SSC-199

STUDY OF THE FACTORS WHICH AFFECT THE ADEQUACY OF HIGH-STRENGTH LOW-ALLOY STEEL WELDMENTS FOR CARGO SHIP HULLS

SHIP STRUCTURE COMMITTEE

AUGUST 1969

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:
SECRETARY
SHIP STRUCTURE COMMITTEE
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C. 20591

August 1969

Dear Sir:

The impetus behind the use of high-strength steels in shipbuilding has been largely due to the savings in weight of the ship. Since the high-strength steels used have a different character than the traditional lower strength steels, a criteria for material selection, design, and fabrication is necessary. Ship Structure Committee project, "High-Strength, Low-Alloy Steel Weldments", with Southwest Research Institute as the investigator, is intended to provide background for criteria development. The enclosed report, "High-Strength, Low-Alloy Steel Weldments", describes the results of a first phase effort to identify what information is available on high-strength, low-alloy steels and what data must be developed by research.

This report has been distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerely,

C. P. Murphy
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-199

First Technical Report
on
Project SR-177
"High-Strength, Low-Alloy Steel Weldments"
to the
Ship Structure Committee

STUDY OF THE FACTORS WHICH AFFECT THE ADEQUACY OF HIGH-STRENGTH LOW-ALLOY STEEL WELDMENTS FOR CARGO SHIP HULLS

by

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under

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U. S. Coast Guard Headquarters
Washington, D. C.

August 1969

ABSTRACT

A recent advent in ship construction is the use of high-strength low-alloy steels with 100,000-psi yield strengths for ship hull structural elements, making unique design concepts possible. This application is a significant step, but the mateerial's behavior needs to be further defined. For the benefit of the owners, designers, and fabricators, a project was initiated by the Ship Structure Committee to establish which mechanical properties should be used as criteria for judging performance, to evaluate large-scale weldments to determine the suitability of these criteria, and to select small-scale laboratory tests that correlate with the large scale tests. A survey of shipyards and ship repairers revealed that these newer materials are being used only in critical strength elements of ship hulls. Welding procedures are qualified by explosion bulge tests to define safe operating temperature limits. A survey of the properties of these materials and their weldments indicated that the HAZ might be suspected to be more susceptible to crack initiation and growth than the unaffected base plate, but it was concluded that more data are needed to establish serviceability criteria. It is recommended that laboratory investigations be performed to determine the effect of environment and cyclic stresses on slow crack growth and establish the fracture toughness of weldments, including the effects of residual stress and metallurgical and geometric discontinuities.

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I. INTRODUCTION

Merchant ship hull structural elements are currently being constructed of a wide variety of steels that can be classified into several groups such as the as-rolled or normalized structural carbon steels with yield points up to 40,000 psi, the low-alloy steels with yield points ranging from 40,000 to 75,000 psi, and the quenched and tempered low-alloy steels with minimum specified yield strengths above 75,000 psi (HSLA Q and T steels). Figure 1 depicts two hybrid steel hulls and the specific structural elements made of HSLA Q and T steels in current designs.

The behavior of as-rolled and normalized steels in marine service is known well enough to establish requirements for their usage in ship hull construction.(1, 2, 3)* This is not the case for HSLA Q and T steels, although there is a considerable body of information on the behavior of these steels derived from laboratory investigations and from their use in other engineering structures.(4, 5, 6)

A three-phase program has been undertaken to define the relationship between material properties and performance characteristics of HSLA Q and T steel weldments being used in the construction of merchant ship hulls, and to delineate investigations required to develop the criteria which will assure long term satisfactory service. This scope of the overall program is as follows:

> Phase I, Item 1 - Determine, using existing knowledge, those mechanical properties and quantitative values of HSLA weldments which should be used as criteria for judging satisfactory performance in the various service environments of a cargo ship hull.
>
> Phase I, Item 2 - Undertake a study of the available welding procedures applicable across the board for repair welding any combination of HSLA and plain carbon ship steels and provide a welding technique capable of producing an adequate temporary weld in small remote parts or at sea where welding supplies, procedure controls, and welder qualifications are limited.
>
> Phase II - Evaluate large-scale weldments to determine the suitability of the criteria selected in Phase I, Item 1.
>
> Phase III - Select small-scale laboratory tests that correlate with the large-scale weldment tests.

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*Superscript numbers in parentheses refer to the Bibliography at the end of this paper.

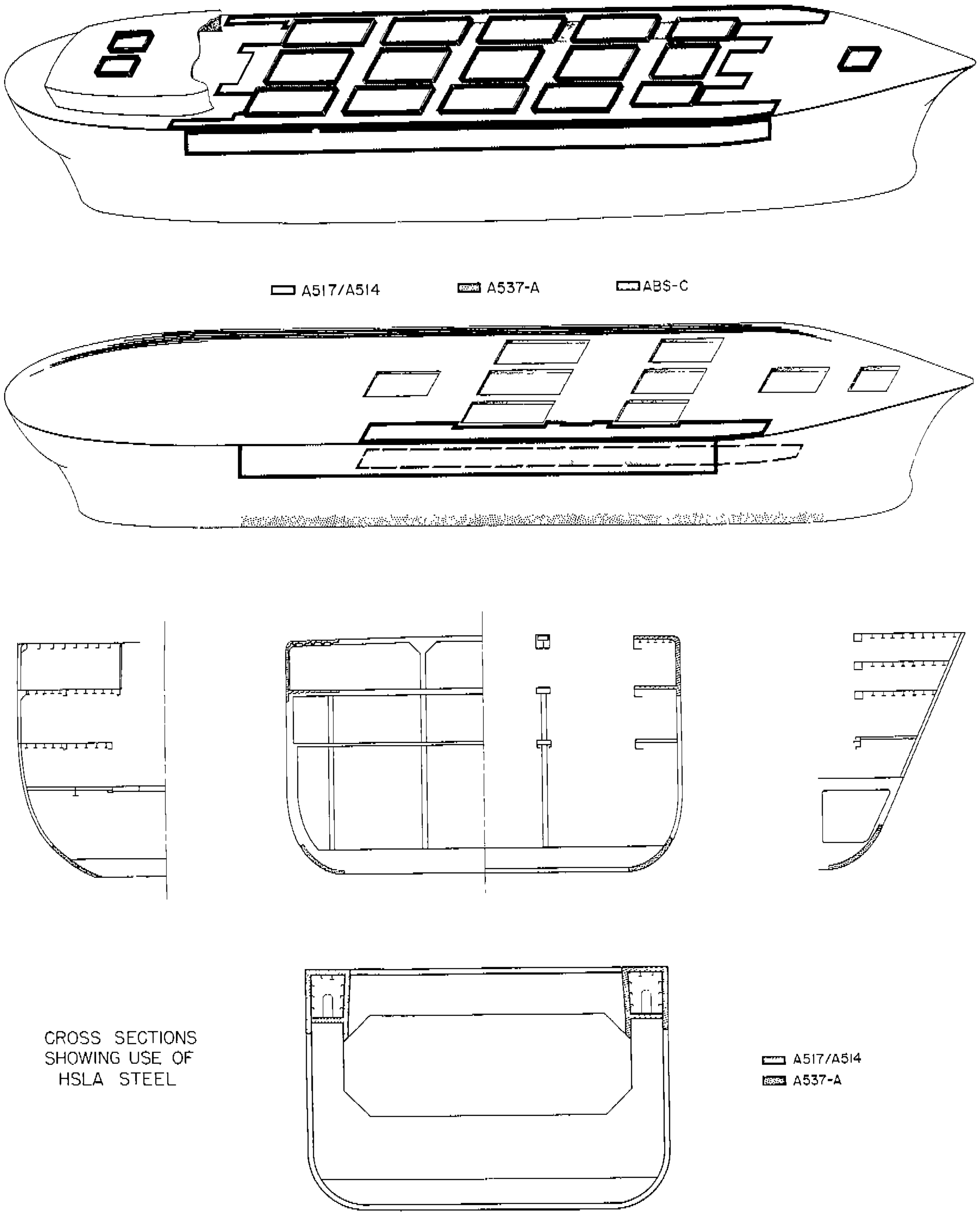


Fig. 1. Use of HSLA Steel in Modern Ships

This report summarizes the results obtained in Phase I, Item 1. This study included a survey of the use of HSLA Q and T steels in shipbuilding, with emphasis on fabrication and inspection procedures, and a review of relevant data on the mechanical properties of these materials.

II. RESULTS OF SURVEY

The shipbuilding, ship repairing, and steel industries were surveyed to determine the present state of utilization of HSLA Q and T materials and to delineate investigations required to establish the criteria which will assure long term satisfactory service of merchant ship hulls.

The survey produced the following information:

- HSLA Q and T materials are currently used only in critical highly stressed elements of ship structure.

- This class of material is more highly stressed, both from residual and service stresses, than similarly used carbon steel. For example, changes in overall design and reduced section sizes raise the stress levels in localized areas by increasing the flexibility of hulls. Also, residual stresses in HSLA Q and T weldments are expected to be higher than in carbon steel weldments because of the higher yield strength of the HSLA materials.

- The occurrence of fabrication flaws and defects creates a more severe problem in HSLA Q and T materials than in carbon steels. Quality control and inspection procedures in ship structures have not been refined to a degree commensurate with the materials fabrication problems, where HSLA Q and T materials are used. It is essential that these refinements be made.

- Typical HSLA Q and T base metal properties are as follows:

UTS (ksi)	0.2% YS (ksi)	Elong. (%)	Hardness (Rc)	E208 NDTT (°F)	C_V at - 60 (ft-lb)	
					L	T
115-125	105-115	20	25-30	-50	30-55	20-40

- HSLA Q and T submerged arc weldments exhibit the following general behavior:

Hardness (R_C)		C_V at -50° F (ft-lb)		Explosion Bulge
Weld Metal	HAZ	Weld Metal	HAZ	FTE (°F)
25-30	20-40	20-35	20-40	-10 to +40

- There are very little data on HSLA Q and T materials which are applicable to the evaluation of ship structure serviceability. Steels with hardness values equal to those of the HAZ in A514/A517 ship structure weldments exhibit susceptibility to crack initiation and slow crack growth in marine environments when subjected to stresses less than the values expected in ship structures. These steels may also have appreciably shorter notched specimen fatigue lives in marine environments than do carbon steels when the difference in service stress levels is considered.

- The HAZ in HSLA Q and T weldments is suspected to be more susceptible to crack initiation and growth than the unaffected base plate because of its properties and its geometric location with respect to discontinuities and highest combined stresses. The only HAZ property that can be accurately measured in an actual weldment is hardness. This is useful information because hardness values correlate with tensile strength and fracture toughness properties for a particular steel alloy.(7)

III. SURVEY OF THE USE OF HSLA Q AND T MATERIALS IN MERCHANT SHIP HULL CONSTRUCTION

A. Survey Procedure

The initial program effort was the determination of why, where, and how HSLA Q and T steels are used in current and planned merchant ship hull construction. This information is requisite to selecting the performance requirements of the materials of construction, establishing the relationships between properties and serviceability, and program development.

A questionnaire was prepared and sent to all of the shipbuilders and and ship repair facilities in the country who are potential users of HSLA Q and T steel structural elements in merchant ships. A sample questionnaire is included as the Appendix. Of the 56 questionnaires distributed, 10 were returned. The Coast Guard, ABS, and HSLA Q and T steel suppliers were also queried to assure that a complete list of shipyards using this class of materials was developed. The data from the questionnaires and other sources were compiled, summarized, and reviewed and a field trip itinerary developed. The itinerary included visits to all of the shipyards using A514/A517 materials in hull construction. The itinerary also included visits to welding supply manufacturers, the R&D laboratories of steel suppliers, and other R&D laboratories that had studied the properties or participated in the development of these materials. It also included visits to Japanese shipbuilders, research and development laboratories, and universities.

The shipyard visits were made by a welding engineer and a structural engineer, each of whom had experience with HSLA Q and T materials of construction. It was agreed that specific information obtained in these visits would be kept confidential except for that information whose publication was considered essential to the program effort and for which specific written authorization for its release was obtained from the source organization. Full cooperation was obtained from all of the shipyards visited which provided a realistic basis for problem assessment.

The basic plan for a shipyard visit was to:

- Review plans and specifications including design details, welding procedures, quality control, and inspection practices.
- Observe fabrication practices in detail, including auditing of workmanship.
- Critique of materials of construction, practices, and problems encountered in HSLA Q and T fabrication with shipyard personnel directly concerned with a responsibility for welding.

Specific documents, information, and data of particular interest to the program were requested and obtained for project files to serve as a basis for future work.

The other visits were made to determine and collect the information available on HSLA Q and T materials, including weldments, and on specific laboratory tests that best simulate the serviceability of a structure. This information was received on the same confidential basis as the shipyard information. The experience record of HSLA Q and T materials in other structures, including fabrication problems and failure investigation, was reviewed in relationship to shipyard practices and marine environments.

B. Survey Results

1. Design

There are several mechanisms of failure which should be considered in merchant ship hull design, including:

- Excessive plastic deformation, including plastic instability
- Excessive elastic deformation, including elastic instability
- Tensile (ductile or overload) failure
- Low cycle (high strain) fatigue
- Corrosion

- Stress corrosion
- Corrosion fatigue
- Fast fracture, including cleavage and low energy tear fracture.

An actual service failure, of course, is usually the result of more than one of the aforementioned mechanisms.

The structural design problem should include:

- Assurance that an as-built structure is adequate to withstand service loading
- Assurance that service loads, or environments and incidents, do not degrade structural or materials properties below acceptable limits during required service life
- Assurance that joint details are reviewed in light of materials properties to minimize flaws that would degrade performance in which the calculated stress magnitude does not exceed an allowable stress value derived from mechanical test properties of the materials of construction. Environmental effects can be considered by the inclusion of this parameter in a specified materials test procedure. The effects of fabrication flaws, defects, and residual stresses can seldom be so included, because of the limitations of test specimen size and other practical difficulties, and must be developed separately. The evidence is that the problem of fabrication flaws, both in character and effect, is different in HSLA Q and T steels than in low-carbon steels.(8-13)

Quality control and inspection procedures must consequently be reconsidered in the light of properties of materials of construction. The construction details should provide inspectable joints.

This study is limited to the effects of changes in mechanical properties of materials of ship hull construction on serviceability. The fact that the structural geometry of ships utilizing HSLA Q and T steels is also different from the carbon steel ship hulls whose service record is the present basis for design must not be forgotten. In general, these differences derive from the new cargo handling systems that require modification of strength deck design. The factors required for satisfactory utilization of carbon steels in merchant ship hull construction have been established and the task at hand is to establish like factors for HSLA Q and T steels to provide equal serviceability and permit economic construction for the particular case of shipyard construction and marine service.(14-17)

The design details of the several ships using HSLA Q and T steels were reviewed during visits to various shipyards. See Figure 1 for typical hull sections presently being fabricated.(18-22) The increased area of hatches in such ships is compensated for by using higher-strength steels in lieu of heavy section carbon steel plates and shapes. This avoids several adverse geometry and fabrication factors.

2. Fabrication

The most common weld joints observed during the visits to various shipyards were the double welded "V" joint, intermittent fillet joint, double fillet "T" joint, double bevel "T" joint, and the double bevel corner joint (fillet reinforced). These weld joint configurations are standard for all types of stiffened plate and structural construction. The only joint configuration which caused some concern was a double bevel corner detail used to joint the deck scantlings to gunnel bar and sheerstrake. The concern is that the joint does not lend itself to radiographic inspection. The difficulty of inspection, coupled with the high restraint of the weld joint and the high stress through the thickness of the deck plating, can lead to problems. These problems can be overcome by changing the joint design to make it more readily inspectable, or by employing a more reliable welding process. Properly designed joints usually reduce filler metal requirements, the number of passes, and distortion. They also facilitate good workmanship.

At shipyards, most joint details are prepared by oxygen-gas torch cutting. This method, when properly used, leaves very little slag or oxide on the prepared joint. In the case of alloy steels with relatively high hardenability, there are two factors which must be considered when joints are prepared in this manner. The first and most important factor is the possibility of cracking along the torch cut edge. The second factor is the lack of ductility and increase in hardness in the HAZ caused by the torch cutting. In the case of HSLA Q and T steels, it may be necessary to grind the torch-prepared edge of thicker plates to eliminate cracks and hard transformation products. As steel hardenability increases, the more likely grinding will be needed. Relative calculated hardenability numbers are shown in Table I.

All welding involving A514/517 materials is supposed to be performed using low hydrogen techniques in conjunction with controlled preheat and interpass temperatures. The observed welding procedures vary little from yard to yard and essentially conform to those for HY80 as specified in NAVSHIPS 0900-006-9010.

The majority of the welding performed on A514/517 materials is accomplished using the shielded metal arc process with E11018 M or G Electrodes.

Table I. Composition and Properties of ASTM A514/A517 Steels and Other Steels Used in Ship Construction

	ASTM A514/A517												ASTM A537
Grade	A	B	C	D	E	F	G	H	J	K	ASTM A441	ASTM A242	A
Chemistry (Ladle)													
C	0.15 - 0.21	0.12 - 0.21	0.10 - 0.20	0.13 - 0.20	0.12 - 0.21	0.10 - 0.20	0.15 - 0.21	0.12 - 0.21	0.12 - 0.21	0.10 - 0.20	0.22 Max	0.20 Max	0.20 Max
Mn	0.80 - 1.10	0.70 - 1.00	1.10 - 1.50	0.40 - 0.70	0.40 - 0.70	0.60 - 1.00	0.80 - 1.10	0.95 - 1.30	0.45 - 0.70	1.10 - 1.50	0.85 - 1.25	1.25 Max	0.70 - 1.40
P	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.035 Max	0.04 Max	--	0.040 Max
S	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.040 Max	0.05 Max	0.05 Max	0.050 Max
Si	0.40 - 0.80	0.20 - 0.35	0.15 - 0.30	0.20 - 0.35	0.20 - 0.35	0.15 - 0.30	0.50 - 0.90	0.20 - 0.35	0.20 - 0.35	0.15 - 0.30	0.30 Max	--	0.15 - 0.50
Ni	--	--	--	--	--	0.70 - 1.00	--	0.30 - 0.70	--	--	--	--	--
Cr	0.50 - 0.80	0.40 - 0.80	--	0.85 - 1.20	1.40 - 2.00	0.40 - 0.65	0.50 - 0.90	0.40 - 0.65	--	--	--	--	--
Mo	0.18 - 0.28	0.15 - 0.25	0.20 - 0.30	0.15 - 0.25	0.40 - 0.60	0.40 - 0.60	0.40 - 0.60	0.20 - 0.30	0.50 - 0.65	0.45 - 0.55	--	--	--
Va	--	0.03 - 0.08	--	--	--	0.03 - 0.08	--	0.03 - 0.08	--	--	0.02 Min	--	--
Ti	--	0.01 - 0.03	--	0.04 - 0.10	0.04 - 0.10	--	--	--	--	--	--	--	--
Zr	0.05 - 0.15	--	--	--	--	--	0.05 - 0.15	--	--	--	--	--	--
Cu	--	--	--	0.20 - 0.40	0.20 - 0.40	0.15 - 0.50	--	--	--	--	0.20 Min	--	--
B	0.0025 Max	0.0005 - 0.005	0.001 - 0.005	0.0015 - 0.005	0.0015 - 0.005	0.002 - 0.006	0.0025 Max	0.0005 Min	0.001 - 0.005	0.001 - 0.005	--	--	--
Hardenability (Approx.) D_I	14.2	11.1	4.5	8.0	17.2	24.2	23.7	25.0	4.62	8.1	1.46	1.02	1.17
Carbon (Equiv.) E_w	0.60	0.56	0.71	0.65	0.89	0.71	0.75	0.62	0.46	0.56	0.43	0.41	0.43
Tensile Properties	All Grades												
Tensile	115,000 to 135,000 psi										63,000 - 70,000	63,000 - 70,000	65,000 - 85,000
Yield	100,000 psi Min										42,000 - 50,000	42,000 - 50,000	46,000 - 50,000
Elong. 2 in.	18% Min										16 - 18%	16 - 19%	19 - 23%
Hardness													
Bend Test 180°	Radius = 2 X Thickness for 1 in. and under Radius = 3 X Thickness for over 1 to 2-1/2 in. Incl.										Radius 1 T to 3/4 in. Incl. Radius 1-1/2 T over 1 to 1-1/2 in. Incl. Radius 2 T over 1-1/2 in.		Radius 1-1/2 T to 1-1/4 in. Incl. Radius 2 T over 1-1/4 to 2 in. Incl.

When A514/517 material is welded to one of the medium strength materials, the usual procedure is to use the preheat, interpass, and low hydrogen techniques required by the high-strength, quenched and tempered material. The weld metal strength is usually chosen such that it matches that of the lower strength steel. However, one of the yards visited chose to match the weld metal strength to the higher-strength base material.

With one yard excepted, the root pass of groove and tee welds and single pass fillet welds are made using E8018 or E9018 electrodes. This is done in an effort to minimize the chance of root cracking in groove welds and transverse cracking in fillet welds. This selection was based on tests which indicated that dilution with the base metal raises the strength of the deposited weld metal to near that of the base plate.

The use of the lower strength electrodes for root and single pass fillet welding seems to be an effective method in reducing the chance of root cracks. The only drawback to this procedure is the possibility of the welder using the lower strength electrode for welding subsequent filler layers. Any procedure which requires multiple filler metals has the same drawback and requires close supervision by those in charge of quality control.

One semiautomatic process, short circuiting MIG, is currently used by the shipyards in HSLA Q and T welding. This process is being used to make a full penetration corner weld of deck plating to sheerstrake.

Two full automatic processes were in use, the submerged arc and MIG processes. The only submerged arc welding procedure in use for which details were available limits the heat input to 25,000 joules/in. for 1-in.-thick plate because of the results obtained on two explosion bulge test series which were fabricated and tested for welding procedure qualification. One series was fabricated with a maximum heat input of 55,000 joules/in. and the second was fabricated using a maximum of 25,000 joules/inch. Although the former did not qualify with the explosion bulge test, the authors do not consider the latter to be economical. It is possible that a successful test series could have been fabricated using an intermediate heat input that would be more economical than the 25,000 joules/in. procedure.

The automatic MIG procedure which was observed used a heat input of 55,000 joules/inch. This procedure was also qualified by the explosion bulge test.

The two preceding paragraphs indicate that the calculated heat input may not be an accurate measure of the heat actually transmitted to the base plate. Apparently, a large portion of the arc energy of the MIG process is dissipated as arc radiation and is not transmitted to the weld puddle and ultimately to the base plate. This would mean that each zone in the HAZ would be at temperature for a shorter length of time and that each zone would be narrower. Since most metallurgical reactions are time as well as temperature dependent, it can be assumed that HAZ degradation may be a function of time at temperature. For this reason, it appears that data must be gathered or generated so that a factor can be added to the heat input formula which would give a more accurate value when considering a specific welding process.

The major problem which concerns fabricators of high-strength, quenched and tempered steels is weldment cracking. There are essentially three types of cracking which can occur when these types of steels are welded. They are:

- Weld metal and HAZ cracking - Associated with the transformation of austenite to martensite, this type of cracking is a function of cooling rate and seems to be independent of external restraint.
- Hot and cold cracking - Hot cracking is associated with low melting point constituents which lack ductility at the high temperature end of the solidification range. Cold cracking is a function of external restraint coupled with cooling rates and metallurgical transformations.
- Delayed cracking - This type of cracking is the most serious as it can occur days after nondestructive testing and can lead to failure by fatigue and/or fast fracture.

The U. S. Naval Applied Science Laboratory (NASL) has performed considerable research on weldment cracking problems which are associated with high-strength, quenched and tempered steels. Although their work has been on the "high chemistry" steels, their approach and tests should be applicable to the A514/517 variety of steels. The NASL Weldability Test System is logical and appears to be a good approach to testing for crack susceptibility.(23)

The NASL system is actually a series of tests which includes a modified Controlled Thermal Severity (CTS) test, Keyhole Slotted Plate test, and NASL Circular Fillet Weldability (NCFW) test. This test system essentially evaluates a filler metal/base metal system for the types of cracking described above. This system can be used to evaluate base metal and filler metal chemistry, degree of restraint, welding parameters, and their interaction on a given base metal/filler metal combination. The results reported in the paper(23) correlate with fabrication experience gathered in shipyards and with experimental work performed on large models.

3. Inspection

Economy, soundness, and mechanical properties are determinded by welding procedure factors including material thickness, material quality, joint design, welding position and sequence, filler metal, shielding system, preheat and interpass temperatures, heat input, postweld heat treatment and weld surface treatment. Quality control and inspection procedures assure that the best possible weldment is obtained. The lack of sufficient quality control of HSLA Q and T base plate used in shipbuilding makes it likely that many of the factors which contribute to weldment cracking are present, such as segregates of nonmetallic inclusions and alloying elements and voids such as laminations. The shipyard environment makes it difficult to eliminate hydrogen induced cracking. Consequently, there is a likelihood that many buried flaws and extensive cracking could exist in HSLA Q and T weldments whose orientation would prevent their detection by radiography. This has been the cause of failure in other structures made of this class of materials.(24) Only one shipyard visited used both radiography and ultrasonic inspection for buried flaw and defect detection. All others rely on radiography alone.

IV. SURVEY OF THE MECHANICAL PROPERTIES OF HSLA Q AND T MATERIALS AND WELDMENTS

A. Mechanical Properties and Service Performance

The mechanical properties of steels are altered by heat treatment and plastic deformation. Welding processes impose complex and severe thermal and mechanical conditions that produce gradients in microstructures and properties in the zones adjacent to the fusion lines. Fabrication flaws and defects, and residual and restraint stresses associated with welding processes, also affect the strength of the resulting structures.

Proper welding procedures for low-carbon steels provide weldments with soundness and mechanical properties superior to base metal. This limits the problem of serviceability determination to welding procedure development and measurement of base plate properties. At the present time, however, the properties of the heat-affected zone of the HSLA Q and T steels are inferior to base and weld metal properties in weldments made by the best available welding procedures. Hence the problem of serviceability determination of HSLA Q and T steels must include measurement of HAZ properties and consideration of the interaction of the accompanying effects of fabrication flaws and residual stresses on behavior.(24-27)

The factors applied to mechanical test results to obtain design stress values to account for these parameters cannot be assumed to be the same for HSLA Q and T and low-carbon steels, hence they must be developed by experience or experiment. In addition, there is insufficient information available to properly assess the behavior of HSLA Q and T steel base metal in marine service; this includes lack of knowledge of ship structural mechanics as well as of materials properties. Nevertheless, the experiences with the use of HSLA Q and T materials in other structural applications and the results of laboratory experiments provide a background for delineating investigations required to establish a design basis for the use of HSLA Q and T steels. They will also provide preliminary predictions of service behavior of ship hull structural elements made of these materials.

A requirement of the welding procedure is that it will provide specimens that will "qualify" using assigned specimen test procedures. These "standard" specimen test procedures (tensile, hardness, and notch toughness) may or may not be related to serviceability and mechanisms of failure. The problem here is that the specimen test procedure and data interpretation criteria may be established for a specific set of materials properties, such as one might obtain for low-carbon steels, by correlation with service experience. They are not necessarily applicable to different materials, such as HSLA Q and T steels, yet have common acceptance requirements.

There are a set of important properties which are not currently evaluated as a standardized procedure. These properties include fatigue strength, fracture toughness and the effects of environment on serviceability. The fatigue strength is the only property for which data on HSLA materials are available and which relates directly to known design requirements of 25,000 psi for 2×10^6 cycles.(28) Laboratory data on the fatigue properties in air, aqueous, and saline water environments are available. There are also limited data on corrosion resistance which are insufficient to establish quantitative predictions of behavior but do indicate trends suitable for comparing the serviceability of HSLA Q and T materials to carbon steels in marine environment. A fracture mechanics approach can be used to establish a relationship between stress level and crack size which can initiate an unstable fast fracture.

The effect of test specimen size is equally important, and equally difficult to assess. Test specimen and actual hardware size effects involve several variables that affect hardware behavior. In a weldment, there is the unpredictable presence and distribution of residual stresses, flaws, and material properties. It can safely be said that no selected segment of a weldment will have characteristics identical to those of another segment. Consequently, no segment can be expected to behave exactly as another segment. In a large welded structure, the likelihood is high that the worst conditions will exist somewhere, so this must be the basis for an engineering estimate of structural behavior.

It is obvious that considerable empirical work is required, in lieu of experience, to resolve these problems. In particular, it is essential to determine for HAZ material:

- The slow crack growth behavior of flaws in regions of high stress and in marine environments
- Crack initiation and growth in response to cyclic loads in the marine environment as related to ship loadings
- Fast fracture behavior in marine environments.

These data can be used to establish surveillance procedures as well as quality control and inspection requirements for structural elements made of HSLA Q and T materials. It should be noted that this information is not available for carbon steel materials of the thickness required in the structures which use HSLA Q and T materials. Consideration must also be given to the differences in behavior between HSLA Q and T materials and their predecessors. In other types of hardware, this has resulted in initial unacceptable failure experience that has further resulted in restrictive requirements to eliminate the problems encountered.(5) Hopefully, this can be avoided in ship structures by development of the information requisite to establishing the limitations of these materials of construction as well as their attributes.

B. Hardness

The problem at hand is to evaluate the serviceability of HSLA Q and T weldments made by acceptable welding procedures. The first insight into the nature of this problem is obtained by microhardness surveys across the weldment. Hardness is an indicator of the tensile properties of steels and, because materials behavior varies with tensile properties, indicates trends in behavior. Increase in yield and tensile strength of a material generally indicates decrease in fracture toughness and ductility, and increase in sensitivity to environmental effects on flaw growth. Diamond pyramid hardness surveys made on A514 and A517 materials indicate HAZ strength levels are in the range of sensitivity to stress corrosion cracking and low fracture toughness. Typical measured maximum HAZ hardness values are DPH 425 which converts to Rockwell C43.

C. Tensile Strength

A basic source of data for estimating serviceability is the tension test.(22) The materials properties obtained are yield point, tensile strength, elongation, and reduction in area. This test is performed on as-received base plate, weld, and sometimes on base plate heat treated to simulate heat-affected zone material. The evaluation of residual stress, plastic strain, and notch effects on real hardware materials of construction properties are not included in this test. These data are primarily useful for quality control and material comparison.

The initial tension test properties specified are for as-received base plate. The as-received base plate properties must be considered from the standpoint of eventual HAZ properties as well as from that of the required base plate properties. It is considered desirable to have optimum obtainable properties in as-received base plate.

The minimum 0.2% offset yield strength required for the class of materials considered is 100,000 psi; this value is used as a design basis for stability analysis. The mill test yield strength is usually higher than 100,000 psi and can be increased further by reducing the tempering temperature or by cold work. The tensile strength of these materials is usually in the range of 115, 000 to 135, 000 psi and can also be increased by thermal or mechanical treatment, but not to the same degree. An increase in these values is usually accompanied by a reduction in notched fatigue strength, ductility, and notch toughness; hence, it is essential to establish control on these properties.

Ductility is another measure of process control. Since this property is also affected by material flaws and defects in specimens stressed in the tensile instability region of the stress-strain curve (above maximum tensile load), ductility is not an intrinsic materials property. Typical values for ductility are 20% elongation in a 2-in. gage length and 65% reduction of area measured on a standard ASTM specimen.

The weld material should have equal or better tensile properties. HAZ material tensile properties are too difficult to measure independently to serve as a quality control tension test requirement. The only index of these properties is hardness measurements and not enough work has been done to provide a guide for selection of suitable values of this property.

D. Notch Toughness

Three fracture toughness tests are currently used which are suitable for quality control (see Section VI on terminal failure). These are the Charpy V-notch (ASTM E23), the Drop-Weight (ASTM E208), and the Explosion Bulge Crack Starter (NAVSHIPS 0900-005-5000).

1. Charpy V-Notch Test

The Charpy V-notch test is suitable for evaluating base plate and weld materials. Correlations with fracture mechanics values have been developed by Westinghouse, U. S. Steel, and the Naval Research Laboratory (NRL) which provide a suitable basis for using the results of this test. These results indicate that 25 ft-lb absorbed energy is a minimum value for 1-in. -thick plate which will provide an acceptable critical crack size at yield strength loadings.(29, 30)

Laboratory investigations using other brittle fracture tests have demonstrated the severe degradation of fracture toughness in HAZ material. Consequently, it is necessary to offset this reduction by increasing minimum toughness in base plate.

Figures 2 and 3 present some notch toughness data on A517 F materials that have been used for these correlations.

2. Drop-Weight Test

The drop-weight test defines the nil ductility transition temperature (NDTT).(26) This test has several deficiencies (for example, material tempering by brittle bead deposition) but does provide a better

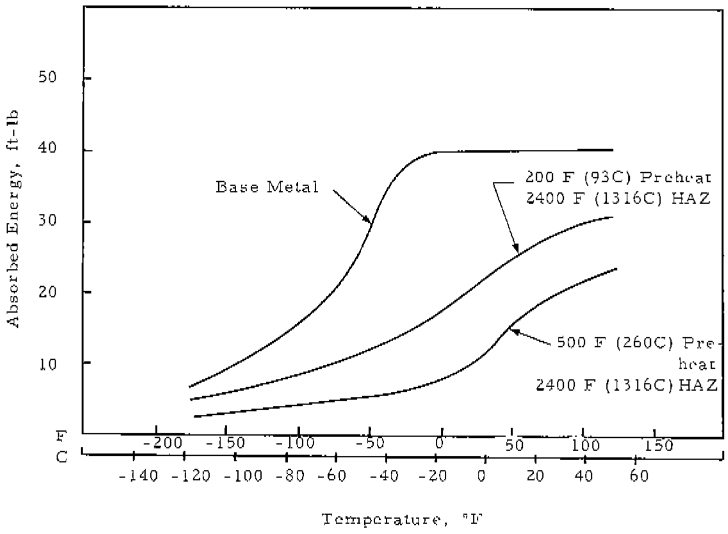
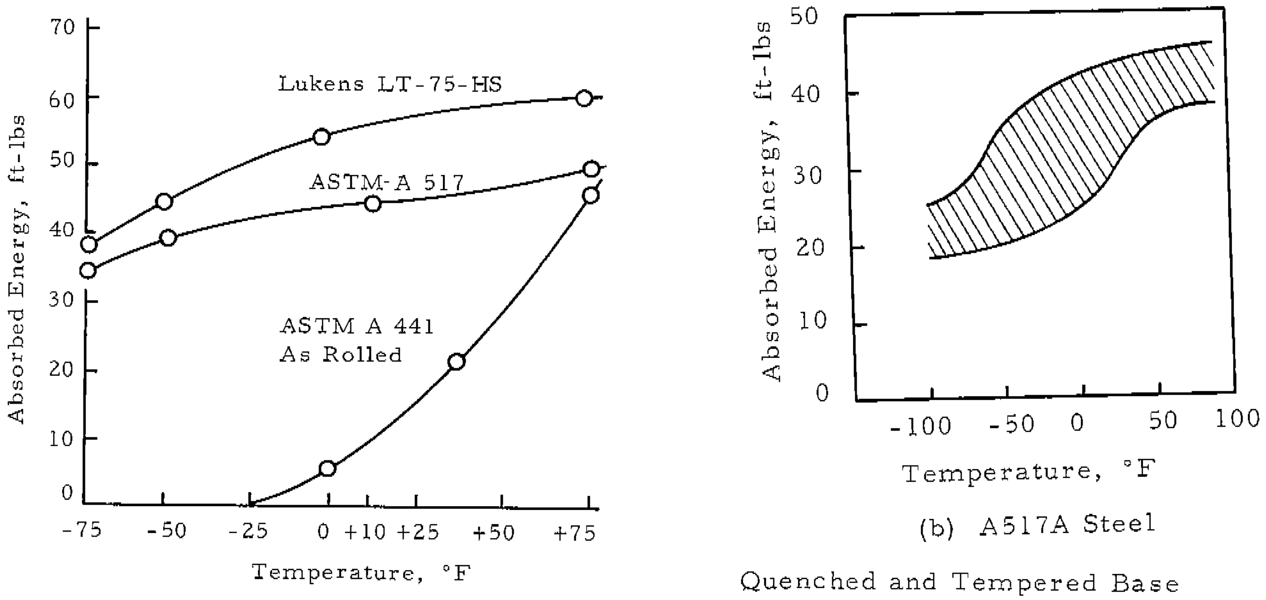


Fig. 2. Effect of Weld Preheat at 47,000 Joules/in. on Charpy V-Notch Curves for Simulated Grain-Coarsened Heat-Affected Zone in ½ in. ASTM A517F [5]



(a) A441, LT-75-HS, and A517 Steels

(b) A517A Steel

Quenched and Tempered Base Plate Tensile Properties

Steel	Tensile Strength (psi)	Yield Strength (psi)
A441	70,000	50,000
LT-75-HS	90,000	75,000
A 517	115,000	100,000

Fig. 3 Charpy V-Notch Impact Energy Curves

index of temperature transition from ductile to brittle behavior than the Charpy V-notch test and is more convenient than the explosion bulge test for shipyard use. If drop-weight tests cannot be run because of material limitations, it is recommended that the Charpy V-notch impact energy value of 40 ft-lb be used as the NDTT correlation energy level for estimating the NDTT of the base plate. That is, the as-received base plate Charpy V-notch impact energy should be at least 40 ft-lb at a test temperature 60° F below the minimum design temperature.

3. Explosion Bulge Test

A fundamental problem is the evaluation of actual weldments whose complexity cannot be simulated in simple small specimens. The explosion bulge test is one procedure currently used, on a limited scale, for this purpose and from which a considerable amount of information is gradually being accumulated.

Some of these data are included in Tables II through VI. Several observations have been made which are important with regard to the use of this test for establishing the performance of weldments in high-strength, low-alloy steels. The test defines three transition temperatures as described by NRL in Reference 26. These transition temperatures are nil ductility transition temperature (NDTT), fracture transition elastic (FTE) and fracture transition plastic (FTP). In ferritic materials, the FTE is usually 60° F higher than the NDTT. The observation has been made that for the quenched and tempered low alloy steels, the actual FTE and NDTT temperatures are often very close together and nearly identical. The observation has also been made that in explosion bulge testing these steels, it is nearly impossible to obtain a so-called "flat break" which has also been used as the definition of NDTT temperature. It is believed that, because of the very high yield strength to tensile strength ratio, to force a crack to propagate one needs to exceed the yield strength, even in the hold-down area.

The most desirable results are: (1) fracture paths that do not indicate severe degradation of weldment materials with respect to as-received base plate; (2) greater than 5% plastic deformation before fracture; and (3) FTP below operating temperature. This behavior cannot often be obtained in shipyard HSLA Q and T weldments.

At the present time, the recommendation for weldment quality control is that the FTE, as defined by the explosion bulge test, must be below the operating temperature. This test does not provide a measure of fracture toughness in the HAZ, but defines the lower limit of safe operating temperature according to present concepts of fracture safe design. This test may be replaced by the dynamic tear test being

Table II. General Welding Procedures and Test Results for U. S. Steel Explosion Bulge Tests on Welded Plates of A517 F Steel

				Electrode						Base Metal			Weld Metal		
Plate Thick., in	Joint Design	Prehea Temp., F	Number of Passes	Type	Dia., in.	Current Range, amps	Voltage, volts	Travel Speed Range, ipm	Heat Input Range, KJ/in.	Drop-Weight NDT, °F	C_v at -50°F (Long.) ft-lb	Cv at -50°F (Trans.) ft-lb	C_v at 0°F, ft-lb	C_v at -50°F ft-lb	FTE Temp, °F[1]
1/2	60° Single	75	9	E11018G	1/8 Root, 5/32	125-170	21	6.1-13.0	16.5-35.0	-70	29	23	52	37	-40
1	60° Double	75	12	E11018G	1/8 Root, 5/32, 3/16	120-210	21	2.8-8.5	25.8-56.2	-50	53	32	52	32	-30
2	60° Double	200	44	E11018G	5/32, 3/16	170-210	21	3.2-8.6	32.0-70.0	-80	50	45	70	54	--

Multiple-Shot Explosion Bulge Tests at 30°F (Average of Duplicate Tests)

Plate Thick., in.	Shot No.	Bulge Height, in.	Thickness Reduction, %	Max. Length of Diametric Crack, in.
1/2	1	1-1/2	3-1/2	0
	2	1-15/16	6-1/2	0
	3	2-5/16	9-1/2	1
	4	2-11/16	13-1/2	2-5/8
	5	3-1/2	21	8
1	1	-	3-1/2	0
	2	2-1/8	6-1/2	0
	3	2-11/16	11	0
	4	3-3/16	17	9-3/4
2	1	--	2-3/4	0
	2	--	4	9-3/4
	3	--	6-3/4	15

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1. FTE determined by crack-starter explosion bulge tests.

NOTE: All tests performed in the as-welded condition with weld reinforcement intact.

Table IIIA. Material--Identification and Properties of Armco SSS-100A/100 Plates

					Mechanical Properties							Chemical Composition									
					Tensile Properties				Impact Properties			Final Heat Analysis, %									
										Cv at -60°F											
Mat'l Code	Thick., in.	ASTM Grade	Heat No.	H/T Chg.No.	0.2% Y.S., ksi	T.S., ksi	% El. in 2 in.	% R.A.	E208 NDT, °F	L	T	C	Mn	P	S	Si	Cr	Cu	Mo	Ti	B
A	1	A517-D	50627	P-26974	112.1	122.3	20.0	69.9	-50[1]	-30	27	0.18	0.66	0.010	0.020	0.28	1.00	0.24	0.24	0.070	0.002
B	1-3/4	A514-E	50826	P-28507	114.7	124.8	21.0	54.7	-50[1]	47	18	0.16	0.70	0.012	0.022	0.35	1.92	0.26	0.52	0.058	0.002
C	1-3/4	A517-E	50826	P-28504	109.0	118.7	21.0	64.3	-40	48	26[2]	Same as above									
D	1	A517-D	43862	P-53850	108.5	118.4	23.0	61.9	-50[1]	48	38	0.16	0.54	0.010	0.014	0.26	0.95	0.25	0.20	0.075	0.002
				P-53852	106.3	115.8	23.0	68.7	4	48	38										
E	1	A517-D	43862	P-53849	109.1	119.0	21.0	64.5	4	3	3	Same as above									
				P-53851	105.8	116.8	22.0	68.0	4	3	3										
F	1	A517-D	43862	P-53848	108.3	117.3	23.0	68.7	4	57	29										
G	1	A517-D	52802	P-52639	112.2	122.3	20.0	70.1	-50[1]	38	35	0.16	0.52	0.010	0.006	0.25	0.92	0.28	0.21	0.070	0.002
H	1-3/4	A517-E	43723	P-53569	119.8	130.3	17.0	56.5	<-20[4]	40	31	0.16	0.58	0.013	0.010	0.28	1.73	0.23	0.50	0.061	0.002
J	1	A517-E	50576	P-64043	111.1	122.5	18.0	59.6	-70[1]	33	22	0.13	0.62	0.012	0.020	0.34	1.89	0.23	0.42	0.066	0.002
K	1-3/4	A517-E	51519	P-36361	118.9	126.0	20.0	68.8	-30[1]	56	28	0.17	0.58	0.010	0.012	0.28	1.82	0.24	0.52	0.062	0.002
L	1	A517-D	53592	P-64044	113.9	122.5	19.5	66.9	-70[1]	51	40	0.18	0.50	0.010	0.016	0.28	0.96	0.26	0.23	0.091	0.002

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1. P-2 Specimen.
2. -30°F data. No tests at -60°F.
3. Not obtained.
4. This NDT was determined from Explosion Bulge Test.

Table IIIB. Explosion Tests[1] of Armco 1-In.-Thick SSS-100A Unwelded Base Plate

(Material Code L - A517GRD)

Type Test	Test No.	Test Temp, °F	Shot No.	Results	Fracture Characteristics
Crack Starter	E1	0	1	Two ⊥ cracks in bulge region - 8 in. and 12 in. long	0°F above FTE
	E4	-40	1	Five pieces blown from center, two cracks through to plate edge	-40°F above NDT
	E3	-80	1	Nine pieces blown from center, one crack through to plate edge	-80°F is about NDT
Bulge[2]	E2	0	1	6% Thinning 1-½-in. Bulge	
			2	8% Thinning 2-1/8-in. Bulge	No cracks in plate. 0°F is FTP of unwelded plate.
			3	12% Thinning 2-5/8-in. Bulge	
			4	19.8% Thinning 3-1/8-in. Bulge	

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1. 7-lb pentolite at 15-in. standoff.
2. Thickness reductions exceeds minimum required by 100% on first shot.

Table IV. Welding Procedures for Armco SSS-100A/100 Explosion Test Plates

Thick., in.	ASTM Grade	Mat'l Code	Test Series	Sample Ident.	Welding Procedure[1]			Root Passes			Total Passes	Filler Metal and/or Flux Data
					Process	Heat Input, J/in.	Joint Design	No.	d	Material		
1	A517-D	A	1	2, 3	SMAW	36,000 - 45,000	60° Dbl-V 1/2 - 1/2	2	1/8	E11017-M	7	5/32 in. E11018-M
		A	2	1, 2, 3	SAW	33,500 - 52,000	Same as above		1/8	OX-100 w/709-5	11	1/8 in. OX-100 w/709-5
		D, E, G	4	D, E, G	SAW	34,000 - 45,000	70° Dbl-V 2/3 - 1/3		5/32	W-25 w/709-5	22	5/32 in. W-25 w/709-5
	A517-E	J	5	B-1[2]	SAW	42,500 - 52,500	70° Dbl-V 1/3 - 2/3	1	5/32	E8018-C3	19	5/32 in. W-25 w/709-5
	A517-D	L	5	A-1, A-2[3]	SAW	22,500 - 28,000	Same as above	1	5/32	E8018-C3	36	1/8 in. W-25 w/709-5
		L	5	C-1	SAW	42,500 - 52,500	Same as above	1	5/32	E8018-C3	19	5/32 in. W-25 w/709-5
	A517-D/E	L/J	5	C-2[4]	SAW	42,500 - 52,500	Same as above	1	5/32	E8018-C3	19	5/32 in. W-25 w/709-5
	A517-D	A	3	1 - 4	GMAW-FC	32,000 - 48,000	60° Dbl-V 1/2 - 1/2		7/64	McKay Flux Core	12	7/64 in. McKay FC Wire
		A	3	5 - 8	GMAW	34,000 - 44,000	Same as above		1/16	Airco Solid	13	1/16 in. Airco Solid Wire
1-3/4	A517-E	C	2	7, 8, 9	SMAW	26,500 - 47,000	Same as above		5/32	E11018-M	48	5/32 in. E11018-M
		C	2	4, 5, 6	SAW	39,000 - 63,000	Same as above	4	1/8	M188 w/709-5	25	1/8 in. M188 w/709-5
		H	4	B, C	SAW	37,500 - 60,000	70° Dbl-V 1/2 - 1/2	1	5/32	E11018	37-43	5/32 in. W-25 w/709-5
		K	5	D1, D2, D4	SAW	42,500 - 52,500	70° Dbl-V 1/3 - 2/3		5/32	E8018-C3	42	5/32 in. W-25 w/709-5
1-3/4	A514-E	B	1	5 - 9	SMAW	27,000 - 39,000	60° Dbl-V 1/2 - 1/2	4	1/8	E11018-M	48	5/32 in. E11018-M

1a. Preheat temperature for test series 1 - 4 was 100 - 150°F. For test 5, it was 200°F.
1b. All samples welded with 0-in. to 1/8-in. land and 0-in. to 1/16-in. gap.
1c. All samples torch beveled and ground to bright metal.
1d. All samples welded in flat position; DCRP; 300°F max. interpass temperature.
2. All 1-in. plate samples are A517-D except this one.
3. Weld reinforcement ground flush. All other test weldments had weld reinforcement left in place. All weldments tested in as welded condition.
4. This sample was a composite of A517-E welded to A517-D.

Table V. Notch Toughness Data for Armco SSS-100A/100 Weldments

Thick., in.	ASTM Grade	Mat'l Code	Test Series	Sample Ident.	Welding Procedure[1]		Base Plate			Weld Metal, Cv		H-A-Z Cv		Explosion Crack Starter Test Results		
							E-208	Cv at -60°F						FTE, °F	Failure Location	Comments
					Process	Heat Input, J/in.	NDT, °F	L	T	0°F	-50°F	0°F	-50°F			
1	A517-D	A	1	2, 3	SMAW	36,000 - 45,000	-50[2]	30	27	61	35	57	45	-40	BM-WM-HAZ	Weld zone toughness equal to base metal
		A	2	1, 2, 3	SAW	33,500 - 52,000	-50[2]	30	27	45	35	58	32	+40	Fusion Zone	Lowest toughness in fusion zone
		D	4	D	SAW	34,000 - 45,000	-50[2]	48	38	37	22	51	28	<0	BM-WM-HAZ	Weld zone toughness equal to base metal
		E	4	E	SAW	34,000 - 45,000	-50[2]	48	38	--	34	--	36	<-20	BM-WM-HAZ	Same as above
		G	4	G	SAW	34,000 - 45,000	-50[2]	38	35	41	26	40	20	-10	BM-WM-HAZ	Same as above
	A517-E	J	5	B-1[3]	SAW	42,500 - 52,500	-70[2]	33	22	47	--	44	--	≤0	BM-WM-HAZ	Same as above
	A517-D	L	5	A-1, A-2[4]	SAW	22,500 - 28,000	-70[2]	51	40	35	29	60	42	<0	BM-WM-HAZ	Good uniform toughness. FTE below 0°F
		L	5	C-1	SAW	42,500 - 52,500	-70[2]	51	40	56	20	42	--	0	BM-WM-HAZ	Weld zone toughness equal to base metal
	A517-D/E	L/J	5	C-2[5]	SAW	42,500 - 52,500	-70[2]	See above		--	39	--	--	+10	BM-WM-HAZ	Lower toughness in A517E plate side
	A517-D	A	3	1 - 4	GMAW-FC	32,000 - 48,000	-50[2]	30	27	44	38[5]	55	28[5]	-40	BM-HAZ	Weld zone toughness equal to base metal
		A	3	5 - 8	GMAW	34,000 - 44,000	-50[2]	30	27	46	34[5]	51	24[5]	-30	BM-HAZ	Same as above
1-3/4	A517-E	C	2	7, 8, 9	SMAW	26,500 - 47,000	-40	48	26[9]	54	39	38	28	-10	BM-WM-HAZ	Same as above
		C	2	4, 5, 6	SAW	39,000 - 63,000	-40	48	26[9]	44	36	36	26	+10	BM-WM-HAZ	Same as above
		H	4	B	SAW	37,500 - 60,000	<-20[7]	40	31	37	28[5]	66	30[5]	-10	BM-WM-HAZ	Same as above
		H	4	C	SAW	37,500 - 60,000	<-20[7]	40	31	32	29[5]	52	43[5]	-10	BM-WM-HAZ	Same as above
		K	5	D1, D2, D4	SAW	42,500 - 52,500	-30[2]	56[8]	28[8]	36	29	50	48	0	BM-WM-HAZ	Same as above
1-3/4	A514-E	B	1	5 - 9	SMAW	27,000 - 39,000	-50[3]	47	18	56	37	54	--	+20	BM	Weld zone toughness superior to plate

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1a. Preheat temperature for tests 1 - 4 was 100° - 150°F. For test 5, it was 200°F.
1b. All samples welded with 0-in. to 1/8-in. land and 0-in. to 1/16-in. gap.
1c. All samples torch beveled and ground to bright metal.
1d. All samples welded in flat position, DCRP, 300°F max. interpass temperature.
2. P-2 type specimen.
3. All 1-in. plate samples are A517-D except this one.
4. Metal reinforcement removed by grinding, all others tested with this in place as welded.
5. This sample was a composite of A517-E welded to A517-D.
6. Test temperature -60°F.
7. This NDT was determined from Explosion Bulge Test.
8. Test temperature -50°F.
9. -30°F data. No tests at -60°F.

Table VIA. Results of Explosion Bulge Tests of Armco SSS-100A Weldments

Material Identification					Weld Procedure		Explosion Bulge Test Results[1]					
Thick., in.	ASTM Grade	Mat'l Code	Test Series	Sample Ident.	Process	Heat Input, J/in	Test Temp, °F	Shot No.	Thinning, %	Bulge Ht, in.	Results	Fracture Characteristic
1	A517-D	A	1	1A[2]	SMAW	36,000 - 45,000	+30	1	5	1-3/8	None	30°F above FTE and near FTP
								2	6	2-1/8	1/2-in. crack - toe of weld	0°F HAZ
								3	12	2-1/2	Extend to 9 in. along weld	
				1B[2]	SMAW	36,000 - 45,000	0	1	5.7	1-1/2	None	0°F is at FTP of HAZ, Weldand Base Plate
								2	8.2	2-1/16	None	
								3	11	2-1/2	Short crack across weld	
								4	13	2-7/8	Crack did not increase	
		D	4	D-B1[2]	SAW	34,000 - 45,000	+40	1	5.8	1-9/16	None	+40°F is near FTP of HAZ
								2	8.9	2-1/4	None	
								3	12.6	2-3/4	Small tears in weld and at toe	
								4	18.4	3-5/8	Extended along toe and BM in bulge	
		L	5	A1-2[2]	SAW	22,500 - 28,000	0	1	6.2	1-3/8	None	0°F is below FTP of HAZ
								2	9.1	2-5/16	Cracking at toe of weld and thru hold down in base metal	
				A2-2[3]	SAW	22,500 - 28,000	0	1	5.4	1-7/16	None	0°F is FTP of HAZ, Weld and Base Plate
								2	7.4	2-3/16	None	
								3	10.8	2-5/8	None	
								4	17.6	3-1/8	None	
			5	C1-2[2]	SAW	42,500 - 52,500	0	1	3.9	1-7/8	Extensive cracking in HAZ	0°F is below FTE & FTP of HAZ
	A517-D/E	L/J	5	C2-2[2]	SAW	42,500 - 52,500	0	1	3.1	1-3/4	Same as above. Confined to A517-D side of weld	Same as above
	A517-D	A	3	9[2]	GMAW	34,000 - 44,000	+30	1	5.8	1-3/8	None	+30°F is at FTP of HAZ, Weld and Base Plate
								2	7.8	1-15/16	None	
								3	10.2	2-7/16	Small crack in weld	
								4	16.0	2-13/16	No extension of crack	

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1. 7-lb pentolite at 15-in. standoff for 1-in. plate.
2. As-welded condition with weld bead reinforcement in place.
3. Weld reinforcement removed by grinding.

Table VIB. Results of Explosion Bulge Tests of Armco SSS-100 Weldments

Material Description					Weld Procedure		Explosion Bulge Test Results[1]					
Thick., in.	ASTM Grade	Mat'l Code	Test Series	Sample Ident.	Process	Heat Input, J/in.	Test Temp, °F	Shot No.	Thinning, %	Bulge Ht, in.	Results	Fracture Characteristic
1-3/4	A517-E	H	4	C-B1[2]	SAW	37,500 - 60,000	+40	1	2.5	1-1/2	Slight cracking along toe	+40°F is below FTP of HAZ, Weld and Plate
								2	7.6	3	Cracking in weld and plate in bulge	
		K	5	D2-2[2]	SAW	42,500 - 52,500	0	1	2.3	1-1/2	None	0°F is below FTP of Weld and Plate
								2	7.2	3-1/2	Cracking in weld and plate	
				D4-2[2]	SAW	Same as above	0	1	2.2	1-9/16	None	0°F is below FTP of Weld, HAZ and plate
								2	6.6	3-1/2	Cracking in weld, HAZ and plate	
	A514-E	B	1	4[2]	SAW	27,000 - 39,000	+60	1	1.6	1-3/8	Extensive cracks along toe	+60°F is below FTP of HAZ
								2	3.2	2-7/8	Separation of plate at toe	

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1. 28-lb pentolite at 17-in. standoff.
2. As-welded condition with weld bead reinforcement in place.

developed at NRL which shows considerable promise for defining dynamic fracture toughness values in addition to transition temperatures.

The basic objective of explosion bulge tests is to demonstrate that the weldment will not propagate fast fracture at elastic stress levels. As previously indicated, this supposition is not necessarily true for Q and T materials and the other data presented indicate that it is not a sufficient test to determine likelihood of fast fracture at less than yield strength stress loading in the presence of reasonable size flaws. It is a useful test for determining the zone of lowest fracture toughness and providing fracture appearance criteria for interpretation.

E. Fatigue and Corrosion Fatigue

The conventional (smooth, polished, flaw free) fatigue specimen tests display fatigue strengths that increase monotonically with increase in tensile strength. As-rolled surfaces and the presence of mechanical and metallurgical discontinuities, such as might be present in a weldment, can significantly degrade the fatigue strength of constructional steels, Figure 4.(31)

Figure 5 depicts small specimen A517 F data which further demonstrate the effects of surface discontinuities on fatigue strength. The stress concentration factor for these discontinuities is low, relative to that for many kinds of fabrication flaws which could occur in HSLA Q and T materials. The small specimen size limits crack propagation life to such a degree that these data can be considered as crack initiation life for the material and indicated discontinuity in a large structure. Figure 6 also shows the degradation of fatigue life of base plate material as a function of material strength, but on a normalized load intensity basis. Figure 7 depicts a comparison of initiation and propagation fatigue lives for HY-80 base plate material in air and saltwater. Figure 8 shows the effect of a 3.5% saltwater environment on the fatigue crack growth rate in A517 F material. These trends, together with higher design stresses, indicate that HSLA Q and T ship structural elements may have considerably shorter fatigue lives than carbon steel elements. However, if attention is given to design details and fabrication quality control, a structure with adequate fatigue strength can be fabricated.

F. Environmental Effects

1. Corrosion

The corrosion resistance of unstressed HSLA Q and T base plate materials exposed to marine environments appears to be equal or superior to that of carbon steel materials.(32) Steels with very high

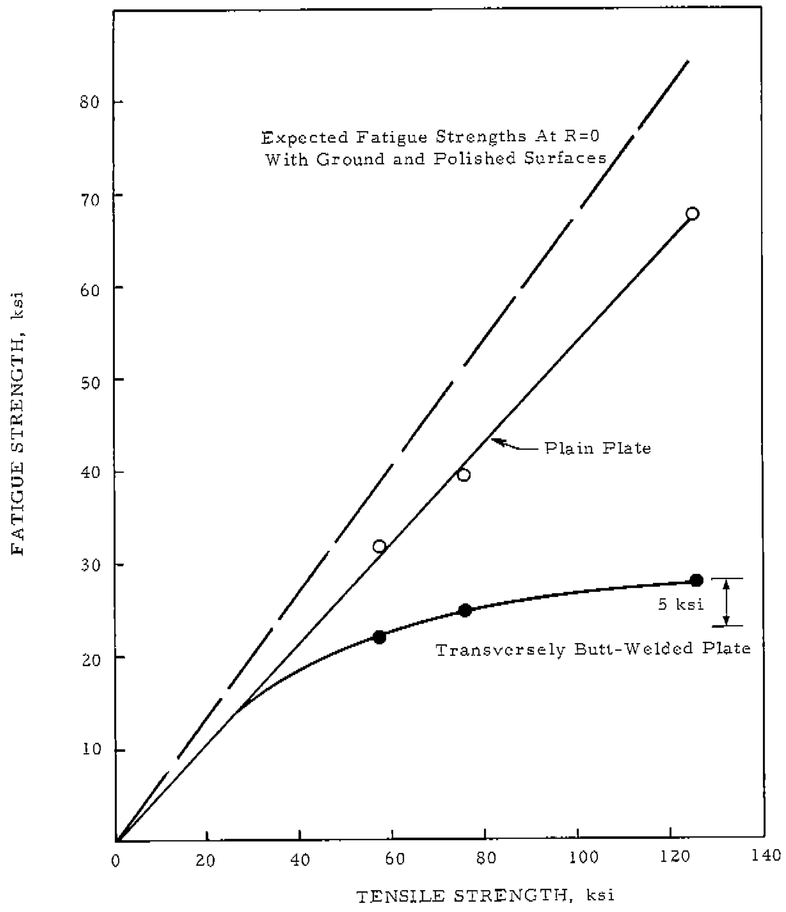


Fig. 4. Average Fatigue Strengths of Constructional Steels at 2,000,000 Cycles at a Stress Ratio of 0.[31]

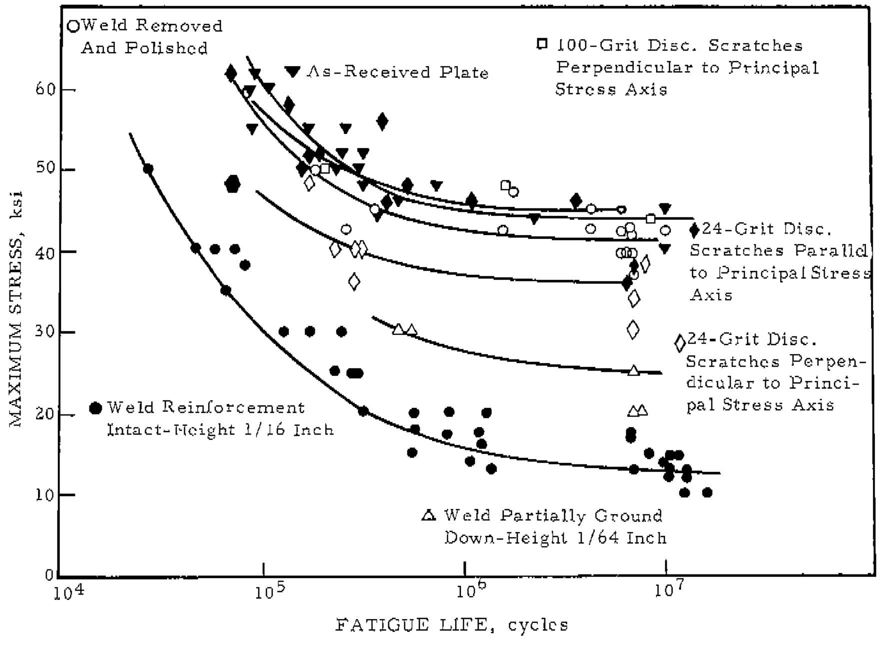


Fig. 5. Effect of Removal of Weld Reinforcement on Axial-Load Fatigue Strength of Transversely Butt-Welded 1/4-in-Thick Constructional Alloy Steel Plates (R = -1)[19]

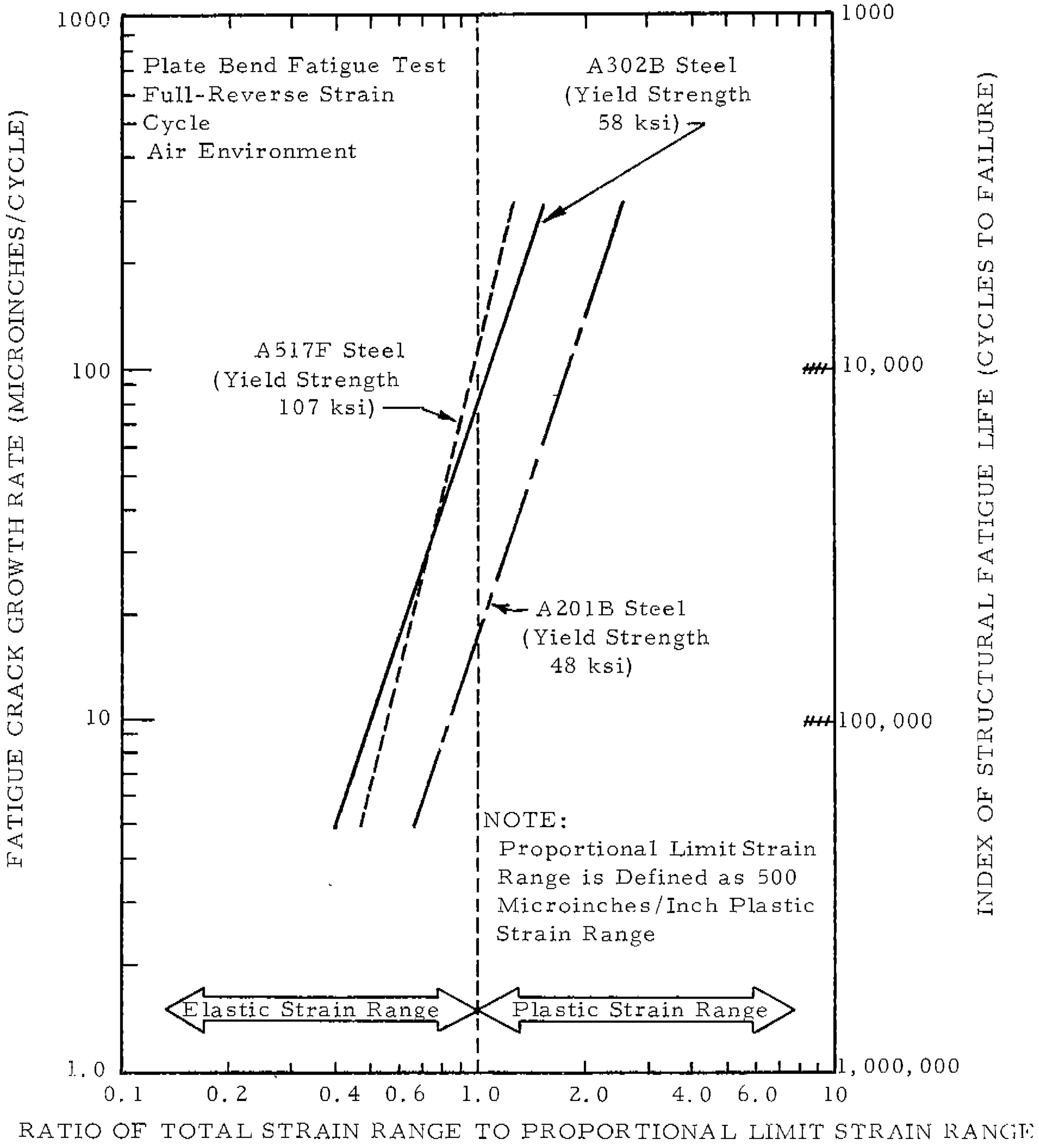


Fig. 6. Air Environment Low Cycle Fatigue Crack Propagation Characteristics of A201B, A302B and A517F Steels on a Normalized Load Intensity Basis[31]

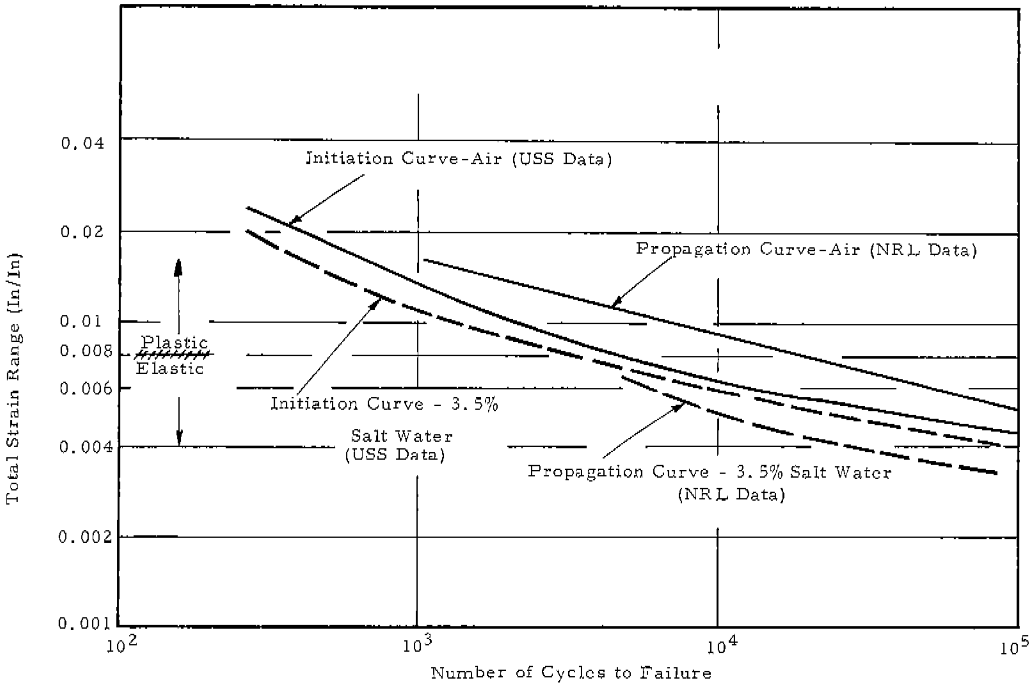


Fig. 7. Log-Log Plot of Total Strain Range Versus Cycles to Failure For HY-80 Steels. The Curves Indicate Failure by Initiation and Failure by Propagation (ISFL) in Both Air and 3.5% Salt Water Environments [34]

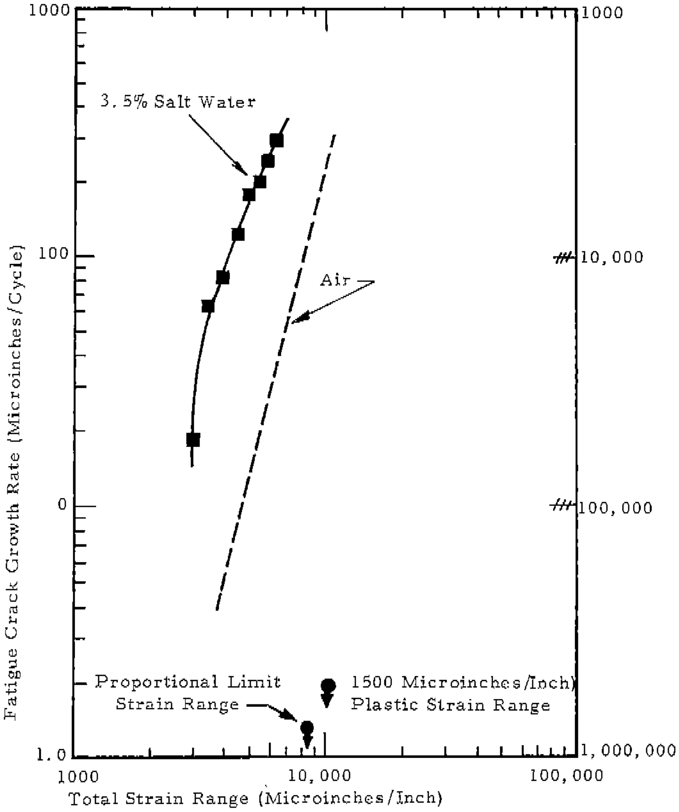


Fig. 8. Log-Log Plot of Fatigue Crack Growth Rate VS. Total Strain Range for A517F Steel in a 3.5% Salt Water Environment (Full-Reverse Strain Cycle) [38]

strengths (or of high hardness) may be susceptible to corrosive environments other than hydrogen sulfide. The chloride ion may be detrimental or beneficial to corrosion resistance.

2. Stress Corrosion and Hydrogen Embrittlement

U. S. Steel Corporation tests(33) showed that a marine atmosphere environment was more severe than seawater and semi-industrial environments on the stress-corrosion properties of unwelded stressed steel specimens. These steels represented a range of strength levels produced by variations in chemistry and heat treatment. The results indicated that susceptibility to specimen delayed failures (from stress corrosion cracking or hydrogen embrittlement) in marine environments can occur in steels having yield strengths as low as 175,000 psi. Since hardness traverses taken across A514/A517 weldments indicate that ultimate tensile strength levels in excess of 175,000 psi are possible in the HAZ, it appears likely that marine environments can be expected to induce crack initiation and slow crack growth in these materials.

It has also been demonstrated that H_2S, in concentrations as low as 100 ppm, induces delayed failure in HSLA Q and T HAZ materials stressed to less than yield strength values.(35) It is generally thought that the mechanism involved is hydrogen embrittlement. This is a particularly severe environment and no correlation has been developed between behavior in this environment and failure in specimens exposed to other environments.(24)

V. THE CONTRIBUTION OF VARIOUS FAILURE MECHANISMS TO CRACK INITIATION, CRACK GROWTH, AND TERMINAL FAILURE

A. Flaw Nature and Growth

1. Background

The evidence is that a structural crack will initiate sooner and grow faster in HSLA Q and T structural elements than they will in comparable carbon steel structural elements subjected to the same structural loadings over a period of time. This situation arises because of the increased likelihood of sharp flaws early in the service life, higher residual and imposed stresses, and environmental sensitivity.

The HSLA Q and T steel structural element weldments are more likely to have fabrication flaws and defects than those of carbon steel built and inspected to the same standards. The primary concern is weldment cracking. Unless adequate controls are applied, delayed cracking can occur after the weldment has been subjected to nondestructive tests. Nonmetalic inclusions and laminations contribute to the formation of buried flaws with orientations unfavorable for detection by radiography.

The stress concentration factor of notches in carbon steels may often be reduced by occasional high service loads (referred to as "shakedown"). HSLA Q and T steels, because of a high ratio of yield to ultimate strength, resist the blunting of a notch so that sharp flaws in regions of yield stress loading may persist during the ship service life.

2. Initiation and Propagation by Fatigue

Experience has demonstrated that crack initiation and growth by fatigue is a likely occurrence in ship structures and that the most likely locations are at discontinuities which provide points of stress concentration. The greater likelihood of having cracklike flaws in HSLA Q and T weldments increases the possibility of having sites for fatigue crack initiation.

Low cycle fatigue has been considered to be the only significant source of crack growth by fatigue in carbon steel ship structural elements because, in materials with small ratios of yield to ultimate tensile strengths, occasional high loadings "wipe out" high tensile residual stresses to provide the favorable case of mean stress equal to zero. This is not the case for the HSLA Q and T steels used in ship construction. The extremely high residual tensile stress that can be maintained in HSLA Q and T weldments requires that high cycle fatigue crack growth under conditions of high mean stress be considered in addition to low cycle fatigue.

Fatigue crack initiation life is shorter in the presence of notches and fatigue crack propagation rate is higher, on a normalized stress basis (considering peak service stresses to be linearly related to material yield strength), for HSLA Q and T base plate materials than for carbon steel materials. This trend can be expected to be accentuated in high hardness, high-strength HAZ material.(34, 35)

3. Environmental Effects

Slow crack growth, by mechanisms such as stress corrosion cracking, hydrogen embrittlement, or the other postulated environmentally affected mechanisms must be considered as possible in HSLA Q and T HAZ materials until investigation demonstrates otherwise. The only evidence available as to the likelihood that this mechanism of crack growth can contribute to failure is measured hardness of HAZ materials and the experience that many materials of these hardness levels are sensitive to the combination of sharp flaws, high stresses, and aqueous environments.(36, 37) A517 F materials have been observed to develop corrosion pits in regions of high strain and these geometric discontinuities have been observed to be the site of fatigue crack initiation.(31)

Crack initiation and slow crack growth by hydrogen embrittlement is particularly insidious because it is more difficult to protect against by coating and cathodic protection. The following mechanisms are also suspected of contributing to slow crack growth in marine atmospheres or seawater environments:

- Corrosion pitting
- Stress corrosion
- Crack loading by wedging of corrosion products.

Stress corrosion is a problem not encountered in carbon steel materials and is, as yet, only suspect in HSLA Q and T materials because there is no definitive evidence that the problem does exist. It should be emphasized that crack initiation and growth behavior of this type involve the interaction of a complex set of variables, including stress magnitudes and distributions, flaw and defect character, and metallurgical variations that cannot be developed in small, simple specimens. Also, the attainment of a particularly deleterious set of conditions in a weldment must be regarded as a statistical occurrence related to sample size which is more likely to occur in a ship than in a laboratory specimen.

B. Terminal Failure

The failure of a structural element may or may not endanger the structure depending on the structural function of the element, structural redundancy, and load characteristics. The current usage of HSLA Q and T materials in ship structures is such that failure of these elements would likely result in serious structural damage if not hull failure. The two types of failure that can be envisioned are weakening of the hull girder so that it cannot withstand service loads or introducing a fast running crack into the carbon steel material that would not be arrested by that material.

Structural element failure (other than excessive deformation or compression instability) can be classified as:

- Tensile failure in response to unforeseen overload or to service damage that reduces the cross-sectional area required to carry applied service loads

- Fast fracture or unstable crack propagation.

Tensile failure analysis criteria are the same for both carbon and HSLA Q and T steels, but fast fracture analysis criteria are different. In general, the transition temperature approach is adequate to predict the fast fracture characteristics of carbon steels, but fracture mechanics criteria must be considered in the case of HSLA Q and T materials.

This may be explained by reference to Figure 9, which depicts fracture toughness concepts for steels on the basis of a normalized transition temperature. Qualitatively, carbon steels fit the tough steel category and HSLA Q and T base plate material are in the low-toughness steel category. However, HSLA Q and T HAZ material can be in the high-strength, brittle alloy category which does not exhibit a transition from low to high fracture energy. In this diagram, the effects of size, rate of loading, etc., are neglected but can be considered as accounted for by normalization of transition temperature and fracture energy.

Considering (1) that energy available for fast fracture crack propagation increases with material strength level because of higher design stresses, (2) that laboratory test results cannot be correlated directly with service behavior except for materials and test specimens analyzable by fracture mechanics, and (3) that the different laboratory test procedure results do not correlate, it is obvious that the likelihood of fast fracture of similar structures made of different materials cannot be easily developed into a form such as is depicted by Figure 9. However, the Naval Research Laboratory has accomplished the development of a method for fast fracture correlation analysis that is suitable for use, as described below.(26)

Carbon steel fast fracture properties can be characterized by the NDTT indexed Fracture Analysis Diagram as depicted by Figure 10(a), in which correlation was developed from service experience. The establishing of FTE at 60°F and FTP at 120°F above NDTT is conservative since many steels have much less than this temperature difference between the index points. Since NDTT may actually be located at any point on the Charpy V-notch impact transition curve for steels, the crack arrest curve cannot be derived reliably from Charpy V-notch impact test results. Once correlation between C_V properties and NDTT is established, however, the Charpy V-notch test data are sufficient for fracture analysis for carbon steel ship hull materials where base plate fracture toughness is less than weldment material toughness.

The first problem encountered in the use of the Fracture Analysis Diagram procedure was in its application to HSLA Q and T materials in which the weldment HAZ ductile fracture energy was less than the base plate brittle fracture energy as depicted by Figure 10(b), and fast fracture was observed to occur at less than yield strength stress and higher than FTE temperature conditions established for the base material. In this case, the fracture analysis diagram provides an upper bound for prediction of fast fracture behavior of low toughness steel, such as the HSLA Q and T materials of interest. This is useful, but not sufficient for analysis.

The other available quantitative approach to the problem is the fracture mechanics procedure for high-strength, brittle alloys or materials loaded below NDTT.(38-46) Figure 11 and Table VII depict the specimen used and data obtained with this procedure for HSLA Q and T materials. The as-quenched condition was hypothesized for HSLA Q and T properties of HAZ material, and the measured hardness values tend to support this thesis although the material was not subjected to as much

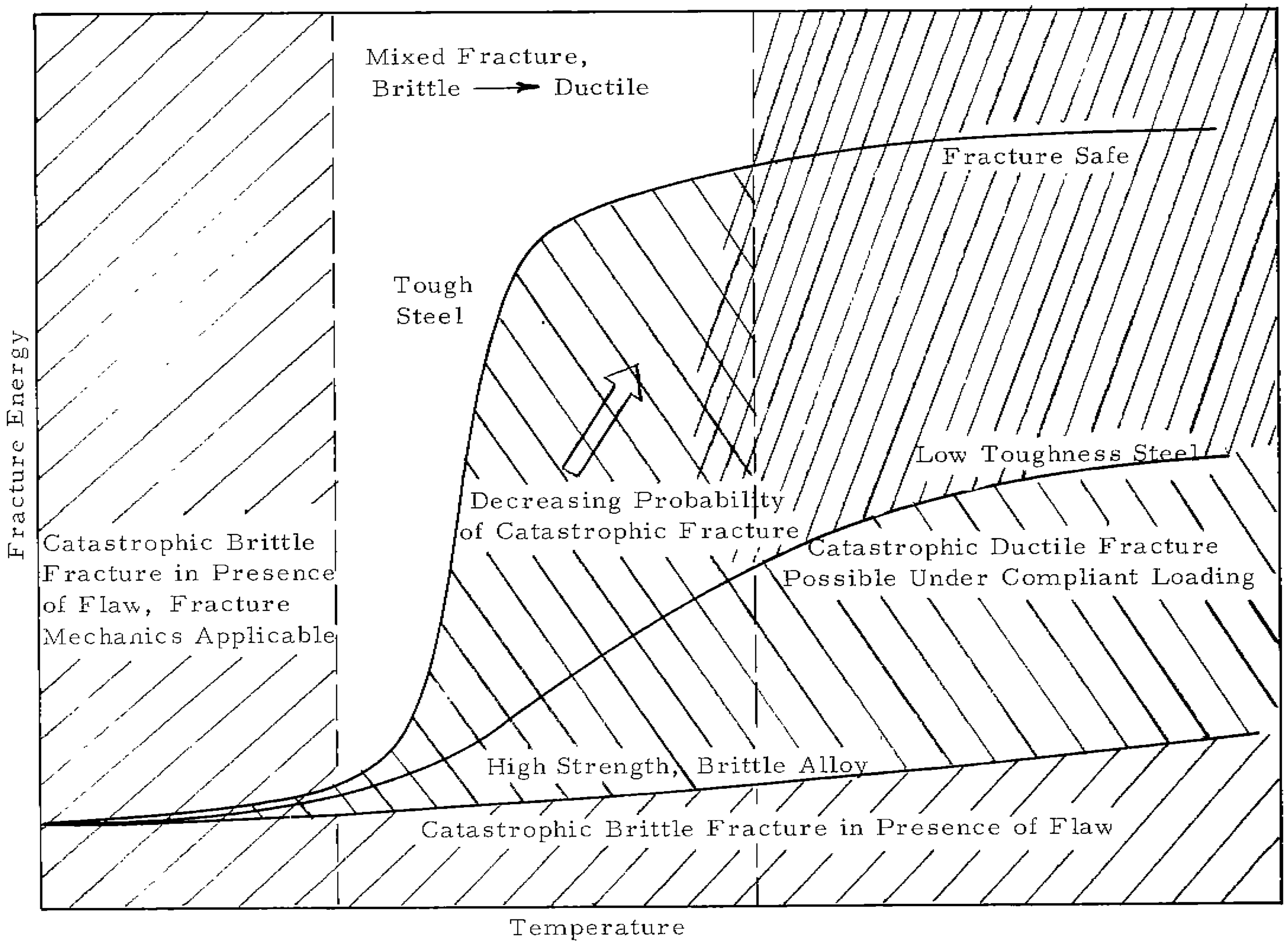
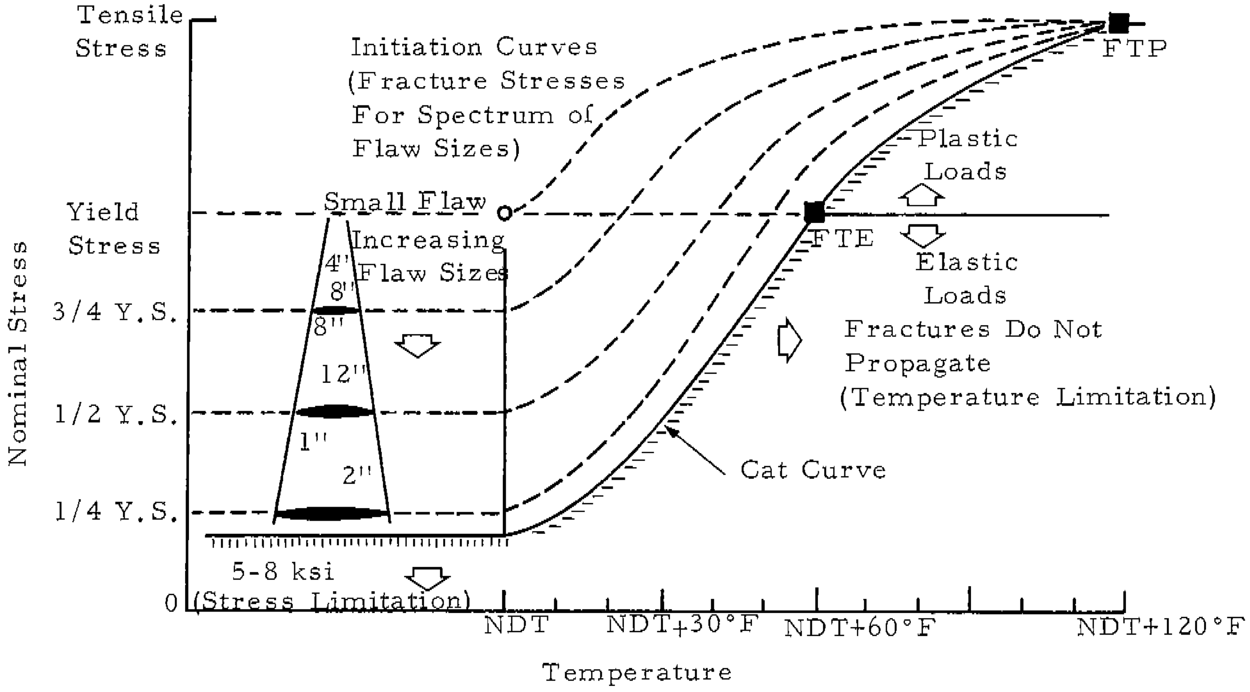
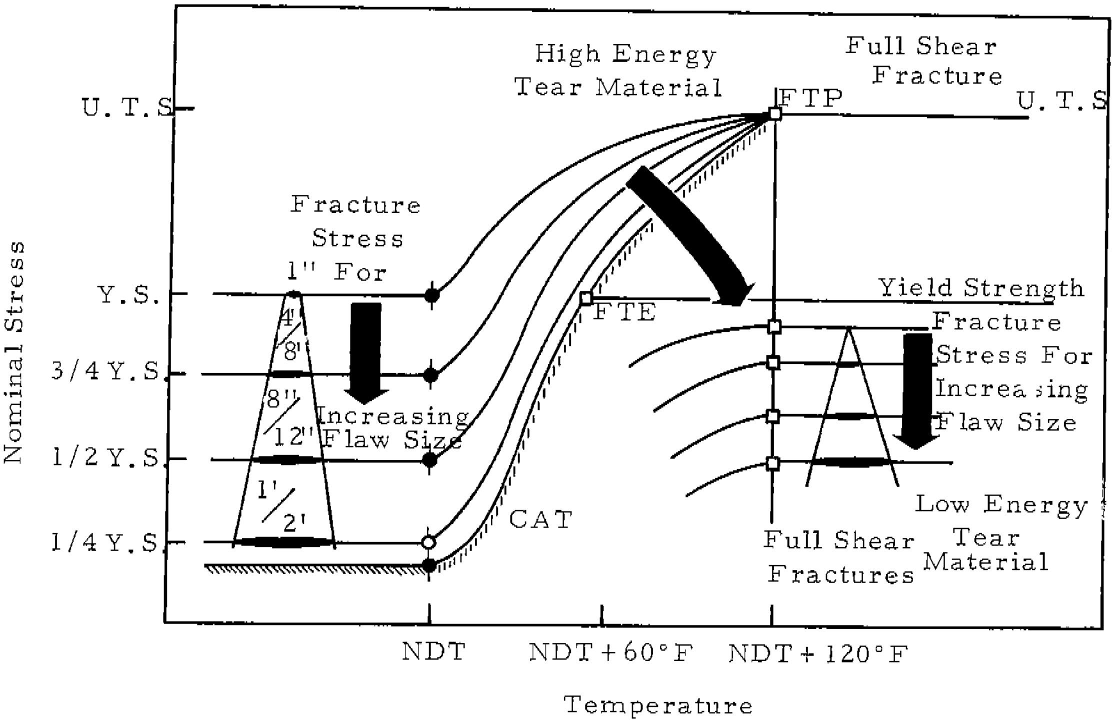


Fig. 2. Typical Fracture Energy Versus Temperature Curves[40]



a. Generalized fracture analysis diagram, as referenced by the NDT temperature

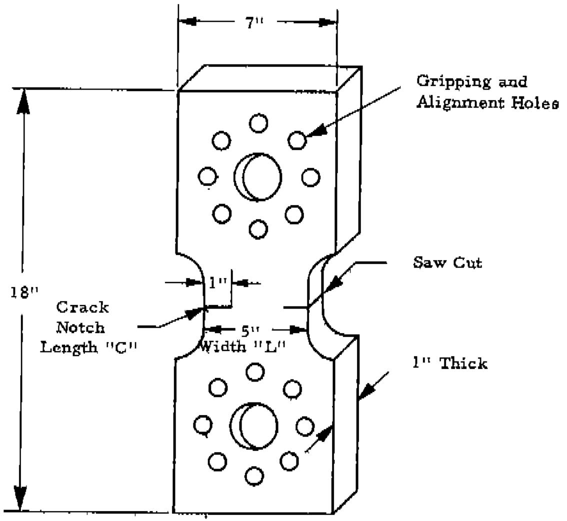


b. Features of fracture analysis diagram modifications for steels of "low energy tear" characteristics

Fig. 10. Fracture Analysis Diagrams from W. S. Pellini and P. P. Puzak [26]

Table VII. Fracture Toughness Data for ASTM A517F Steel

Specimen	Temp, °F	Thickness, t, in.	Width, L, in.	Crack length, C, in.	Net section, Fr Str, σ_N, 1000 psi	Gross section, Fr Str, σ_G, 1000 psi	Fracture toughness, G_c, in. lb/in^2	Stress intensity factor, K_c, psi $\sqrt{in.}$	Relative plate thickness parameter, α	Plastic zone approx, c, in.	Fracture toughness, G_{c1}, in. lb/in^2	Stress intensity factor, K_{c1}, psi $\sqrt{in.}$	Shear lip, %
Quenched and tempered condition													
T1-11 QT	-300	0.901	5.011	1.365	52.4	31.0	200	77, 500	2.70	0.05	216	80, 000	0
T1-16 QT	-150	0.908	5.005	1.457	72.4	34.4	275	91, 000	1.10	0.13	327	99, 000	2
T1-14 QT	-60	0.903	5.019	1.207	91.8	41.0	293	94, 000	0.83	0.17	361	104, 000	100
T1-13 QT	0	0.895	4.995	1.260	91.5	47.0	410	111, 000	0.53	0,27	566	130, 000	100
T1-2 QT	RT	0.891	4.992	1.287	90.1	45.2	391	108, 000	0.49	0,29	554	129, 000	100
T1-8 QT	300	0.896	4.955	1.240	87.5	45.8	381	107, 000	0.38	0.37	650	139, 000	100
T1-9 QT	600	0.904	5.000	1.340	88.1	43.5	387	107, 500	0.42	0.38	610	135, 000	100
T1-17 QT	1000	0.902	4.955	1.301	74.6	37.3	272	90, 000	0.44	0.36	437	115, 000	100
Furnace cooled condition													
T1-7 ANN	-100	0.893	4.976	1.298	45.5	22.6	98	54, 000	2.90	0.05	105	56, 000	0
T1-18 ANN	0	0.902	5.016	1.128	69.5	36.7	216	81, 000	1.10	0.13	250	86, 500	1
T1-4 ANN	RT	0.881	5.021	1.197	87.7	45.7	360	104, 000	0.68	0.21	459	117, 000	2
T1-6 ANN	300	0.900	4.924	1.146	86.9	41.5	283	108, 500	0.86	0.17	374	106, 000	100
T1-5 ANN	600	0.898	4.984	1.363	88.4	43.4	394	92, 000	0.62	0.23	507	123, 000	100
As-quenched condition													
T1-3 QTQ	-200	0.901	4.418	1.137	68.8	35.2	209	79, 000	4.90	0.03	222	81, 500	0
T1-15 QTQ	0	0.900	4.424	1.150	90.2	45.3	353	103, 000	2.50	0.06	384	107, 000	6
T1-1 QTQ	RT	0.905	4.302	0.893	104.6	60.8	456	117, 000	1.80	0.08	455	117, 000	40
T1-12 QTQ	300	0.913	5.040	1.314	81.4	40.2	317	97, 500	2.60	0.06	342	101, 000	40
T1-10 QTQ	600	0.903	4.017	1.032	79.1	39.7	241	85, 000	2.90	0.06	241	85, 000	35



General Configuration of Crack-Notch Tensile Specimen

HEAT TREATMENT OF STEEL USED IN BENCH-MARK TEST PROGRAM

Steel	Condition	Heat Treatment	Grain Size, ASTM	Hardness, R_c
517F 1-in. Plate	As-quenched	Held 1 hr/in. of thickness at 1650°F and water quenched.	9	42
	Quenched & tempered (by supplier)	Held 1 hr/in. of thickness at 1650 - 1700°F and water quenched. Then tempered at 1150 - 1250°F, held 1 hr/in. of thickness and water quenched.	9	28
	Annealed	Held 1 hr/in. of thickness at 1650°F and then furnace cooled (30°F/hr) to 1000°F. Then air cooled to room temperature.	9	12.5

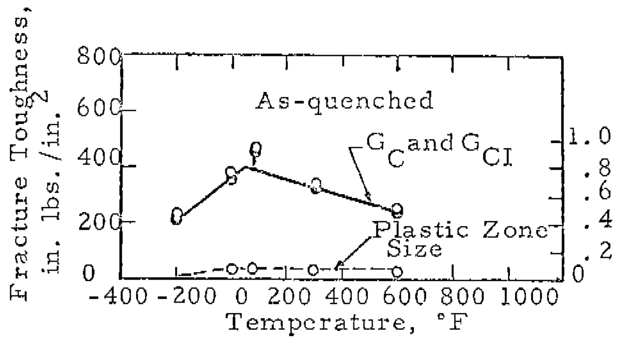
Fig. 11. Fracture Toughness Data for ASTM A517F Steel[24]

plastic deformation as had the HAZ material. The data for the as-quenched condition are depicted by Figure 12(a) where it can be noted that the specimen was not of adequate size to measure fracture mechanics plane strain fracture toughness much above 0°F. Figure 12(b) depicts the correlation obtained by the investigators between fracture toughness values and Charpy V-notch impact energy which is useful because it enables use of the bulk of the fracture toughness data available. Figure 12(c) presents the theoretical relationship between crack length, stress level, and "fracture mechanics" fracture toughness for the uniaxial tensile case. It should be noted that, at about 30°F, the material of Figure 12(a) would be expected to fracture at one-half yield strength stress if a through crack of 2 in. in length were present. Subsequent work, using a more sophisticated specimen, has resulted in obtaining plane strain fracture toughness values for A517 F base plate material at room temperature and correlation between these values and Charpy V-notch impact values. These values are consistent with the values of Figures 11 and 12 at temperatures below 0°F where the specimen size was adequate. The fracture mechanics approach provides a lower bound for prediction of fast fracture behavior of low toughness steel and appears to be sufficient for analysis, especially in the weldment HAZ which is certainly less tough than base plate material.

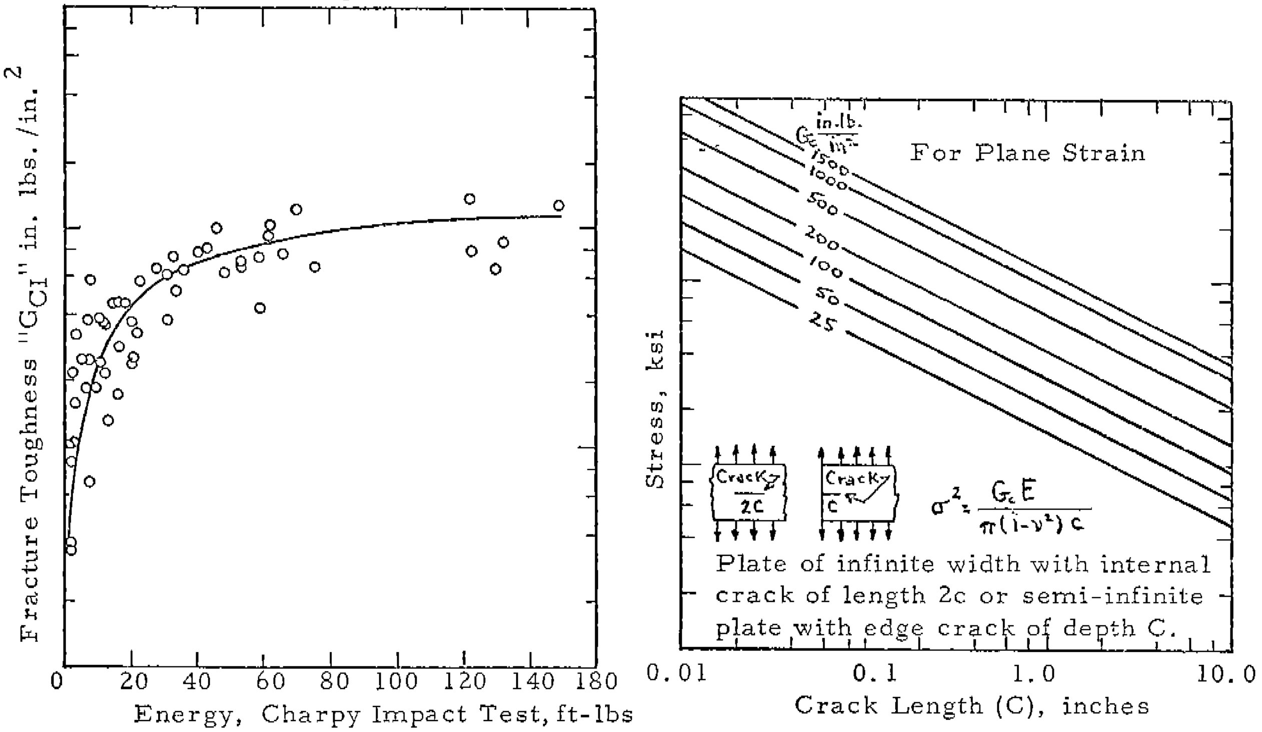
The A517 F point on the Figure 13 correlation curve corresponds to base plate material with a yield strength of 110 ksi, K_{Ic} of 170 ksi $\sqrt{in.}$ and a Charpy V-notch impact energy value at test temperature of 62 ft-lb. This is roughly equivalent to stating that a 2-ft-long through crack in strength deck plating loaded to one-half yield could initiate fast fracture in this material, if the material is thick enough to develop plane strain crack loading conditions. For the case of a material with a yield strength of 120 ksi, Charpy V-notch impact energy value of 30 ft-lb, Figure 13 indicates a K_{Ic} of 110 ksi $\sqrt{in.}$ which is equivalent to a critical through crack length at one-half yield strength of about 8 inches. Similarly, the simulated HAZ material of Figure 11 would have critical through crack length as low as 2 in. for one-half yield strength stress loading at 30°F as was previously indicated by other work.

Figure 14 depicts a carbon steel pressure vessel whose behavior is analyzable by the transition temperature approach, and Figure 15, its behavior in relationship to the NRL fracture analysis diagram.

Figure 16 depicts an A517 F pressure vessel whose behavior is not analyzable by the transition temperature approach. This vessel failed from a small flaw at a nominal stress less than one-half of the yield stress. This vessel was stress relieved. It is interesting to note that the failure apparently did not initiate at the largest flaws, which were fatigue cracks. It has been noted in fracture toughness tests that such behavior apparently results from compressive residual stress at crack tips derived from plastic loading at fatigue crack tips which results in apparently high fracture toughness values. This failure is one of several HSLA Q and T pressure vessel test results that fit the correlation fracture mechanics prediction.



a. Effect of temperature on fracture toughness parameters for A517, Grade F steel



b. Correlation of $G_0{}^1$ fracture toughness with Charpy impact energy for benchmark steels.

c. Relationship of fracture strength to crack length for different levels of fracture toughness

Fig. 12. Fracture Toughness of A517, Grade F Steel and Summary of Fracture Mechanics Procedures [24]

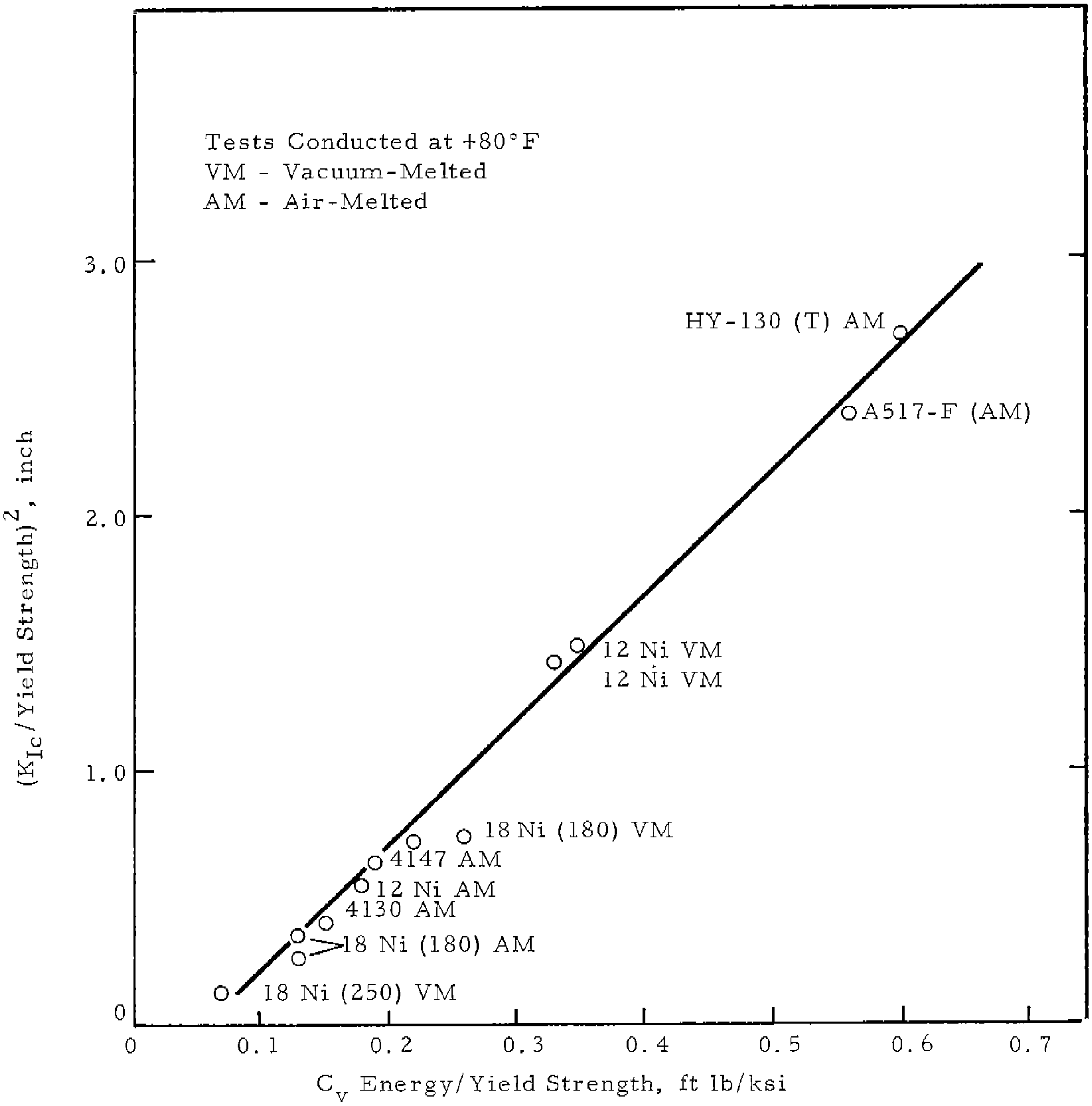


Fig. 13. Relation Between Plane-Strain Stress-Intensity Factor, K_{Ic}, and Charpy V-Notch Energy Absorption (CVN)

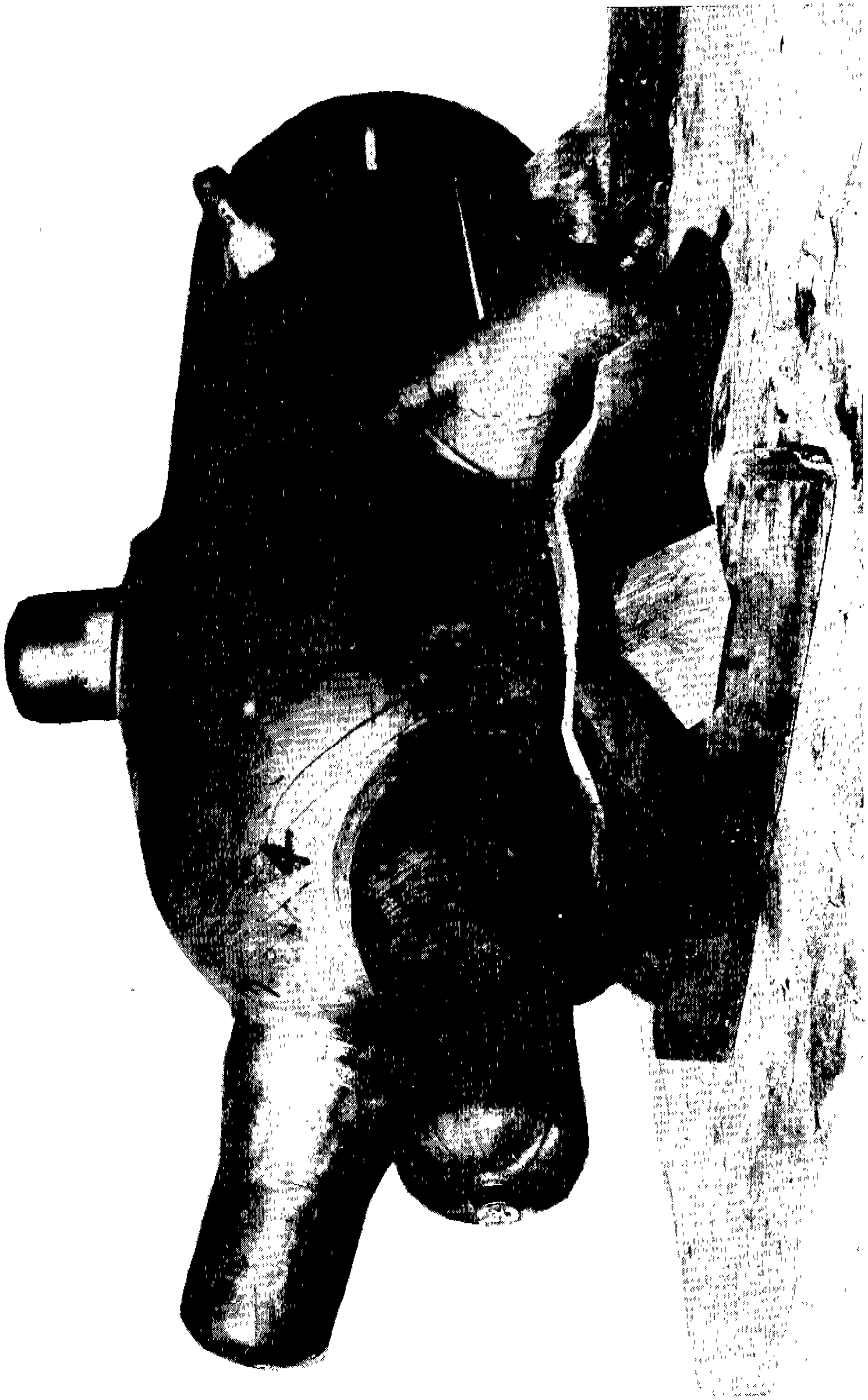
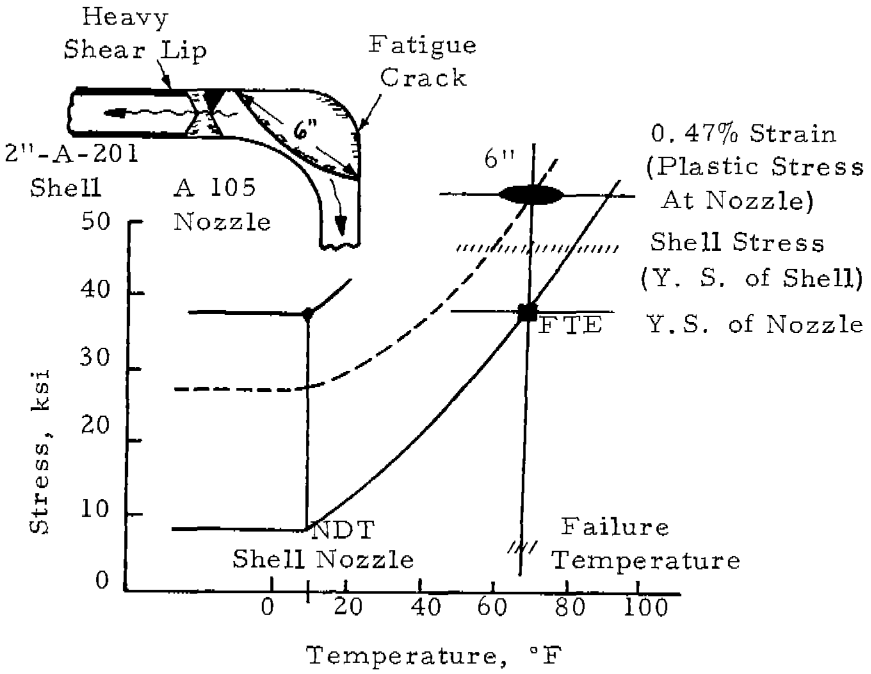


Fig. 14. Terminal Failure of Vessel No. 1 [11]

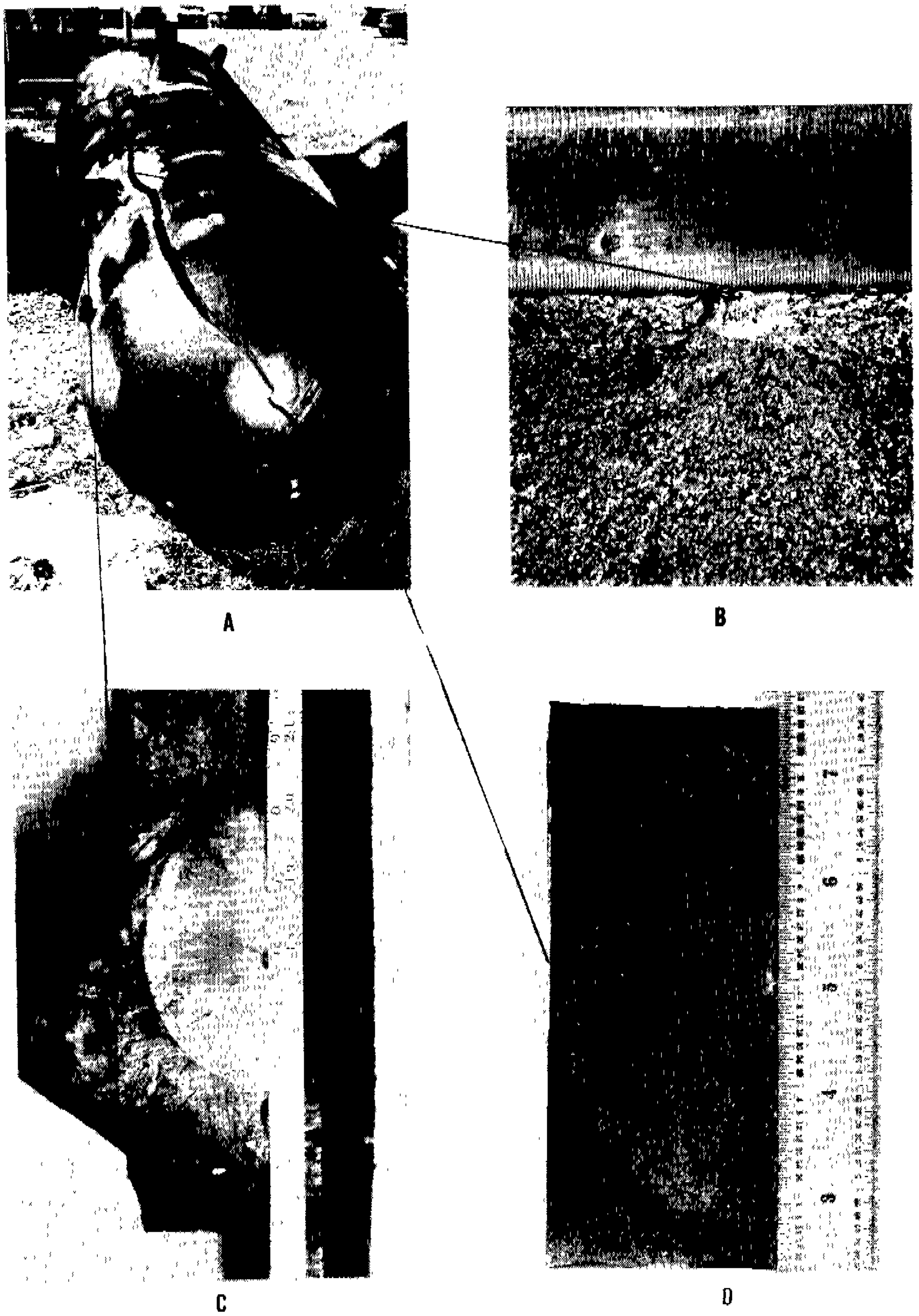


Material			Composition, wt-%		
	C	Mn	Si	P	S
A201 Shell	0.18	0.65	0.21	0.010	0.024
A105 Nozzle	0.25	0.72	0.22	0.007	0.034

	Yield Strength, ksi	Tensile Strength, ksi	Elongation, %	Reduction of Area, %
A201 Shell	48.0	67.9	40.0	54.6
A105 Nozzle	36.4	66.6	34.4	50.5

	NDT, °F	C_VNDT, ft-lb	FT, °F	C_VFt, ft-lb
A201 Shell	0	26	60/70	63/72
A105 Nozzle	10	13	60/70	25/30

Fig. 15. Fracture Analysis Relating to Failure of PVRC Vessel No. 1, Which Originated from a 6-inch Fatigue Crack in a Forged ASTM A105 Nozzle [11]



(a) After brittle fracture test at 30°F and 5200 psi
(b) Arc strike which initiated brittle fracture
(c) Fatigue crack adjacent to Nozzle No. 9
(d) Fatigue crack in shell which leaked at 48,772 cycles and 4400 psi peak internal pressure

Fig. 16. Terminal Failure of Vessel No. 6 [11]

Direct application of the data obtained to date has been difficult because test machine load capabilities have limited specimen size. This in turn can produce invalid fracture toughness data and does not permit an evaluation of a complex weld joint in terms of mechanical properties, residual stresses, and geometric discontinuities that can only be studied with large-sized specimens.

VI. CONCLUSIONS

These data indicate that:

(1) Fast fracture is possible in weldments fabricated of HSLA Q and T materials at nominal stress levels less than one-half of the yield stress from cracks of small size relative to ship hull dimensions.

(2) Fast fracture of many of the HSLA Q and T materials which are being used in ship hull construction should be predictable by the fracture mechanics approach.

(3) There is a general lack of quantitative data required to predict crack size as a function of service history and loads corresponding to potential fast fracture initiation. This information is basic to the establishment of serviceability criteria for the HSLA Q and T steels being used in merchant ship hull construction. These serviceability criteria include quality control, inspection, and surveillance specifications and standards.

(4) A crack or flow can grow to critical size under the combined influence of service stresses and environmental conditions.

VII. RECOMMENDATIONS

It is recommended that the following laboratory investigations be performed to obtain the essential data required to establish the serviceability criteria for HSLA Q and T weldments:

(1) Study the environmental effects on specimens subjected to high static tensile stresses to determine if mechanisms such as stress corrosion cracking and hydrogen embrittlement cause slow crack growth.

(2) Determine the crack initiation and growth response to cyclic stresses in a marine environment.

(3) Establish the fracture toughness of HAZ materials in quantitative terms using fracture mechanics test procedures.

(4) Test complex specimens (which include the various effects of residual stress, cracklike flaws, and geometric and metallurgical discontinuities found in real hardware weldments) to determine the relationship between specimen tests and hardware behavior.

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GLOSSARY

As-rolled - Rolled material which has no postfabrication heat treatment.

Austenite - A solid solution of one or more elements in face-centered cubic iron. Unless otherwise designated, the solute is assumed to be carbon.

Cv, Charpy V-notch, test - A pendulum-type, single-blow impact test of a specimen containing a vee notch in one side. See ASTM Method E23.

Corrosion fatigue - The reduction in fatigue properties resulting from the application of cyclic stresses in a corrosive environment.

Delayed cracking - Cracking observed in weldments, usually a number of hours or days after completion of the weld.

DPH, diamond pyramid hardness - Hardness of a material determined with a pyramid-shaped diamond indentor under various loads. Also called the Vickers hardness test.

Drop-weight test - A guillotine, single-blow impact test on a specimen containing a brittle weld crack starter to define the nil ductility transition temperature. See ASTM Method E208.

Elastic deformation - Change of dimensions when a structure is stressed below the elastic limit, the original dimensions being restored after the stress has been removed.

Elastic instability - Failure of a structural member by exceeding a critical value of load above which the deflections and stresses are no longer proportional to load although the materials of construction are still in the elastic range. Also called elastic buckling.

Elongation - In tensile testing, the change in the length of the gage section when fractured within the gage section. Usually presented as a percentage of the original gage length.

Explosion bulge test - The subjection of a test plate to an explosive force sufficient to produce biaxial stresses above the elastic limit in a circular test section.

Explosion bulge crack starter test - The subjection of a test plate having a brittle weld crack starter to an explosive force sufficient to produce biaxial stresses above the elastic limit in a circular test section. See NAVSHIPS 0900-005-5000.

Fast fracture - The rapid, uncontrolled propagation of a fracture at stresses either above or below the elastic limit. Fast fracture may be brittle or ductile.

Fatigue - The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.

Fatigue crack initiation life - The number of cycles of alternating stress required to develop a detectable fatigue crack in a material.

FTE, fracture transition for elastic loading - That temperature, usually NDTT +60°F, above which a flaw cannot become unstable when subjected to stresses below the yield strength.

FTP, fracture transition for plastic loading - That temperature, usually NDTT +120°F, above which failure must occur by plastic instability.

Fully automatic welding processes - Welding with equipment which performs the entire welding operation without constant observation and adjustment of the controls by an operator.

H_2S - Hydrogen sulfide.

Hardenability - The property of a ferrous alloy which affects the depth of hardness induced by quenching.

R_c, Rockwell "C" hardness - Hardness of a material determined with a 120° conical diamond indentor and a 150-kg load.

HAZ, heat affected zone - In a weldment, the unfused material immediately adjacent to the weld puddle which is heated sufficiently to change its microstructure or properties.

HSLA Q and T - High-strength, low-alloy steels which are quenched and tempered to develop the desired tensile properties.

Hydrogen embrittlement - The loss in ductility of metals which have absorbed hydrogen.

Interpass temperature - Temperature of the weld metal and adjacent base metal prior to subsequent welding.

K_{Ic}, critical stress intensity factor - The value of the stress intensity factor sufficient to result in unstable crack propagation.

Low cycle fatigue - Failure of a material in less than 100,000 cyclic load applications. Generally, the loads are high enough to cause plastic deformation of the material of construction. Sometimes referred to as "plastic fatigue" or "high strain" fatigue.

Low hydrogen techniques - Techniques such as preheating, baking of electrodes, etc., which control the hydrogen content of the weld metal. This includes the use of low hydrogen-mineral coated electrodes.

Martensite - A metastable phase of steel, formed by transformation from austenite when the critical cooling rate is exceeded.

Microhardness - Hardness of a phase or other small area of a polished metal specimen, determined with the Tukon or Knoop methods.

NDTT, nil ductility transition temperature - That temperature below which a small flaw can initiate fast fracture at yield strength stress levels.

Nonmetallic inclusions - Nonmetallic materials (usually oxides, silicates, or sulfides) in a solid metallic matrix.

Normalized steels - Steels which have been heated above the transformation temperature range then air cooled to room temperature.

Notched fatigue strength - The fatigue strength of a material as determined with specimens containing a notch.

Plastic deformation - The permanent deformation achieved when a stress is removed after exceeding the elastic limit.

Plastic instability - Failure of a structural member by exceeding a critical value of load above which deflections and stresses are no longer proportional to load because the yield strength of the material has been exceeded.

Postheat - Thermal treatment applied after the completion of a welding or cutting operation.

PPM - Parts per million.

Preheat - Thermal treatment applied prior to a welding or cutting operation.

Semiautomatic welding process - Welding with equipment which controls the feed of filler metal and arc characteristics. The advance speed of welding and manipulation of the arc are manually controlled.

Shakedown - The development of a steady-state relationship between stress and strain in a low cycle fatigue test or in a structure.

Shielding system - A gas or combination of gases and/or slag which protects the molten puddle from the atmosphere until metal solidifies.

Short circuiting MIG process - An arc welding process wherein coalescence is produced by heating with repeated short circuits between the filler metal electrode and the work. Shielding is obtained with a suitable gas or mixture of gases.

Stress corrosion cracking - Development of transgranular or intergranular cracks under the combined influence of stress and a corrosive atmosphere.

Stress concentration factor - The ratio of the maximum stress at the root of a notch to the average stress over the entire cross section.

Submerged arc welding process - An arc welding process wherein coalescence is produced with one or more electric arcs between a bare metal electrode or electrodes and the work. Shielding is obtained by a blanket of granular fusible material on the work.

Tensile failure - Fracture resulting from stresses exceeding the tensile strength of the material.

UTS, ultimate tensile strength - In the tensile test, the maximum load that the material can withstand divided by the initial cross-sectional area.

Weldments - An assembly whose parts are joined by welding.

Yield point - The stress at which an increase in deformation occurs without an increase in load. It occurs only in mild or medium carbon steels.

Yield strength, 0.2% offset - The stress at which the gage section of a tensile specimen has undergone a plastic deformation of 0.2%.

SOUTHWEST RESEARCH INSTITUTE QUESTIONNAIRE
SHIP STRUCTURE COMMITTEE CONTRACT N00024-67-C-5416

1. Have you used quenched and tempered HSLA steels? (yes)______ (no)______

   For surface ship construction (yes)______ (no)______

   For repair of surface ships (yes)______ (no)______

   For reconstruction of surface ships (yes)______ (no)______

2. What specific types of quenched and tempered HSLA steels have you used?

3. Are your Welding Procedures for these materials available for use in this program? (yes)______ (no)______

   (We are interested in all procedures, i.e., automatic, manual, all positions, fillet, tee, etc.)

4.1 Do you have formal procedures for control of moisture in:

   (a) Low hydrogen electrodes (yes)______ (no)______

   (b) Submerged arc fluxes (yes)______ (no)______

   If the above answers are yes, are they available for use in this program? (yes)______ (no)______

4.2 If you do not have formal procedures for control of moisture do you exercise any form of control?

   Please explain.

   (a) Low hydrogen electrodes

   (b) Submerged arc fluxes

5. What preheat and interpass temperature

would be realistic for welding A517 materials in the construction of merchant cargo ships in the following thicknesses?

Thickness	Preheat °F	Interpass °F
1/2"		
1"		
1-1/2"		
Over		

6. Do you feel that it would be practical to have more than one procedure for the same material? i.e., a strict procedure for critical areas with a downgraded procedure for less critical areas. (yes)______ (no)______

7. Are your nondestructive testing procedures available for use in this program? (yes)______ (no)______

8. What type(s) of nondestructive techniques have you used to inspect weldments of HSLA on merchant cargo vessels?

Visual____________________ Magnetic Particle__________

Radiography_______________ Ultrasonic_____________

9. What types of impact of fracture toughness testing have you used when qualifying welding procedures for quenched and tempered steels?

10. (a) Do you have a recommended minimum welding procedure for repair welding any combination of HSLA steels and plain carbon steels that may be found in cargo ship weldments, to be performed in small remote ports and at sea where welding supplies, procedure

controls and welder qualifications are limited? (yes)______ (no)______

(b) Is this procedure available for use in this program? (yes)______ (no)______

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13. ABSTRACT

A recent advent in ship construction is the use of high-strength low-alloy steels with 100,000-psi yield strengths for ship hull structural elements, making unique design concepts possible. This application is a significant step, but the material's behavior needs to be further defined. For the benefit of the owners, designers, and fabricators, a project was initiated by the Ship Structure Committee to establish which mechanical properties should be used as criteria for judging performance, to evaluate large-scale weldments to determine the suitability of these criteria, and to select small-scale laboratory tests that correlate with the large-scale tests. A survey of shipyards and ship repairers revealed that these newer materials are being used only in critical strength elements of ship hulls. Welding procedures are qualified by explosion bulge tests to define safe operating temperature limits. A survey of the properties of these materials and their weldments indicated that the HAZ might be suspected to be more susceptible to crack initiation and growth than the unaffected base plate, but it was concluded that more data are needed to establish serviceability criteria. It is recommended that laboratory investigations be performed to determine the effect of environment and cyclic stresses on slow crack growth and establish the fracture toughness of weldments, including the effects of residual stress and metallurgical and geometric discontinuities.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Merchant Cargo Ships						
High-Strength Low-Alloy Steels						
HSLA Weldments						
ASTM 514 Steel						
ASTM 517 Steel						
Fracture Toughness of HSLA Steels and Weldments						

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