tested. The standard test conditions shown in Table 1 have been developed by experience and shall be used for the test series of a given steel unless No-Test performance is experienced. The indicated energies can be obtained by lifting the weight the required distance from the compression surface of the specimen.

10.2 Proper contact of the tension surface of the specimen with the deflection stop shall be defined as follows: Scribe a wax-pencil line on the tension surface of a standard specimen parallel to and in line with the mechanical notch cut in the crack-starter weld deposit, Fig. 13(*a*). Apply clean masking tape, or a similar material, to the top surface of the anvil deflection stop blocks, Fig. 13(*b*). Align the test specimen on the anvil and strike once by the weight with the standard conditions, Table 1, for the steel involved. Transfer of the wax-pencil line from specimen to the tape shall indicate that the specimen was bent sufficiently (Fig. 13(*c*)). The above procedure, to ensure proper contact of the tension surface of the specimen with the deflection stop blocks, is considered a "built-in" standardization feature of the test method, and it shall be employed for each drop-weight test to preclude "No-Test" performance as described in 13.2.3 and 13.3.

TABLE 2—SUGGESTED SEQUENCE OF DROP-WEIGHT TEST TEMPERATURES.

Specimen Condition After Test at Temperature T_n	Suggested Test Temperature for Succeeding Test	
No crack in weld notch	No-Test performance (see 13.2.3 and 13.3)	
Weld crack extending less than 1/16 in. into specimen surface.	$T_n - 60$ F	$T_n - 30$ C
Weld crack extending 1/8 to 1/4 in. into specimen surface	$T_n - 40$ F	$T_n - 20$ C
Weld crack extending approximately 1/2 the distance between specimen edge and toe of crack-starter weld bead	$T_n - 20$ F	$T_n - 10$ C
Weld crack extending to within 1/4 in. of specimen edge	$T_n - 10$ F	$T_n - 5$ C
Specimen "Breaks" (see 13.2.1)	$T_n + 40$ F	$T_n + 20$ C
	Continue testing as described in 11.1 and 11.2	

10.3 If the weld crack and anvil stop contact criteria are not met by the Table 1 energies, increase the drop-weight energy in 100-ft-lb increments for the Type P-1 specimens or 50-ft-lb increments for the Type P-2 and P-3 specimens until they are met. Do not use drop-weight energies above those posted on the table unless the above procedure has been followed to determine the excess energy requirements.

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11. Selection of Test Temperatures

11.1 The selection of test temperatures is based on finding, with as few specimens as possible, a lower temperature where the specimen breaks and an upper temperature where it does not break, and then testing at intervals between these temperatures until the temperature limits for break and no-break performance are determined within 10 F (5 C). The NDT temperature is the highest temperature where a specimen breaks when the test is conducted by this procedure. Test at least two specimens that show no-break performance at a temperature 10 F (5 C) above the temperature judged to be the NDT point.

11.2 Conduct the initial test at a temperature estimated to be near the NDT. This temperature and all subsequent test temperatures shall be integral multiples of 10 F or 5 C. Additional tests can be conducted at temperatures based on the experience of the operator or on those suggested in Table 2.

12. Measurement of Specimen Temperatures

12.1 The entire test specimen shall be at a known and uniform temperature during the test. It shall be assumed that if it is fully immersed in a stirred-liquid, constant-temperature bath of known temperature and separated from an adjacent specimen by a minimum of 1 in. all around for a period of at least 45 min prior to the test, the specimen temperature shall be the same as the bath temperature. If a gas heat-transfer medium is used, increase the required minimum holding time to 60 min. If it can be shown by appropriate test techniques, such as using a thermocouple buried in the center of a dummy test specimen, that specimen equilibrium temperatures can be developed in a shorter period, the tester can reduce the specimen-holding period provided that he has prior approval of the purchaser. The constant-temperature baths or ovens may be of any type that will heat or cool the specimens to a known and uniform temperature.

12.2 Measure the bath temperature by a device with calibration known to ± 2 F or ± 1 C.

12.3 Any convenient means may be used to remove the specimen from the temperature bath and transfer it to the test machine provided it shall not affect the specimen temperature control. Tongs, if used, shall be kept in the temperature bath to maintain a temperature equivalent to the specimen temperature. Rubber-gloved hands, in general, are the most convenient handling tool. The specimen shall be handled away from the fracture area.

12.4 If more than 20 sec elapse in the period of removing the specimen from the bath prior to release of the weight, temperature control shall presume to have been lost and the specimen shall be returned to the bath.

12.5 Considerable experience has been accumulated with baths of the following type, and it is described here for the convenience of the tester. A deep, insulated metal container holding from ½ to 10 gal of a suitable heat-transfer liquid, such as alcohol, will maintain a given temperature for the required specimen-holding period with minor manual adjustments. By immersing an open basket of cracked dry ice or a high-wattage electrical heater in the bath, its temperature can be adjusted slightly or can be lowered or raised to a new constant level in a short period. For low-density heat-transfer liquids, a walnut-sized piece of dry ice added to the bath will sink and bubble vigorously and help stir it. If this type of bath is used, it should be deep enough to cover the specimens fully. It has been found by experience that standing the specimens

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on one end in the bath with their upper ends leaning on the vessel wall is most satisfactory. Specimens placed horizontally in the bath should be laid on a screen held at least $\frac{1}{4}$ in. from the bottom. If multiple specimens are placed in one bath, they should be spaced a minimum of 1 in. apart to ensure adequate heat-transfer liquid flow around each. The most convenient method of bath temperature measurement is to use a bare thermocouple connected to an automatic recorder.

13. Interpretation of Test Results

13.1 The success of the drop-weight test depends upon the development of a small cleavage crack in the crack-starter weld after a minute bending of the test specimen. The test evaluates the ability of the steel to withstand yield point loading in the presence of a small flaw. The steel either accepts initiation of fracture readily under these test conditions and the test specimen is broken, or initiation of fracture is resisted and the specimen bends the small, additional amount permitted by the anvil stop without complete fracturing.

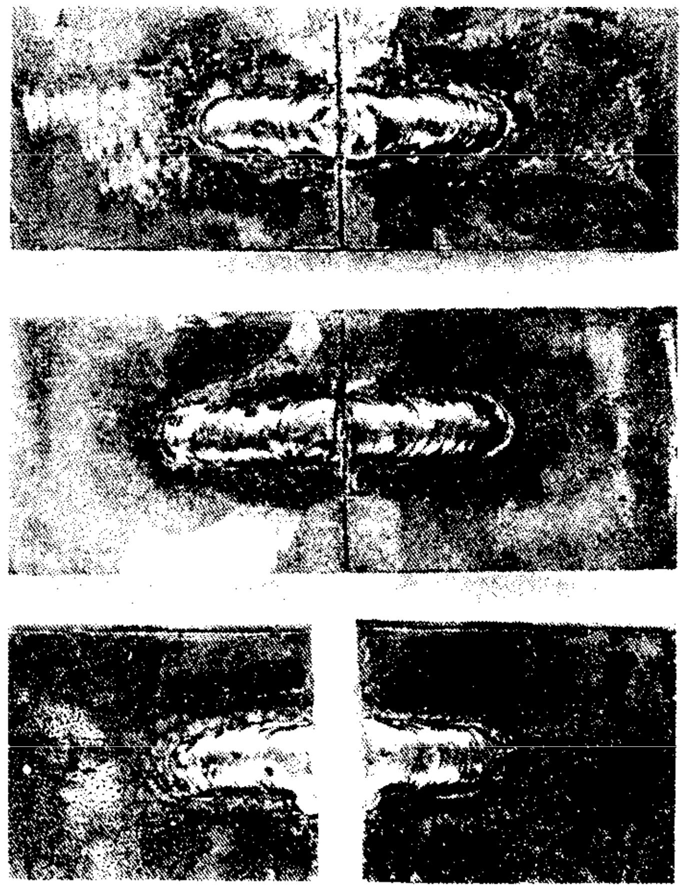

FIG. 14—Typical Examples of Broken Drop-Weight Specimens. Fracture Reaches to at Least One Edge.

13.2 After completion of each drop-weight test, the specimen shall be examined and the result of the test shall be recorded in accordance with the following criteria:

13.2.1 *Break*—A specimen is considered broken if fractured to one or both edges of the tension surface. Complete separation at the compression side of the specimen is not required for break performance. Typical examples of break performance are illustrated in Fig. 14.

13.2.2 *No-Break*—The specimen develops a visible crack in the crack-starter weld bead that is not propagated to either edge of the tension surface. Typical examples of no-break performance are illustrated in Fig. 15.

13.2.3 *No-Test*—The test shall be considered not valid if the weld-deposit notch is not visibly cracked after completion of a test, and if the drop-weight specimen is not deflected fully to contact the anvil stop as evidenced by transfer of the wax-pencil lines to the masking tape on the anvil-deflection stop

13.3 A No-Test performance (13.2.3) may result from the use of insufficient impact energy, the use of a too ductile weld metal for crack-starter purposes, or misalignment of the specimen so that the weld-crown obstructs full deflection to the anvil stop. The No-Test sample shall be discarded and a retest, using another sample, shall be required. Retests, or tests of additional specimens, of a given steel found to develop insufficient deflections with the standard test condition, Table 1, shall be conducted with higher impact energies (see 10.3).

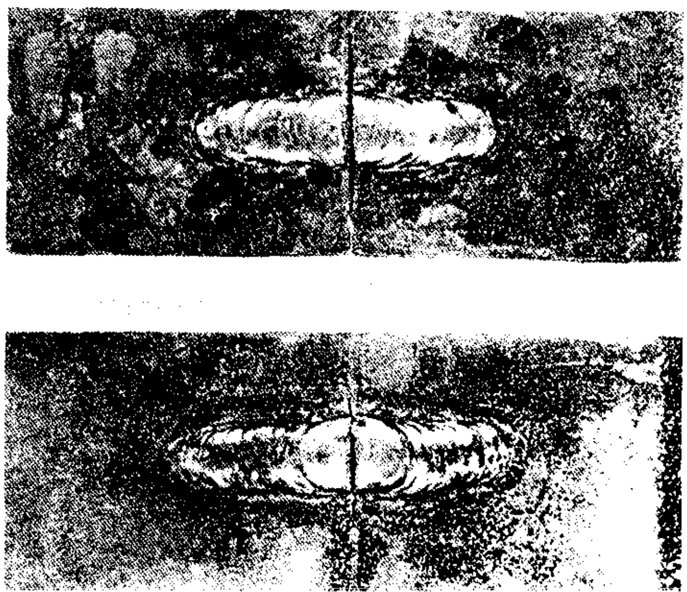

FIG. 15—Typical Examples of No-Break Performance in Drop-Weight Specimens. Fracture Does Not Reach Edge.

14. Report

14.1 The report shall include the following:

14.1.1 Type of steel and heat treatment,

14.1.2 Identification of product tested —heat number, plate number, etc.,

14.1.3 Identification, orientation, and location of test specimens,

14.1.4 Specimen type, test conditions and test temperatures employed,

14.1.5 Result of test (break, no-break, or no-test) for each specimen, and

14.1.6 Deviations, if any, from this test method.

15. Use of Test for Material-Qualification Testing

15.1 Specification tests conducted at

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a given test temperature, on a go, no-go basis, shall require that a minimum of two drop-weight specimens be tested. All specimens thus tested shall exhibit no-break performance to ensure that the NDT temperature of the steel under test is below the specification test temperature. The breaking of one (or more) specimens at the test temperature shall indicate the NDT temperature of the material to be at or above the specification test temperature.

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MIL-STD-1601(SHIPS)
8 MAY 1973

MILITARY STANDARD

METHOD FOR 5/8 INCH DYNAMIC TEAR TESTING OF METALLIC MATERIALS

FSC 95GP

DEPARTMENT OF THE NAVY

NAVAL SHIP SYSTEMS COMMAND

WASHINGTON, D. C. 20360

Method for 5/8 Inch Dynamic Tear Testing of Metallic Materials
MIL-STD-1601(SHIPS)

1. This Military Standard is approved for use by the Naval Ship Systems Command.

2. Recommended corrections, additions, or deletions should be addressed to Commander, Naval Ship Engineering Center, Department of the Navy, Center Building, Prince George's Center, Hyattsville, Maryland 20782.

FORLWORD

This standard is applicable to testing of metal for Navy applications when invoked by the material procurement document(s).

This test represents the latest technical advancement for evaluation of material toughness. It was developed by the Naval Research Laboratory, and published in their report 7159 of 27 August 1970.

The Dynamic Tear (DT) test was evolved at the Naval Research Laboratory starting in 1960, and it has been used extensively for the characterization of fracture resistance of ferrous and nonferrous structural metals. The initial DT specimens were tested in a drop-weight machine, and the test method was defined as the "Drop-Weight Tear Test" (DWTT). Subsequently, pendulum machines with direct readout of the energy required to fracture the specimen were developed, and specimens of improved design with respect to crack-starter conditions were evolved. To reflect these evolutionary improvements, the name of the test method was changed to "Dynamic Tear" test in 1967. DT test facilities have been established at various research laboratories and production plants of major metal-producing companies in this country and abroad.

Structural metals manifest a variety of fracture modes, from square break (brittle) at elastic stress levels to full slant (ductile) requiring gross plastic loading. The basic aim of the DT test is the measurement of the intrinsic fracture propagation resistance under known conditions of mechanical constraint. The specimens incorporate deep, sharp notches or cracks, and tests are conducted under dynamic loading. These conditions are essential for determining the worst (maximum) degree of mechanical constraint that can be produced for the section size of interest.

When fractures occur under elastic stress conditions (brittle), the interpretation of DT energy to structural parameters of flaw size-stress can be accomplished by established linear-elastic fracture mechanics relationships. When fractures occur under gross plastic strain conditions, the DT energy is indicative of the amount of net section plastic strain that is associated with crack extension.

For engineering applications, including fracture-safe design considerations, interpretations of DT energy to flaw-size, stress-level relations for unstable fracture can be made directly by the use of analysis diagrams. For structural steels that feature a temperature induced transition in the service temperature range, the toe region of the DT energy curve can be indexed to the Fracture Analysis Diagram (FAD). The shelf region of DT energy versus temperature relationships and DT energy values for nontransition metals can be translated into structural parameters by the use of the Ratio Analysis Diagram (RAD).

CONTENTS

TABLES

FIGURES

CONTENTS (Cont'd)

APPENDIX

1. SCOPE

1.1 This Standard describes the method for conducting DT tests to determine the DT energy value of metal products using the standard 5/8 DT specimen. It provides a descriptior of the apparatus, the dimensions and preparation of specimens, and details of the testing procedures.

1.2 This method can be used whenever the inquiry, contract, order or specification states that the metal product is subject to fracture resistance requirements as determined by the 5/8 DT test.

2. REFERENCED DOCUMENTS

2.1 This section is not applicable to this Standard.

3. DEFINITIONS

3.1 Dynamic tear energy. The 5/8 DT energy is the total energy required to fracture a standard 5/8 DT specimen when tested according to the provisions of this method. The average 5/8 DT energy shall be based upon a minimum of two specimens or more, if required by the purchaser, or if retest specimens are required.

3.1.1 With pendulum type machines, the 5/8 DT energy value recorded is the difference between the initial and the final potential energies of the pendulum.

3.1.2 With drop-weight type machines, the 5/8 DT energy value recorded is the energy value calculated from the force-time record of a calibrated striker on the hammer or the difference between the initial potential energy of the weight and the final energy of weight as determined by a calibrated energy absorption system.

4. SUMMARY OF METHOD

4.1 The basic 5/8 DT test procedure as shown on figure 1, consists of impacting a simple supported specimen having a notch ("A" on figure 1) on the tension side. There are two types of notches permitted in this method; one is a notch that is prepared by machining (type M), and the other is partially prepared by machining and uses a brittle crack-starter weld to provide a notch with a natural crack tip (type C). The brittle crack-starter welds are prepared by diffusing a small amount of embrittling material in an electron-beam (EB) weld to form a highly crack sensitive region. The crack-starter weld specimen is used when the specified sharp tip on the machined notch cannot readily be obtained; for example, in ultrahigh strength metals. The 5/8 DT specimens are fractured with pendulum or drop-weight machines, and the total energy for fracture is recorded.

5. SIGNIFICANCE OF TEST

5.1 The significance of the DT test derives from the exactly defined mechanical constraint conditions imposed on a sample of the metal of interest. The DT energy value is a measure of fracture resistance under the most severe, mechanical constraint condition that can be imposed for the specified section size. A sufficiently long fracture path is provided so that a measure of intrinsic fracture resistance is obtained with due recognition of the "resistance factor" to crack extension. This feature is essential for proper evaluation of the fracture resistance of metals which exceed unstable plane strain fracture toughness levels.

6. PRECAUTIONS

6.1 Standard specimens. This method established standard 5/8 DT test specimens and conditions to determine the 5/8 DT energy value of a given metal sample for a specific temperature. The use of standard specimens with nonstandard test conditions or the use of nonstandard specimens shall not be allowed under this Standard.

6.2 Fracture interruption. If the crack-starter action of an electron-beam welded specimen is interrupted within the brittle weld due to a gas pocket or a transverse weld crack, the test shall be considered not valid.

7. Apparatus.

7.1 General requirements. The testing machine shall be either a pendulum type or a drop-weight type of capacity more than sufficient to break the specimen in one blow. The

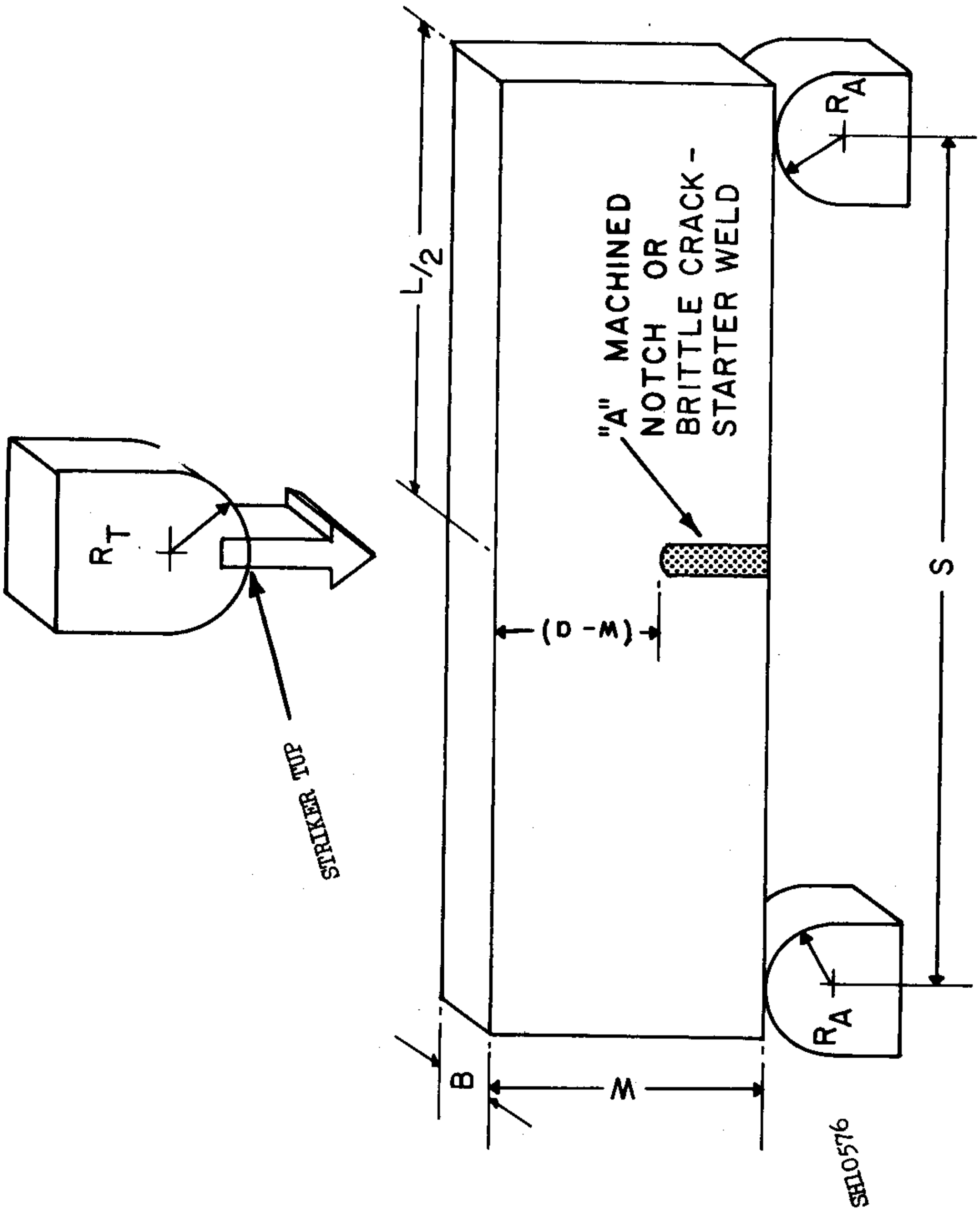


Figure 1. Diagram of basic dynamic tear test setup (parameters are defined in tables I and II).

machine shall not be used for values above 80 percent of the scale range. Description and calibration information for the testing machines for conducting DT tests are given in the appendix to the standard.

7.1.1 Velocity limitations. Tests may be made at various velocities, but these shall be not less than 16 nor more than 29 feet per second (not less than 4.9 nor more than 8.5 meters per second). Velocity shall always be stated as the maximum velocity between the striker and the center of the strike.

7.1.2 Dynamic tear energy definition. The dynamic tear energy (DTE) value shall be taken as the energy absorbed in breaking the specimen and is equal to the difference between the energies of the hammer and the specimen anvil at the instant of impact and the energies remaining after breaking the specimen.

7.1.3 Read-out. The machine shall be furnished with a calibrated scale chart, or direct reading electronic indicator of initial and final energy values. The read-out of these devices may be compensated for windage and friction. The error in reading shall not exceed ± 5 percent of reading, and is not to exceed ± 15 foot-pound (ft-lb) (2.00 kilogram-meter (kg-m)). The error in energy of blow caused by error in the weight of the pendulum or weight shall not exceed 0.4 percent. The actual height of the pendulum or weight in the release position shall not differ from the nominal height by more than 0.4 percent unless windage and friction are compensated for by increasing the height of the drop, in which case the height may exceed the nominal value by not over 1.0 percent. The pendulum and indicating mechanism energy loss from friction and windage shall not be more than 0.4 percent of the total energy of the pendulum during the complete swing to and fro, or the total energy from a free falling weight.

7.1.4 Specimen anvil and striker edge. The specimen anvil and striker edge shall conform to the dimensions shown on figure 1, and in table I, and they shall be steel, with a minimum hardness of Rockwell C48. Clearance between the sides of the hammer and anvil shall not be less than 2.0 inches (51 millimeters (mm)), and the center line of the striker edge shall advance in the plane that is within 0.032 inch (0.80mm) of the midpoint between the supporting edges of the specimen anvils. The striker edge shall be perpendicular to the longitudinal axis of the specimen within 10:1000. The striker edge shall be parallel within 5:1000 to the face of a perfectly square test specimen held against the anvil. Specimen supports shall be square with anvil faces within 2.5:1000. Specimen supports shall be coplanar within 0.005 inch (0.125mm) and parallel within 2:1000.

7.2 Impact machines.

7.2.1 Single-pendulum machine. Single pendulum machines are commonly used for DT testing. A capacity of 2000 ft-lb (280 kilogram force-meter) (kgf-m) is adequate for conducting 5/8 DT tests on all metals.

7.2.2 Double-pendulum machine. A double pendulum machine designed for the 5/8 DT specimen is shown on figure 2. Double pendulum machines have been used to minimize shocks transmitted to support systems and to provide a compact testing machine of 2000 ft-lb (280 kgf-m) capacity.

7.2.3 Drop-weight machine. Figure 3 shows a vertical drop-weight machine with a 250 pound (lb) (11.3 kilogram (kg)) weight used for 5/8 DT testing.

7.3 The specimen anvils and striker tup for 5/8 DT tests are shown schematically on figure 1. The defined dimensions for these parts shall conform to the values given in table I.

Table I - Requirements for striker tup and anvil supports.

Parameter	Units	Dimension	Tolerance
Radius of striker (tup), R_T	in.	0.5	±1/32
	mm	12.7	±0.8
Radius of specimen anvil, R_A	in.	0.5	±1/32
	mm	12.7	±0.8
Anvil span, S	in.	6.5	±1/32
	mm	165.0	±0.8

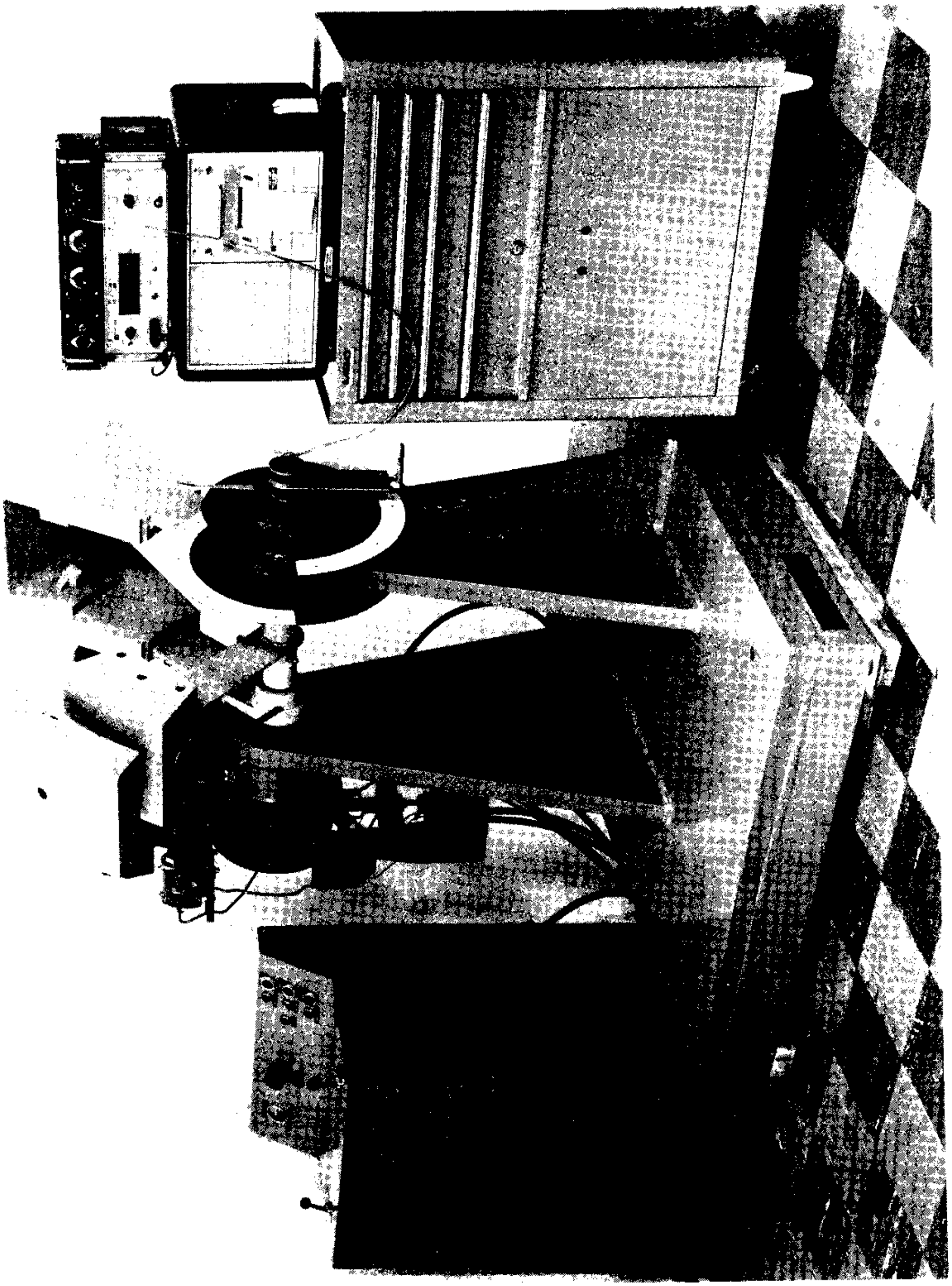


Figure 2 - Double-pendulum machine of 2000 ft-lb (280 kgf-m) capacity used for testing 5/8 DT specimens.

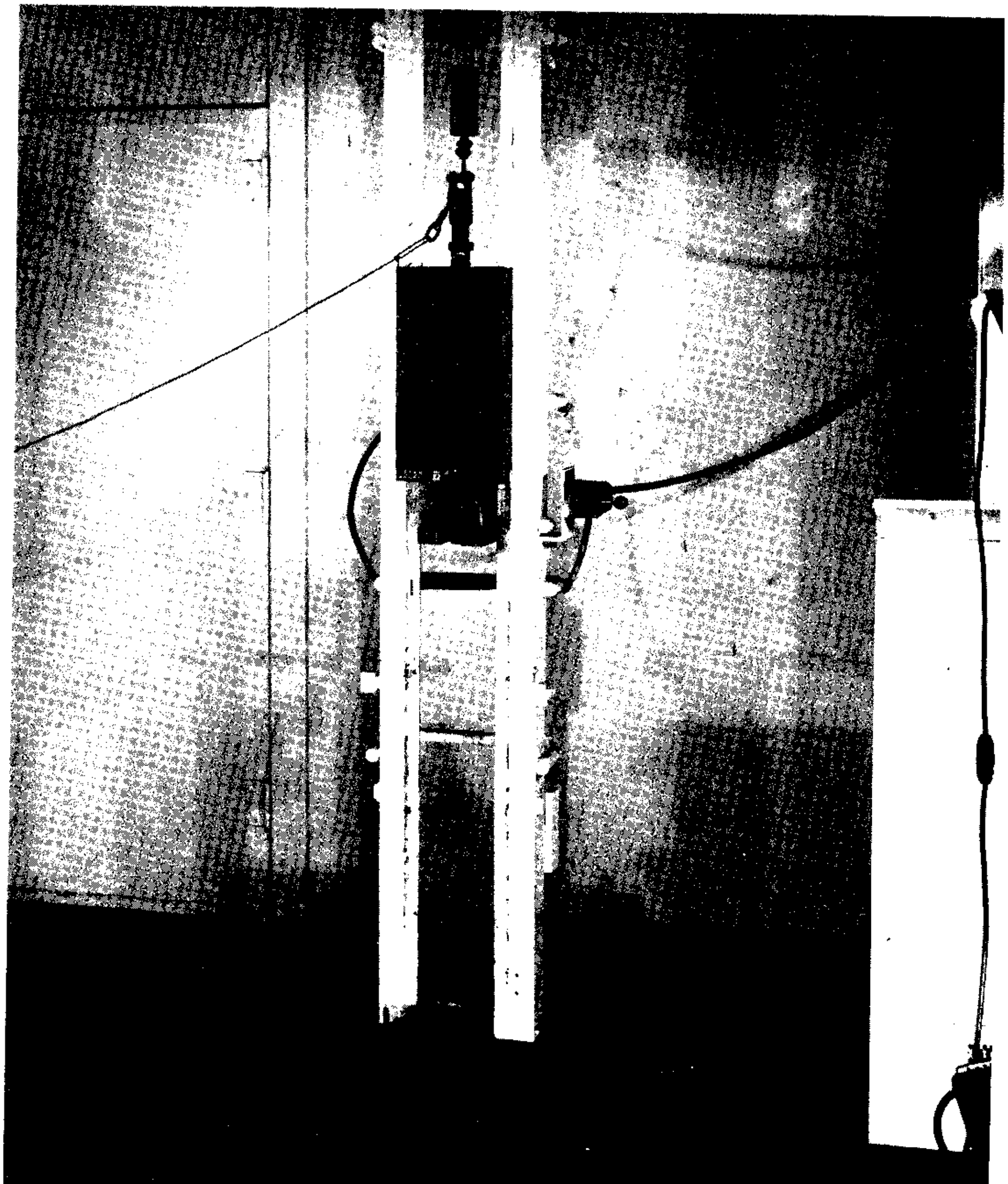


Figure 3 - Drop-weight machine of 2500 ft-lb (350 kgf-m) capacity for testing 5/8 DT specimens.

7.3.2 The anvil supports and striker tup shall be steel, hardened to a minimum hardness value of Rockwell C 48. The dimensions of the test specimens shown schematically on figure 1 are specified in 8.1

7.4 Construction of hammer and anvil. Construction of the hammer and anvil shall allow rotation of the specimen halves around the anvil support without interference with the sides of the hammer. Clearance between the sides of the hammer and the anvil shall not be less than 2.0 inches (51 mm).

7.5 Impact velocity and size of hammer. The limits of vertical heights of the hammer are set to achieve the maximum effect of strain rate on the fracture resistance of the test material without introducing excessive error due to inertial and vibrational aspects of the impact test. The weight of the hammer for a specific machine is dependent upon the desired capacity of the machine. The impact velocity of the machine shall be not less than 16 feet per second (ft/sec) (4.9 meter per second (m/s)) nor more than 28 ft/sec (8.5 m/sec). This impact velocity range corresponds to vertical drop heights of 4 ft (1.2 meters(m)) to 12 ft (3.6m). An effective capacity for conducting 5/8 DT tests is 2000 ft-lb (280 kgf-m).

8. TEST SPECIMENS

8.1 Size of specimen. A schematic of the 5/8 DT specimen is shown on figure 1. The tolerances for the dimensions of the 5/8 DT specimen blank shall conform to the values given in table II.

Table II - Dimension of 5/8 DT specimen blank.

Parameter	Units	Dimension	Tolerance
Length, L	in.	7.125	±0.125
	mm	181.0	±3.2
Width, W	in.	1.6	±0.10
	mm	38.0	±2.5
Thickness, B	in.	0.625	±0.033
	mm	15.8	±0.8

8.2 Notch detail.

8.2.1 Machined notch, type M. The type M specimen shall be considered as the primary 5/8 DT specimen. The notch depth is machined to provide a fracture path in test material of 1-1/8 inches (28.5mm); the small extension required for notch sharpening is considered a portion of the nominal net section. Details of the notch for the type M specimen are shown on figure 4(a), and for the type C specimen on figure 4(b). The tolerances for the notch dimensions shall conform to the values given in table III.

Table III - Dimensions of type M and type C notches.

Parameter	Units	Dimension	Tolerance
Net width, (W-a)	in. mm	1.125 28.5	±0.020 ±0.5
Machined notch width N (edge to centerline of apex)	in. mm	0.0312 0.79	±0.005 ±0.13
Machined notch root angle, N_α	degrees	60	±2
Machined notch root radius, N_r	in. mm	.005 0.13	Max. Max.
Pressed tip depth, N_{td}	in.	.008	±0.003
	mm	.2	±0.08
Pressed tip angle, $N_{t\alpha}$	degrees	45	Max.
Pressed tip root radius, N_{tr}	in. mm	.001 .025	Max. Max.

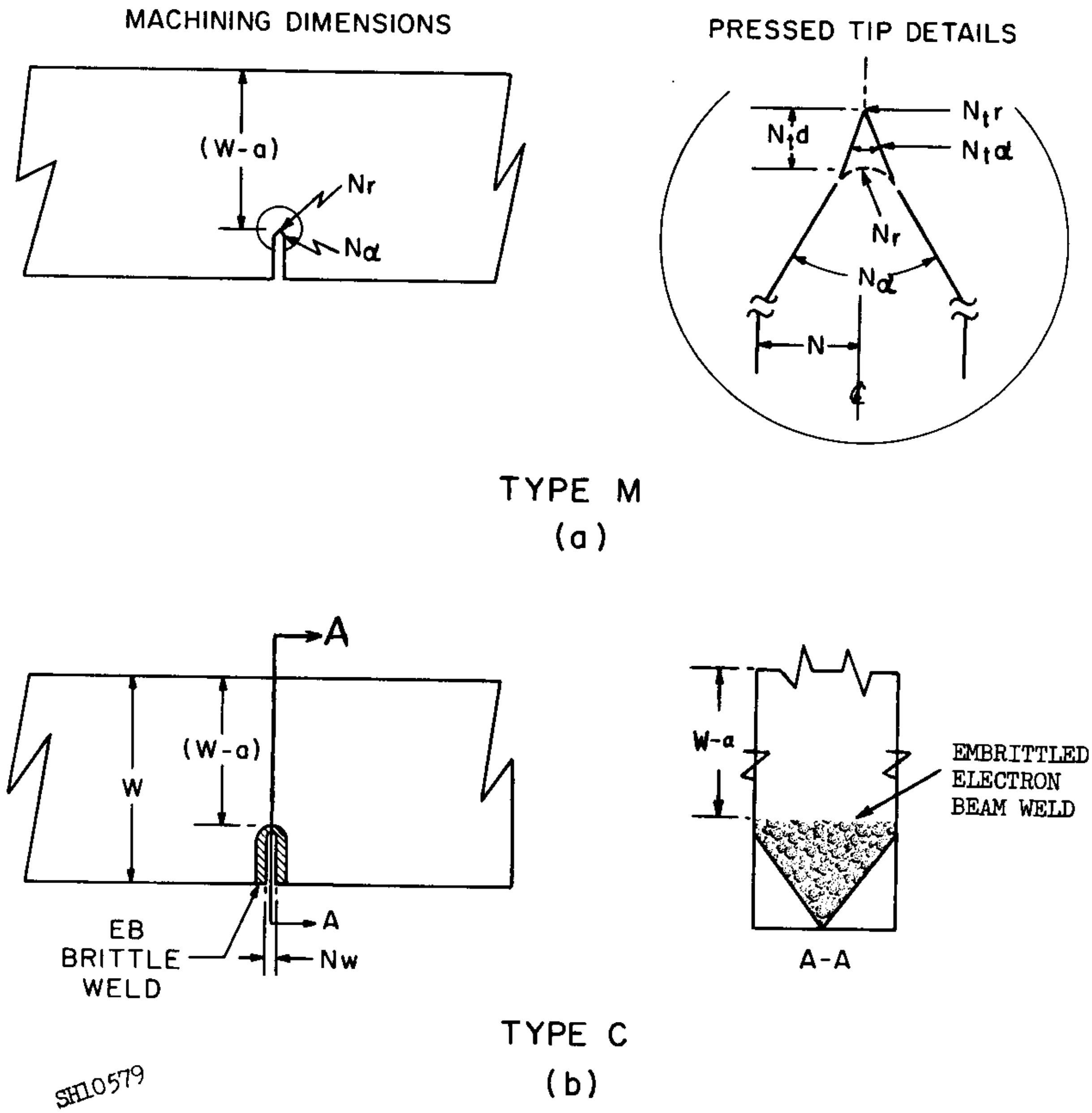


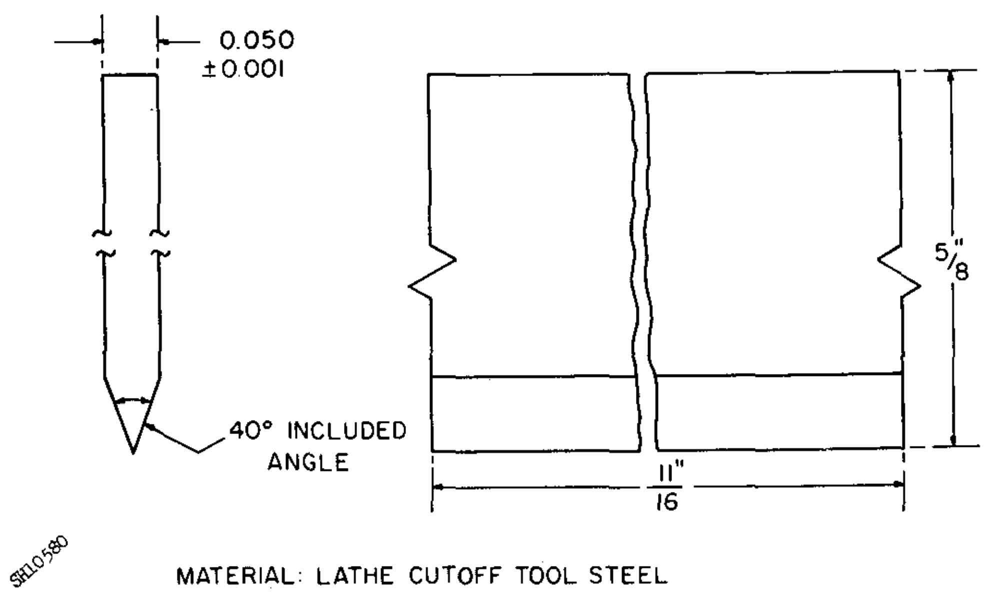
Figure 4 - Details of notches for 5/8 DT specimens: (a) Type M, machined notch; (b) Type C, crack-starter electron beam weld notch.

8.3 Procedure for preparing the type M notch.

8.3.1 Rough machining. Preparation of a type M notch in 5/8 DT specimens should start with rough machining the slit with a slitting saw to the depth of the straight sided portion of the notch (5/16 inch, (8mm)), as shown on figure 5. The angular apex portion and particularly the final cut on the root radius may be completed with a precisely ground saw or cutter to ensure a final root radius less than 0.006 inch (0.18 mm). These machining operations may be performed simultaneously for a group of specimens.

8.3.2 Procedure for pressing notch tip. Pressing the sharp tip on the machined notch shall be performed with individual specimens. A hardened blade of tool steel, 60 Rockwell C hardness (R_c)(min.)) 11/16 inch (17.5 mm) wide, and 0.050 inch (1.27 mm) thick is ground symmetrically to a sharp edge with an included angle of 40 degrees, (see figure 5). Any loading device with sufficient capacity to press the knife into the specimen to the depth prescribed in table II can be used. A setup for performing this operation using a hand operated hydraulic press is shown on figure 6. The sequence of the operation is as follows: (a) the specimen is positioned on the anvil, (b) the piston is advanced to provide contact between the knife and the head of the press, (c) the dial micrometer is set at zero, and (d) sufficient pressure is applied to press the knife into the specimen for the specified distance (see table III). This requires a force of approximately 4,000 pounds (1,900 kg) for mild steel specimens and 2,500 pounds (1,100 kg) for aluminum specimens.

NOTCH SHARPENING KNIFE EDGE BLADE



MATERIAL: LATHE CUTOFF TOOL STEEL

Figure 5 - Knife blade used to sharpen tip of type M notch.

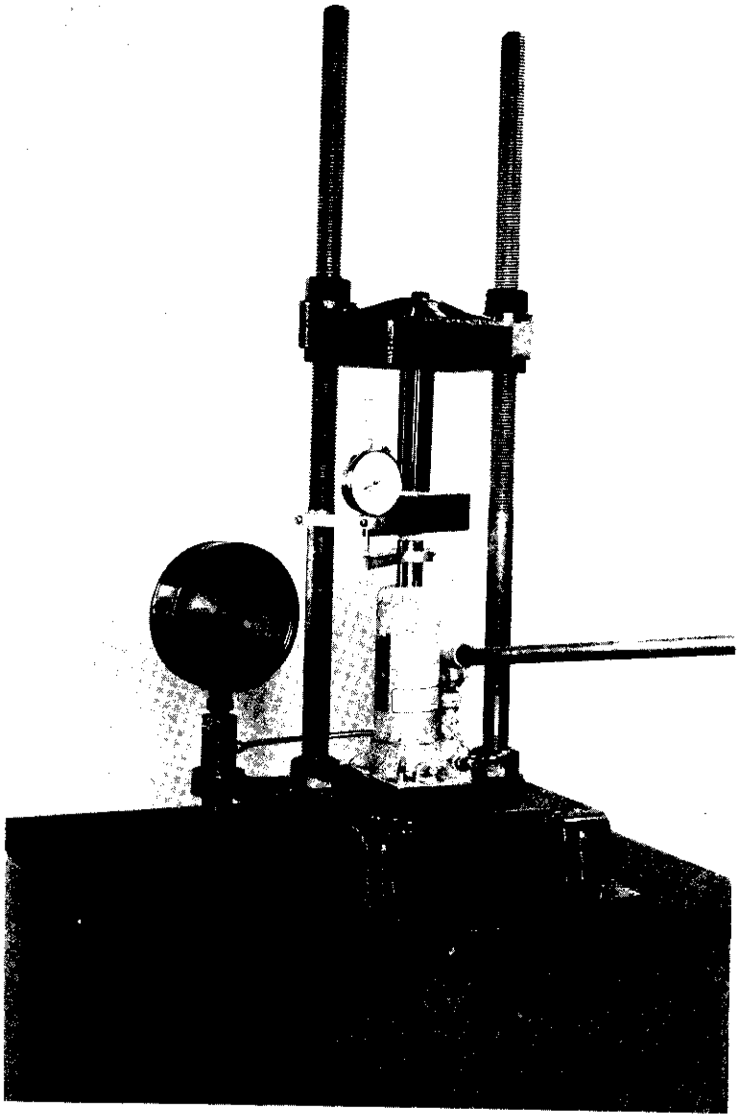


Figure 6 - Hand operated hydraulic press for pressing a sharp tip on a machined notch. Note dial gage micrometer device to indicate depth of penetration.

8.3.3 After each notch is sharpened, the knife blade is examined to detect excessive dulling of the edge. Normally, 15 to 20 specimens of steel with yield strength of 50 thousand pounds per square inch (ksi) (35 kilogram per millimeter squared (35 kg/mm^2)) can be processed before a knife requires a new edge.

8.4 Procedure for preparing the type C notch.

8.4.1 Preparation of the 5/8 DT specimen for the EB crack starter weld requires machining a shallow groove on the tension side of the DT specimen as shown on figure 7. One method for machining the groove is as follows: The tension side of the specimen is sprayed with marking fluid, and a line perpendicular to the specimen sides is scribed at midlength of the specimen. Six or more specimens are aligned in a vise. A 0.050 inch deep groove is then cut across the tension side of the specimen using a 0.050 inch wide, square-bottom, parting tool.

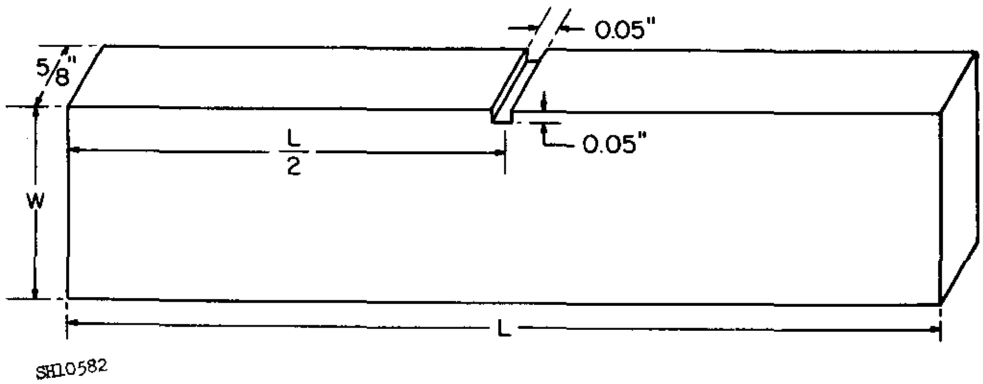


Figure 7 - Preparation of 5/8 DT specimen for placing embrittling wire prior to EB welding of crack-starter weld for type C notch.

8.4.2 A wire of an alloy known to embrittle the test material is placed in the machined groove. Six or more grooved specimen blanks are aligned and clamped together for EB welding. For steel specimens, an unalloyed titanium wire (0.050 inch diameter) is employed. Tin or phosphor bronze wire (0.050 inch diameter) is used to embrittle aluminum specimens, and iron or stainless steel wire is employed with titanium specimens. The wire is placed in the machined groove and upset by light hammering to hold it securely in place. This ensures that a uniform distribution of embrittling alloy along the length of the groove is obtained. If the wire does not make good contact with the base metal, there is a tendency for the electron beam to premelt and eject the wire from the weld zone.

8.4.3 The penetration of the EB weld is primarily dependent upon the power level, the focus or diameter of the beam, and the traverse speed. Typical machine settings to obtain a 3/8 inch penetration for a gun-to-work distance of 4-1/2 inches with the focus on the top surface of the work piece, are as follows:

Metal	Applied voltage (kilovolt (kV))	Traverse (in./min.)	Traverse (m/min.)	EB current (milliampere (mA))
Steel	30	50	(1.3)	153
Titanium	30	50	(1.3)	99
Aluminum	30	50	(1.3)	72

A trial run should be made on each alloy to obtain the correct settings that provide the required penetration with a minimum of spatter. Higher voltage and slower traverse speeds increase the penetration.

8.5 Notching the crack-starter weld. The sides of the crack starter weld shall be notched in a triangular pattern, and not extending into test material (w-a dimension) as shown on figure 4(b). The side notches may be cut with a 1/16 inch (1.5mm) thick mechanical or abrasive saw.

8.6 Preparation of weld metal 5/8 DT specimen.

8.6.1 The 5/8 DT test procedure also provides a method for assessing the fracture toughness characteristics of weld metal. The weld-metal 5/8 specimen shall be sawed from a given length of weldment fabricated with the specific welding procedures, welding process, electrodes, and plate alloys being qualified. The 5/8 DT test weldment shall be a prolongation of the weldment from which other mechanical test samples (such as tension and bend test), are taken. Minimum weld metal area and relationship to weld metal DT specimen shall be as shown on figure 8. Qualification test weld assemblies for mechanical and soundness tests should use normal weld joint geometries.

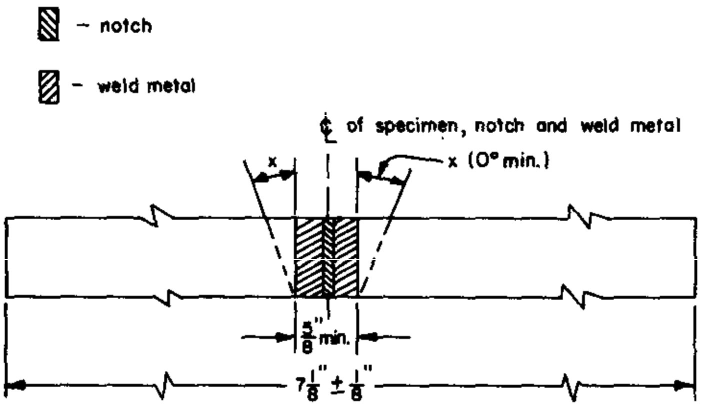


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Figure 8 - Weld metal geometry to specimen dimension relationships for weld metal 5/8 inch DT specimen.

8.6.2 The weld metal 5/8 DT test specimens shall be located as close to the weld's top face (crown) as possible to provide maximum weld metal area in the case of groove joints. A lower integrated DT energy which is not indicative of the intrinsic fracture toughness of the weld metal may be obtained when the fracture surface involves weld metal, heat affected zone, and prime plate areas. The weld's top face (crown) and a minimum of the top plate surface shall be machined flat. All other cutting and machining to the 5/8 inch (16mm) thickness shall be performed from the bottom (root) side of single groove weldments. For thick double groove weldments (suggested minimum of two inches thickness), weld metal 5/8 inch DT specimens may be machined as described above, using blanks removed adjacent to both the top and bottom weld faces as shown on figure 9, and the relationships between weld metal, notch and specimen center lines and minimum dimensions for weld metal areas shall be as shown on figure 8.

8.6.3 The notch of a weld-metal 5/8 DT specimen shall be located on the central axis of the test weld. Preparation and techniques for notching or EB welding of the crack-starter weld shall be the same as those described for plate-metal 5/8 DT specimens.

8.7 Identification of 5/8 DT test specimens.

8.7.1 All sample material and specimens removed from a given plate shall be identified to their particular source such as heat number, slab number and orientation.

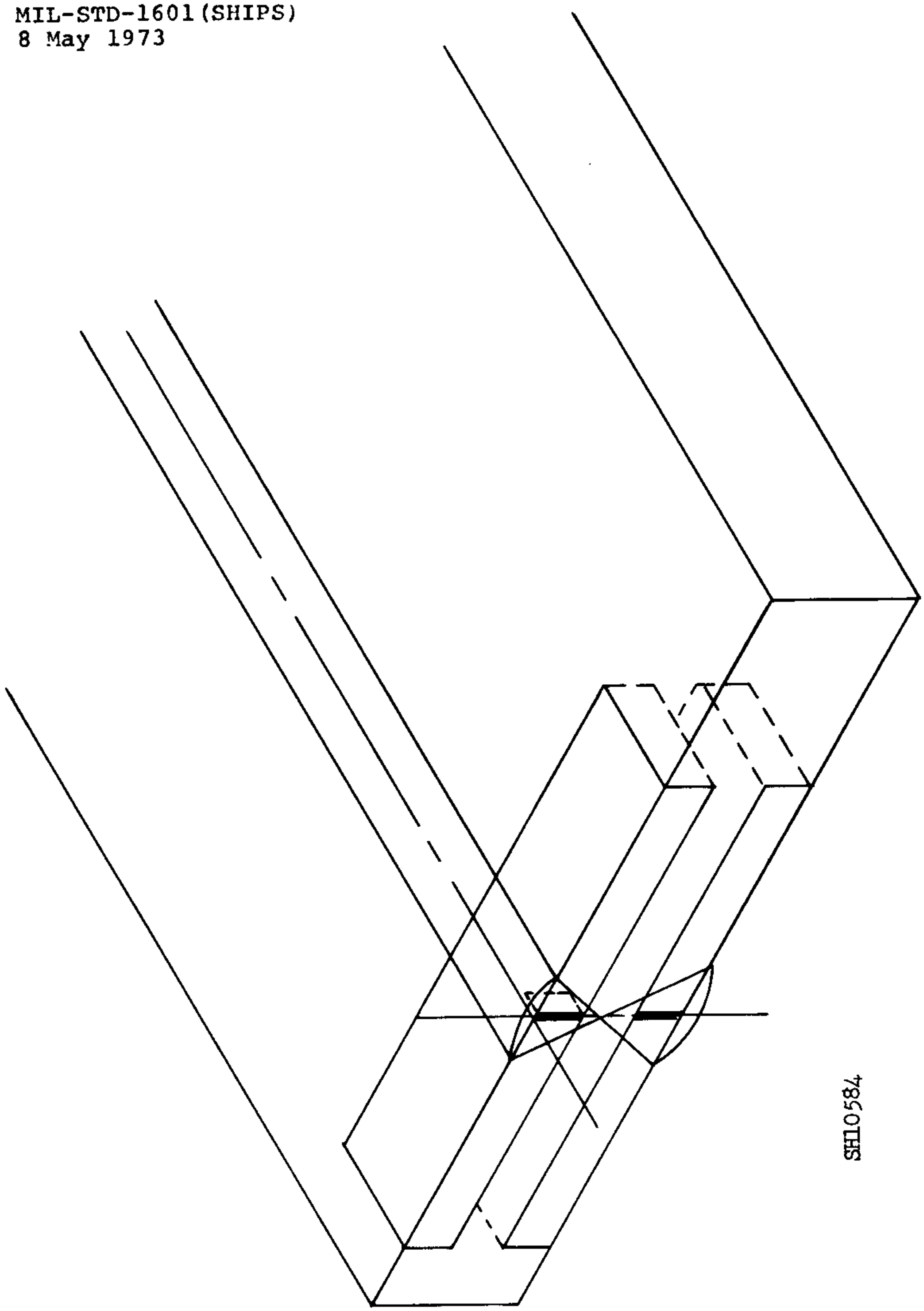

Figure 9 - Orientation of weld metal 5/8 inch DT specimens to a double groove weld joint in thick section weldments.

8.7.2 Weld-metal 5/8 DT test specimens shall be identified as to the heat and lot number of the welding electrode, the welding process and procedures, the preheat and interpass temperatures employed, joint geometry, and prime plate metal used for the qualifving weldment.

8.8 Orientation. Unless otherwise specified in the material specification, all 5/8 DT specimens specified for plate products by the purchaser shall be oriented so that the fracture propagates in the principal rolling direction of the plate (i.e., the ASTM TL orientation). For other metal products, specimen orientation and location shall be as specified in the material specification.

8.9 Relation to other specimens. Unless otherwise specified, the 5/8 DT specimens shall be removed from material at positions adjacent to the location of other required test specimens (for example, tensile test specimens). For products receiving a quenched and tempered heat treatment, the side of the 5/8 DT specimen containing the notch shall be nearest to and a minimum of three plate thicknesses or 4 inches (100mm), whichever is less, from the as-heat-treated end of the plate.

8.10 Specimen cutting. The specimen blank may be saw cut to the dimension tolerances shown in table II. All faces of the specimens associated with the fracture must be a minimum of one-half inch (13mm) from any flame-cut surface. The finished specimen may be tested with saw cut surfaces if all width to thickness angles are maintained normal within ±3 degrees. The end surfaces of the specimens may be flame cut.

9. PROCEDURE

9.1 General. The 5/8 DT test shall be concluded by first placing the specimen in a heating or cooling device until it is at the desired temperature. Then place and align the specimen on the anvil so it will be struck squarely by the hammer within the time specified in 9.3.2.

9.2 Measurement of specimen temperatures. The entire test specimen shall be at a known and uniform temperature prior to the test. When using a liquid medium, the specimens shall be fully immersed in an agitated liquid bath at a known constant temperature and separated from adjacent specimens by a minimum of one inch (25mm) for a period of at least 20 minutes. If a circulating gas heat-transfer medium is used, the required minimum holding time shall be 40 minutes with specimen operation as in liquid bath. When proven that specimen equilibrium temperature can be developed in a short time period by using a thermocouple buried in the center of a dummy test specimen, the specimen-holding period may be reduced. The constant-temperature baths or ovens may be of any type that will heat or cool the specimens to a known and uniform temperature.

9.2.1 Measure the bath temperature by a device with calibration known to ±2 degrees Fahrenheit (°F.), or ±1 degree Celsius (°C).

9.2.2 A suitable well-insulated container which provides a minimum one inch of heat transfer media on all surfaces of the specimen shall be used. By immersing an open basket of cracked dry ice or an electrical heater in the bath, the bath temperature can be precisely adjusted. Specimens placed horizontally in the bath should be laid on a screen or perforated platform at least one inch (25mm) from the bottom. If several specimens are placed in one bath, they should be spaced a minimum of one inch (25mm) apart to ensure an adequate flow of heat-transfer liquid around each specimen. Effective agitation can be provided with oscillating or rotational type mixers.

9.3 Specimen testing and anvil alignment.

9.3.1 Any convenient procedure may be used to remove a specimen from the constant-temperature bath and transfer it to the test machine, provided it does not affect adversely the control of specimen temperature. Tongs, if used, shall be kept in the constant-temperature bath to maintain a temperature equal to the specimen temperature. For conventional test temperatures, transfer and alignment of a specimen can be accomplished by hand, using heavy rubber gloves and grasping the specimen away from the fracture area.

9.3.2 The specimen shall be broken within 10 seconds after it has been removed from the constant-temperature medium or the specimen shall be returned to the medium for reconditioning.

9.3.3 To obtain a valid test, the specimen, anvil, and striker shall be aligned in accordance with section 7. The specimen is broken under the following conditions:

9.3.3.1 The specimen shall be centered on the anvil, and in contact with the anvil supports.

9.3.3.2 The tup of the striker shall strike within ± 0.032 inch (± 0.8mm) of a line drawn normal to the tension surface of the specimen and passing through the centerline of the notch.

9.3.3.3 The specimen sides and ends shall be free from any interference during the test.

10 REPORT

10.1 Contents. The report shall include the following information:

10.1.1 Material identification.

10.1.2 Heat number.

10.1.3 Plate number, if applicable.

10.1.4 For DT test of weld metal, the heat and lot number, the electrode type, the welding process and welding procedures.

10.1.5 Orientation and location of DT test specimens.

10.1.6 Test temperature.

10.1.7 Dynamic tear energy.

11 MATERIAL-QUALIFICATION TESTING

11.1 Use of DT test. A 5/8 DT energy value and test temperature shall be selected as a performance criteria as outlined in the applicable procurement specification(s).

11.2 Single-temperature tests.

11.2.1 Specification tests conducted at a given test temperature, on a go, no-go basis, shall require that a minimum of two DT specimens be tested. Both DT specimens thus tested shall exhibit energy values in excess of the minimum specified in the product specification.

11.2.2 If the DT energy value of one of the two specimens falls below the minimum specified DT energy, a retest of two additional specimens shall be required. Both retest specimens shall exhibit energy values in excess of the minimum specified value. If either of the energy values from the retest specimens fall below the minimum specified value, the lot shall be rejected.

11.2.3 If the DT energy values of both specimens noted in paragraph 11.2.1 above, fall below the minimum specified DT energy of the product specification, retests shall not be allowed and the lot shall be rejected. This does not preclude retest after re-heat treatment as allowed under the procurement specification(s) invoking this document.

Preparing activity:
Navy - SH
(Project 95GP-N001)

APPENDIX

CALIBRATION OF DYNAMIC TEAR TEST APPARATUS

10. SCOPE

10.1 This appendix covers the description of the single and double pendulum machines, and vertical drop weight apparatus used in the 5/8 inch dynamic tear test, as specified in section 7 of the Standard.

20. REFERENCED DOCUMENTS

20.1 The issues of the following documents in effect on the date of invitation for bids form a part of this standard to the extent specified herein.

GOVERNMENTAL

NAVAL RESEARCH LABORATORY
Report 6993 - Vertical Drop Weight Machine for Conducting Drop Weight, NDT, Drop Weight Tear, and Dynamic Tear Tests, January 16, 1970.

(Application for copies should be addressed to the Director, Naval Research Laboratory, Code 6380, 4555 Overlook Avenue, S. W., Washington, D. C. 20390.)

NONGOVERNMENTAL

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)
B221-72 - Aluminum-Alloy Extruded Bars, Rods, Shapes and Tubes.

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pa. 19103.)

30. GENERAL REQUIREMENTS

30.1 Single pendulum apparatus. A single pendulum machine of 2000 ft-lb (280 kg-m) capacity is adequate for conducting 5/8 DT tests on most metals. The machine shall be level to within 3:1000 and securely bolted to a foundation having a mass not less than 40 times that of the pendulum.

30.1.1 The dimensions of the pendulum shall be such that the center of percussion of the pendulum is at the center of strike within 1 percent of the distance from the axis of rotation to the center of the strike. When hanging free, the pendulum shall hang so that the striking edge is within 0.20 inch (5.0mm) of the position where it would just touch the test specimen. When the indicator has been positioned to read zero energy in a free swing, it shall read within 0.2 percent of scale range when the striking edge of the pendulum is held against the test specimen. Transverse play of the pendulum at the striker shall not exceed 0.060 inch (1.50mm) under a transverse force of 4 percent of the effective weight of the pendulum applied at the center of strike. Radial play of the pendulum bearing shall not exceed 0.005 in.(0.125mm).

30.1.2 Calibration of a single-pendulum machine. Place a half-width specimen (0.313 by 1.6 by 7 inches) (8.0 by 40 by 175mm) in test position. With the striking edge in contact with the half-width specimen, a line scribed from the top edge of the specimen to the striking edge will indicate the center of strike of the striking edge. The top edge of the (0.313-inch (8.0mm)) width indicates the center of the striking edge. Support the pendulum horizontally to within 15:1000 with two supports, one at the bearings (or center of rotation), and the other at the center of strike on the striking edge. Arrange the support at the striking edge to react upon some suitable weighing device such as a platform scale, balance, or load cell and determine the weight to within 0.4 percent. Take care to minimize friction at either point of support. Make contact with the striking edge through a round rod crossing the edge at a 90-degree angle. The weight of the pendulum is the scale reading minus the weights of the supporting rod and any shims that may be used to maintain the pendulum in a horizontal position. Measure the length of the pendulum arm from the center of rotation to the center of strike within 0.1 percent. The potential energy of the system is equal to the height from which the pendulum falls times the weight of the pendulum as determined above.

30.1.3 Impact velocity. Determine the impact velocity (v) of the machine, neglecting friction by means of the following equation:

$$v = \sqrt{2\ gh}$$

where: g = acceleration of gravity, ft/s/s (or m/s/s)

and h = initial elevation of the striking edge, ft (or m)

n = striking velocity, ft/s or (m/s)

30.1.4 Center of percussion. To ensure that minimum force is transmitted to the point of rotation, the center of percussion shall be at a point within 1.0 percent of the distance from the axis of rotation to the center of strike in the specimen. Determine the location of the center of percussion as follows:

Using a stop watch or some other suitable timer to within 0.2 second(s), swing the pendulum through a total angle not greater than 15 degrees and record the time for 100 complete cycles (to and fro)
Determine the center of percussion by means of the following equation:

$\ell = 0.8.5\, p^2$, to determine ℓ in feet

$\ell = 24.85\, p^2$, to determine ℓ in centimeters (cm)

where

ℓ = distance, ft (or cm) from the axis to the center of percussion, and
p = time, s, of a complete cycle (to and fro) of the pendulum

30.1.5. Friction. The friction and windage loss in the machine shall not exceed 1.0 percent of the initial energy. The friction and windage loss shall be compensated by adjusting the starting height of the pendulum so that the indicating device reads zero energy when the pendulum is released without a specimen being present. Determine the energy loss from friction and windage as the difference between the energy from the starting position and the energy of the pendulum after it completes its swing without a specimen.

30.2 Double pendulum apparatus. A double pendulum apparatus may be used to conduct DT tests. The pendulum apparatus must comply with all of the requirements in section 7 of the Standard. Double pendulum machines are advantageous when shock to the mounting system must be minimized. One design for a double pendulum DT machine is illustrated on figure 2 of the Standard. The dimensions of the anvil pendulum shall be such that the center of percussion of the pendulum with the specimen in place is within 1 percent of the distance from the axis of rotation to the center of the strike of the hammer pendulum. The weight of the hammer pendulum and the weight of the anvil pendulum shall be equal within 5 percent. The dimensions of the anvil pendulum and the hammer pendulum shall conform to the requirements in section 30.1 of the Appendix, with respect to center of percussion, transverse play and radial play.

30.2.1 Calibration of a double pendulum machine. The procedure for calibration of the hammer pendulum and the anvil pendulum shall be in accordance with the procedure in the appendix, section 30.1.2, for a single pendulum machine. The anvil pendulum shall be calibrated without the specimen in place, and the center of strike shall be taken as the position of the top of a half width specimen or 0.3.3 inch (8.0mm) above the specimen support. The height of the pendulums at the start of a test shall be such that the strike occurs within 5 degrees of their rest position when hanging free.

30.2.2 Specimen anvil details. The anvil pendulum shall be provided with a clamping device that will hold the specimen in place at the start of a test. The clamping force shall provide a friction holding force not to exceed 5 lbs (2.3 kg).

30.2.3 Vertical drop-weight apparatus. An apparatus using a hammer with a guided vertical drop may be used to conduct 5/8 DT tests. A vertical drop-weight apparatus must comply with all of the requirements in section 7 of the Standard. The dimensions of the apparatus shall be such that no arresting device retards the progress of the falling hammer until the striker tup has progressed a vertical distance of 1.75 inches (44mm) beyond the point of contact with the specimen. The dynamic tear energy (DTE) shall be determined with any device that will provide a reading of final energy with an error not to exceed ±5 percent of reading, and not to exceed ±15 ft-lbs (20 kg-m). An illustration of a vertical drop-weight apparatus using an aluminum block system for determining the final energy of the hammer is shown on figure 3 of the Standard. The face of the hammer has two flat surfaces which contact the aluminum compression blocks to arrest the vertical movement of the hammer after the specimen is broken. The surfaces on the hammer and on the anvil that contact the aluminum compression blocks shall have a surface finish of 32 microinch roughness height value (RH). The surfaces shall be parallel within 2:1000. Measurement of the size of the aluminum blocks shall be made with a suitable micrometer. The average height dimension shall be recorded before and after test with an error not to exceed 0.0005 inch (or 0.013mm).

30.2.4 <u>Impact velocity</u>. Determine the impact velocity (v) of the machine, neglecting friction by means of the following equation:

$$v = 2gh$$

where: g = acceleration of gravity (ft/s/s) or (m/s/s)

and h = initial elevation of the striking edge above the point of contact with the specimen; ft (or m)

r = velocity (ft/s) or (m/s)

30.2.5 <u>Friction</u>. The friction and windage loss in the machine shall not exceed 1.0 percent of the initial energy. The friction and windage loss shall be determined as the difference between an energy reading when a test without a specimen is conducted with the guiding columns wiped free of lubricant and an energy reading when a test without a specimen is conducted with the guiding columns lubricated to minimize friction.

30.3 <u>Calibration of aluminum block energy measuring system</u>. The dimensions of the aluminum blocks shall be such that the stiffness at any point in the calibrated range shall not exceed 5 ft-lb/0.001 inch (or 0.7 kg-m/0.025mm). This level of sensitivity can be obtained with the use of two aluminum blocks having an initial height of 1.5 inch (or 38mm) and an initial square cross section of 0.92 to 1.0 inch^2 (or 546 to 645mm^2). The material used is ASTM B221-72 alloy 1060, "O" Temper extruded to a size 1-1/2 by 1 by length inch (or 38 by 25 by length mm). Blocks prepared from one extruded bar shall be segregated and marked for identification purposes. The cross sectional area of specimens in one lot shall not vary in cross sectional area or mass by more than 1:500. A calibration reference chart shall be developed by conducting duplicate tests without a specimen at height increments not to exceed 1 ft. (305mm) throughout the calibrated range. The final height dimension of all the aluminum blocks in the duplicate tests for calibration purposes shall be equal within 0.002 inch (0.05mm). The absorbed energy shall be calculated as the weight of the hammer times the height from the top surface of the aluminum blocks to the surface of the hammer that strikes the aluminum blocks. A graph of absorbed energy vs the compression of the aluminum blocks shall be constructed as a smooth curve through the calibration data points. For general guidance, it is suggested that NRL Report 6993 be consulted.

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APPENDIX D

ECONOMIC ASPECTS OF MEETING TOUGHNESS CRITERION

The design of large complex welded structures generally is based on an attempt to optimize performance and minimize cost. Therefore, a study was made to evaluate to what extent the new toughness criterion may affect the overall cost of a ship because the total cost of purchasing and fabricating all of the steel for a ship represents a significant percentage of the total ship cost. Roughly, this amount varies from about 25 to 50 per cent of the total cost of a ship, depending on size and type. However, the results of a limited study of the economic aspects of ship costs indicate that any increase in overall ship costs resulting from the new toughness criterion appears to be less than 1.5% of the total cost of a ship.

In Section VI, it was estimated that approximately one-half of existing ABS Grades B or C steels meet the proposed main-stress toughness criterion for primary-load-carrying members, and that Grade C-N easily meets this criterion. Grades CS, E, DHN, and EH easily meet this criterio as well as the criterion for crack arresters. Because Grades B and C currently are the most widely used ship hull steels, it would appear that the use of higher-quality grades of steel (or improvement in Grades B and C) will be necessary to comply with the proposed criterion.

An estimate of the total cost of steel and its fabrication for a ship is a very complex process. Once mill prices are established for the particular steels (unit costs), the estimation then must take a large number of additional steel and shipyard costs into account. Typically, these additional costs include the following:

ADDITIONAL STEEL COSTS	ADDITIONAL SHIPYARD COSTS
1. Waste allowance	1. Fabrication
2. Freight rates	2. Assembly
3. Dimensional extras	3. Welding
4. Quantity extras	4. Inspection
5. Other	5. Other

It should be noted that these additional costs will still exist regardless of whether or not the proposed toughness criterion is implemented. However, because there may well be some expenses because of improved welding control, additional testing, etc., the estimated costs will be multiplied by a factor of 1.3 to account for a possible 30% increase in the additional steel and shipyard costs over and above the estimated increase in mill prices.

A precise analysis of the cost of implementing the proposed toughness criterion is beyond the scope of this project. However, an estimate of the maximum projected increase in the original total cost of various ships due to the proposed requirements has been made to obtain a general indication of the economic consequences of meeting the toughness criterion.

The increase in the unit cost of material due to change in grade, improvements in manufacturing, and testing requirements is estimated to be $0.03/lb. Furthermore, the volume of the primary hull steel components affected by the proposed criterion is multiplied by the previo mentioned factor of 1.3 to provide a realistic upper limit of any additional shipyard cost increase resulting from the proposed toughness criterion.

Generalized estimates for cost increases of steel material in welded ship hulls as implied by the proposed criteria are based on separate cost data and specific dimensions of seven ships as presented in various Marad studies [D-1] and SSC reports[D-2]. Their designations, cost procurements, and sizes are as follows:

	DESIGN	COST PROCUREMENT	SIZE, FT (M)
Marad - PD# 158	ore bulk oil	each of series	750, (229) LBP*
Marad - PD# 159	general purpose cargo	each of series	470, (143) LBP
Marad - PD# 160	single screw container	each of series	706, (215) LBP
Marad - PD# 161	twin screw container	each of series	862, (263) LBP
Marad - PD# 162	single screw barge carrier	each of series	771, (235) LBP
Marad - PD# 167	crude carrier (tanker)	each of one	240,000DWT
SSC - 224	bulk carrier	each of five	590 (180) LBP

* LBP = Length Between Perpendiculars

Table D-1 presents the results of a simplified estimation of the total weight of steel that might be affected by the toughness criterion for each of the seven ships. The critical length is taken as 1/2 LBP (assumed to be slightly larger than the midship .4L as defined in ABS rules, Sec. D-3). Using the perimeter of the outer hull shell, this surface is projected as an area (Columns 2 to 5 in Table D-1). For latitude in estimating, two average plate thicknesses were assumed for each case because the supplied cost data for these ships did not include detailed geometry. These same quantitites are also computed assuming that each ship has two longitudinal bulkheads (Table D-2). The density of steel was taken as 490 lbs/ft^3 (7,850 kg/m^3).

Table D-3 compares the maximum total ship cost resulting from an increase in material cost caused by the proposed toughness criterion with the original total ship cost. The total volume of steel affected by the criterion is listed in Column 1 of Table D-3. Column 2 lists the estimated weights of this steel. From these weights the total cost increment for each case is calculated by using a unit cost increment of $0.03/lb and multiplying this value by the factor of 1.3 (to allow for unaccountable costs). Thus the cost increments are added to the original costs in Column 4 and then the desired ratios of new cost to original cost are presented in Column 5.

In general, cargo container and complex special purpose ships can be expected to show the smallest cost increases because of their smaller steel-to-total-ship-cost ratio (due to the expensive outfit and cargo handling gear not used on a tanker). Of greater significance, however, is the observation that Table D-3 shows a cost increase ratio no greater than 1.015 for any of the seven ships investigated. Because the assumptions used in this limited analysis were conservative, the economic consequences of meeting the proposed toughness criterion should be less than 1.5% of the total cost of the ship. In view of the fact that the proposed toughness criterion should lead to safer ships that are more resistant to catastrophic brittle fractures, this increase in cost would appear to be justified.

TABLE D-I

Determination of Volume of Steel in Hull Perimeter Affected by Toughness Criterion

	Total Cost of Ship $\$ \times 10^{-3}$	LBP, ½LBP (Feet)	Beam, Depth (Feet)	Perimeter, 2xBeam + 2xDepth (Feet)	Proj. Area. $ft^2 \times 10^{-3}$	Ave Plate Thickness Assumed (inches)	Volume Projected $ft^3 \times 10^{-3}$
Marad PD# 158	22,355	750 370	105 62	334	125	1.0 1.25	10.4 13.0
Marad PD# 159	13,176	470 235	74 43	234	55	.75 1.00	3.4 4.5
Marad PD# 160	37,936	706 353	101 55	312	110	1.0 1.25	9.2 11.5
Marad PD# 161	51,160	862 431	105 64	338	156	1.0 1.5	12.1 18.2
Marad PD# 162	40,640	771 385	105 60	330	127	1.0 1.5	10.6 15.9
Marad PD# 167	57,520	1085 543	170 84	508	276	1.25 1.75	28.8 40.2
SSC-224	11,919	590 295	89 52	282	83	.75 1.00	5.2 6.9

1 ft = .3048 m

1 inch = 25.4 mm

TABLE D-II

Determination of Total Volume of Steel in Primary Hull Structure Affected by Toughness Criterion

	1 Perimeter, 2 x Depth (feet)	2 Project. Area of 2 Longitudinal Bulkheads ($ft^2 \times 10^{-3}$)	3 Long. Blkhd. Thickness Assumed (inches)	4 Blkhd. Volume ($ft^3 \times 10^{-3}$)	5 Total Vol Projected ($ft^3 \times 10^{-3}$)
Marad PD# 158	124	46.5	.5	1.9	12.3
			.625	2.4	15.4
Marad PD# 159	86	20.2	.375	.6	4.0
			.500	.8	5.4
Marad PD# 160	110	38.8	.500	1.6	10.8
			.625	2.0	13.5
Marad PD# 161	128	55.1	.500	2.3	14.4
			.750	3.4	21.6
Marad PD# 162	120	46.3	.50	1.9	12.5
			.75	2.9	18.9
Marad PD# 167	168	91.1	.625	4.8	33.6
			.85	6.6	46.8
SSC-224	104	30.7	.375	1.0	6.2
			.500	1.3	8.2

1 ft = .3048 m

1 inch = 25.4 mm

TABLE D-III

Analysis of Increment Cost of Ships Caused by Toughness Criterion

	1	2	3		4	5
	Volume Projected ($ft^3 \times 10^{-3}$)	Total Steel Weight (Affected by Toughness Criterion) ($Lbs \times 10^{-3}$)	Cost Increment $\$ \times 10^{-3}$	, x1.3	Original Total Cost + Cost Increment	Ratio New Total/ Original
Marad PD# 158	12.3	6027	180.8	235	22,590	1.010
	15.4	7558	226.7	294.7	22,650	1.010
Marad PD# 159	4.0	1994	59.8	77.7	13,254	1.006
	5.4	2655	79.6	103.5	13,280	1.008
Marad PD# 160	10.8	7066	158.5	206	38,142	1.005
	13.5	6610	198.3	257.8	38,194	1.007
Marad PD# 161	14.4	7066	212	275.6	51,436	1.005
	21.6	10584	317.5	412.8	51,573	1.008
Marad PD# 162	12.5	6140	184.2	239.5	40,880	1.006
	18.9	9207	276.2	359.1	40,999	1.009
Marad PD# 167	33.6	16439	493.2	641.1	58,161	1.011
	46.8	22952	688.6	895.1	58,415	1.015
SSC-224	6.2	3018	90.5	117.7	12,037	1.010
	8.2	4033	121.0	157.3	12,076	1.013

1 ft = .3048 m

1 inch = 25.4 mm

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APPENDIX E

DEVELOPMENT OF CVN VALUES EQUIVALENT TO PROPOSED TOUGHNESS REQUIREMENTS

Many existing toughness specifications are based on CVN impact test results. Therefore, to compare the proposed DT toughness requirements with existing specifications, CVN values that are equivalent to the proposed DT toughness requirements must be developed.

A review of the various K_{Ic}, K_{ID}, DT, and CVN correlations indicates that the most appropriate relation between K_{ID} and CVN impact specimens is the following[E-1]:

$$\frac{K_{ID}^2}{E} = A\,(CVN)$$

where:

K_{ID} = Critical dynamic stress-intensity factor at a particular test temperature

E = Young's Modulus (assumed to be 30,000,000 psi (207 GN/m^2))

A = Constant of proportionality

CVN = Dynamic fatigue-cracked CVN impact value at the same test temperature for which K_{ID} is obtained

The loading rates, test temperatures, and notch acuities were the same for both the K_{ID} and CVN specimens used to develop the above relation. Thus, the correlation would be expected to be quite realistic.

However, most CVN values are for specimens with standard notches (root radius = 0.010 inches (0.25 mm)) rather than fatigue-cracked notches. Thus, the use of the above relation to estimate CVN values for standard-notched specimens assumes that the effect of notch acuity can be accounted for by the constant of proportionality. A value of A = 5 does this [E-2].

At 32°F (0°C), the required K_{ID} is equal to $0.9\sigma_{yD}$. Substituting this requirement into the above equation yields:

$$CVN = \frac{K_{ID}^2}{5E} = \frac{(0.9\,\sigma_{yD})^2}{5E}$$

The equivalent required CVN values are presented in Table E-1 and show that these calculated CVN values range from 19 to 78 ft lb (26 to 106 J) for steels having yield strengths from 40 to 100 ksi (276 to 689 MN/m^2), respectively. The higher values are outside the range for which this correlation is applicable and appear to be too high.

A more direct method of determining the CVN values equivalent to the required DT values is to use the required DT values from Tables I and II and the test results in Fig. E-1 (Correlation Between CVN and DT test results at either +32°F (0°C) or 75°F (24°C)) and determine the CVN values directly. These values range from 20 to 44 ft lb (27 to 60 J), Table E-2. Comparison of the results presented in Tables E-1 and E-2 indicates that both

TABLE E-I

EQUIVALENT CVN VALUES FOR PRIMARY LOAD-CARRYING MEMBERS USING K_{ID} - CVN CORRELATION

Static Yield Strength σ_{ys} ksi	Static Yield Strength σ_{ys} MN/m^2	Dynamic Yield Strength σ_{yD} ksi	Dynamic Yield Strength σ_{yD} MN/m^2	Required K_{ID} $ksi\sqrt{in}$	Required K_{ID} $MN/m^{3/2}$	$CVN = \frac{K_{ID}}{5E} = \frac{(0.9\sigma_{yD})^2}{5E}$ ft lb	CVN J
40	276	60	414	54	59	19	26
50	345	70	483	63	69	26	35
60	414	80	552	72	79	35	47
70	483	90	621	81	89	44	60
80	552	100	689	90	99	54	73
90	621	110	758	99	109	65	88
100	689	120	827	108	119	78	106

TABLE E-II

EQUIVALENT CVN VALUES FOR $\frac{K_{ID}}{\sigma_{yD}} \geq 0.9$ at 32°F (0°C) FOR PRIMARY-LOAD CARRYING MEMBERS USING CVN-DT CORRELATION, FIG.E-1

Static Yield Strength σ_{ys} ksi	Static Yield Strength σ_{ys} MN/m^2	Dynamic Yield Strength σ_{yD} ksi	Dynamic Yield Strength σ_{yD} MN/m^2	Required DT Value ft lb	Required DT Value J	Equivalent CVN Value ft lb	Equivalent CVN Value J
40	276	60	414	250	339	20	27
50	345	70	483	290	393	24	33
60	414	80	552	335	454	28	38
70	483	90	621	375	508	32	43
80	552	100	689	415	563	36	49
90	621	110	758	460	624	40	54
100	689	120	827	500	678	44	60

approaches yield equivalent CVN values of about 20 ft lb (27 J) for steels with yield strengths of 40 ksi (276 MN/m^2). For steels with yield strengths of 100 ksi (689 MN/m^2), the K_{ID} - CVN correlation yields values that appear to be too high on the basis of service experience and engineering judgment. Therefore, for comparison purposes, the values presented in Table E-2 are recommended.

Values for crack arresters were obtained directly using the DT values from Table II and the correlation curve in Fig. E-1. These values are tabulated in Table E-3, and appear to be quite realistic.

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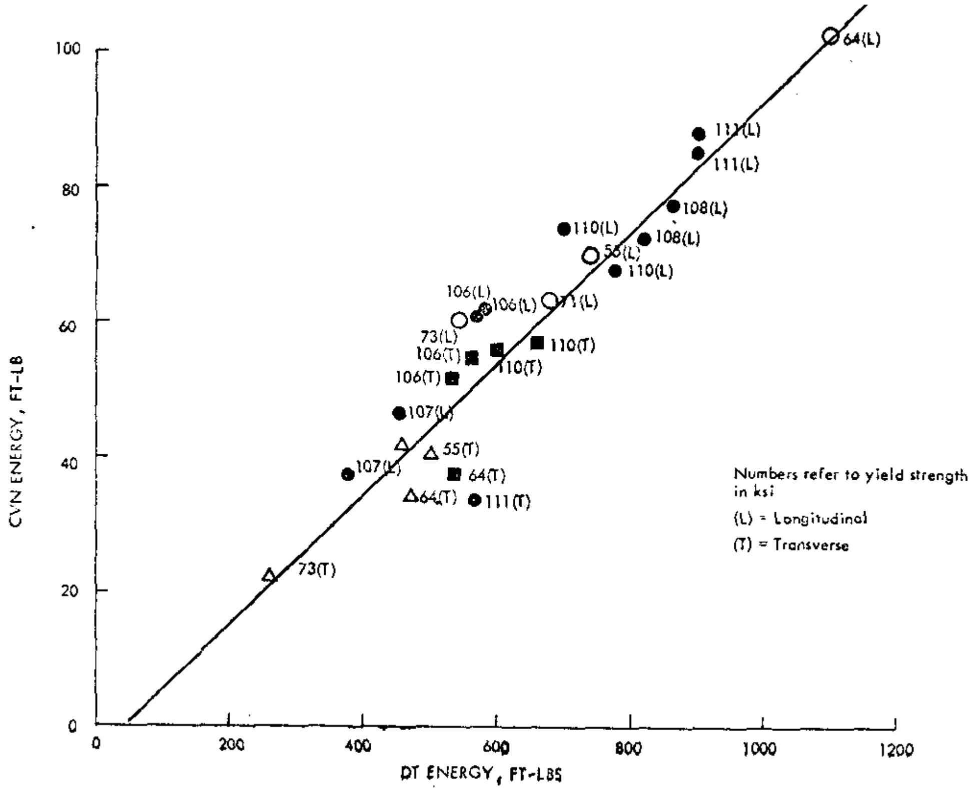

Fig. E. 1. Correlation Between Absorbed Energy in 5/8" DT and Standard CVN Test Specimens at 32°F or 75°F

TABLE E-III

EQUIVALENT CVN VALUES AT 32°F (0°C) FOR CRACK ARRESTERS USING CVN-DT CORRELATION, FIG. E-1

Static Yield Strength σ_{ys}		Dyanmic Yield Strength σ_{yD}		Required DT Value		Equivalent CVN Value	
ksi	MN/m^2	ksi	MN/m^2	ft lb	J	ft lb	J
40	276	60	414	600	813	54	73
50	345	70	483	635	861	57	77
60	414	80	552	670	908	60	81
70	483	90	621	700	949	63	85
80	552	100	689	735	997	67	91
90	621	110	758	770	1044	70	95
100	689	120	827	800	1085	73	99

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13. ABSTRACT

The Report provides comprehensive toughness criteria for welded ship hulls that can be used for steels of all strength levels. Because of the fact that stress concentrations are always present in large complex welded structures and therefore high stresses as well as discontinuities or flaws will be present in welded ship hulls, primary emphasis in the proposed fracture-control guidelines is placed on the use of steels with moderate levels of notch-toughness and on the use of properly designed crack arresters. In general, concepts of fracture mechanics are used to develop the material toughness level that is required for fail-safe operation of welded ship hulls. This toughness level is estimated to be a K_{ID}/σ_{yD} level of 0.9 at 32°F (0°C), where K_{ID} is the critical material toughness under conditions of dynamic loading and σ_{yD} is the yield strength of the material under the same dynamic loading. Because this level of toughness cannot be measured directly using current fracture mechanics tests, these requirements are established in terms of the NDT (nil-ductility transition) temperature and DT (dynamic tear) test values for base metal, weld metal, and heat-affected-zone materials used in primary load-carrying members. Emphasis is also placed on the proper spacing and proportioning of crack arresters fabricated from steels with very high levels of notch toughness to provide a fail-safe design.

Although the criteria presented in this report are primarily materials specifications, the importance of proper design (avoiding details that lead to stress concentrations) and proper fabrication (good quality welding and inspection) is emphasized.

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