ENC ~~DOD~~

SSC-169

ULS

Interpretative Report on Weld-Metal Toughness

by

K. MASUBUCHI
R. E. MONROE
AND
D. C. MARTIN

SHIP STRUCTURE COMMITTEE

Copies available from Secretary, Ship Structure Committee,
U. S. Coast Guard Headquarters, Washington, D. C. 20226

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

ADDRESS CORRESPONDENCE TO:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington, D. C. 20226

July 1965

Dear Sir:

Is the toughness of the normal weld metal in the improved ship steels and in the newer high-strength steels contemplated for ship construction sufficient to assure the absence of a weak link in the system? A preliminary study showed that no compilation was available on which sound conclusions could be drawn. Therefore, the Ship Structure Committee requested that the accompanying interpretive report, prepared by Battelle Memorial Institute, be compiled to present knowledge on toughness of weld metal and adjacent heat-affected zones in steels up to 120,000 psi yield strength.

In sponsoring this research project, the Ship Structure Committee received guidance and review from the National Academy of Sciences through its Ship Hull Research Committee, and a project advisory committee (SR-170, "Weld Metal Toughness") established specifically for liaison with the principal investigator. The Academy undertakes this research advisory service to the Ship Structure Committee through a contract arrangement.

Comments on this report would be welcomed and should be addressed to the Secretary, Ship Structure Committee.

Sincerely yours,

John B. Oren

JOHN B. OREN
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-169

Final Report
of
Project SR-170
"Weld Metal Toughness"

to the

Ship Structure Committee

INTERPRETATIVE REPORT ON WELD-METAL TOUGHNESS

by

K. Masubuchi, R. E. Monroe, and D. C. Martin

Battelle Memorial Institute
Columbus, Ohio

under

Department of the Navy
Bureau of Ships Contract NObs-90504

Washington, D. C.
National Academy of Sciences-National Research Council
July 1965

ABSTRACT

A literature survey was made to review presently available information on the notch toughness of weld metals and the heat-affected zone as they are affected by welding procedures. The base metals discussed in this report include mild steel and low-alloy, high-strength steels with up to 120,000-psi yield strength, such as may be used for merchant-ship construction. Welding processes considered include (1) shielded metal-arc welding, (2) submerged-arc welding, (3) gas metal-arc welding, and (4) electroslag and electrogas welding.

One of the most important observations of this literature survey is that relatively limited information is available on the notch toughness of weld metals and heat-affected zones which can be used to establish behavior trends. Information is especially lacking on what constitutes realistic requirements for notch toughness in these zones compared with that of the base metal. It was also observed that relatively little correlation of such factors as chemical composition, microstructure, and welding variables has been made with the notch toughness of weld metals and heat-affected zones.

CONTENTS

INTRODUCTION

The Ship Structure Committee, recognizing an increasing interest during the last few years in weld-metal toughness, authorized the study reported here. Extensive research during the last 20 years on brittle fracture of structural steels has resulted in considerable improvement in both structural steels and the corresponding weld metals. Numerous publications have covered many aspects of the base-metal fracture problem.(1-7) However, only a few attempts have been made to compile and analyze information on weld-metal toughness.(8, 9) The purposes of this report are twofold:

(1) To review presently available information on the metal toughness of weld metals and the heat-affected zone

(2) To uncover important areas in which the data are insufficient or are in need of clarification.

The base metals discussed in this report include steels with yield strengths up to 120,000-psi. Included are steels in the following classes:

(1) Low carbon
(2) Low alloy, high strength
(3) High strength, heat treated.

The most commonly used steel for merchant ship construction is still low-carbon steel. Steels with improved notch toughness have been used in the main structures of modern merchant ships. High-strength notch-tough steels have been used extensively in naval ships. For example, U. S. Navy HY-80, a quenched and tempered steel with 80,000-psi yield strength, has been widely used in submarine hulls. There has been increasing interest in the use of high-strength steels in merchant-ship structures.

Welding processes discussed in this report are:

(1) Shielded metal-arc welding with covered electrodes
(2) Submerged-arc welding
(3) Gas metal-arc welding: CO_2 and inert-gas shielded
(4) Electroslag and electrogas welding.

Shielded metal-arc welding and submerged-arc welding are the two major processes used in present-day fabrication of ship hulls. The other processes mentioned above are not commonly used in ship-hull fabrication, but they have important potential uses in this field. Discussions cover primarily the notch toughness of butt-joint weld metals in the as-deposited condition.

Among the many tests which have been proposed and used by a number of investigators to evaluate the notch toughness of weld metals, by far the most commonly used are the Charpy-type impact tests, especially the Charpy V-notch test. Charpy V-notch impact test data are used for the most part in this report.* Data obtained with other notch-toughness tests are discussed in Chapter 5.

*In preparing this report, comparisons are made of either notch toughness or transition temperatures. Limitations imposed by the varied data sources have made this necessary. The reader is reminded that an increase in notch toughness reflects a property improvement; an increase in transition temperature reflects a property degradation.

CHAPTER 1. CHARPY IMPACT TESTS FOR EVALUATING THE NOTCH TOUGHNESS OF WELD METALS

This chapter describes (1) the preparation of Charpy impact-test specimens for evaluating the notch toughness of weld metals and (2) the weld-metal notch-toughness requirements of various specifications.

1.1 Preparation of Charpy Specimens for Evaluating Notch Toughness of Weld Metals

The Charpy impact test uses a notched bar 0.394 by 0.394 by 2.165 inches. ASTM specification E23-60[10] covers three types of notches: (1) V-notch, a 45-degree vee-shaped notch 0.079 inch deep, (2) keyhole notch, and (3) U-notch, 0.197 inch (5 mm) deep.* The Charpy impact tests are widely used in the United States, Western European countries, and Japan. There has been a trend toward increasing use of the V-notch specimen. In Russian and other Eastern European countries, the Mesnager specimen is used. This is essentially a Charpy-type specimen with a 2-mm (0.79 inch)-deep U-notch.[11]

Figure 1 shows six different ways of preparing Charpy V-notch specimens from a butt-welded joint. For each of the principal axis directions (weld direction, lateral direction, and thickness direction), there are two notch directions. Specimen Types 5 and 6 are possible only for plates thicker than 2.2 inches. For Types 1 through 4, the location of a specimen with respect to the plate thickness can be changed, i.e., the specimen can be taken near the surface or midthickness.

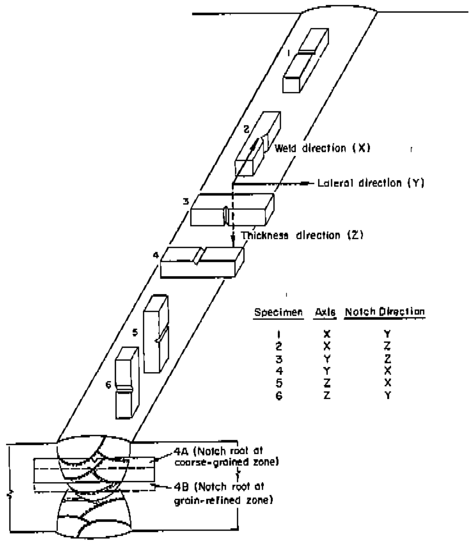


Fig. 1. Six different ways of taking Charpy-type specimens from a butt-welded joint.

*Although test specimens and test methods are standardized, test-temperature ranges are not. A notable lack of consistency is apparent in the temperature ranges covered during testing. To be of maximum usefulness in making comparisons, Charpy tests should be run over the temperature range from room temperature (+80 F) to a low enough temperature (say -80 or -120 F) to establish the lower shelf energy level. It is considered more desirable to define the shape and position of the transition curve than to concentrate on establishing a high level of confidence in the toughness at one or more given temperatures.

Heterogeneity of the weld-metal structure often causes scatter of notch-toughness data. For example, when the notch is placed parallel to the plate surface (Type 4) the notch root may be located in a coarse-grained zone (Type 4A), or it may be located in a zone where heating by subsequent passes has refined the grain structure (Type 4B). The fine grained specimen would have a higher impact value than would a coarse-grained specimen, since more energy is required to initiate fracture in the grain-refined zone than in the coarse-grained zone. It is believed that notch-toughness data scatter is minimum when the notch is placed in the thickness direction (Type 3). Many specifications require that the Type 3 specimens be used.

When Charpy specimens are taken from a butt joint, precautions are necessary to minimize effects of alloying-element dilution or enrichment from the base plate. The beveled edges of the joint are often clad with a layer of weld metal. The effect of the base metal is greater on submerged-arc-deposited metals which are deposited with higher heat input than on covered-electrode-deposited metals.

1.2 Requirements of Various Specifications for the Notch Toughness of Weld Metals

In ship-hull construction, about 3/4 (in length) of the welded joints are fillet joints which are, for the most part, welded by the shielded metal-arc process.[12] About 1/4 of the welded joints are butt joints; about two-thirds are made by the shielded metal-arc process and one-third are made by the submerged-arc process.

Table 1 summarizes the requirements of various specifications for weld metal notch toughness in butt joints. Also shown for comparison are the notch-toughness requirements for some steel plates used in ship construction. Minimum values of

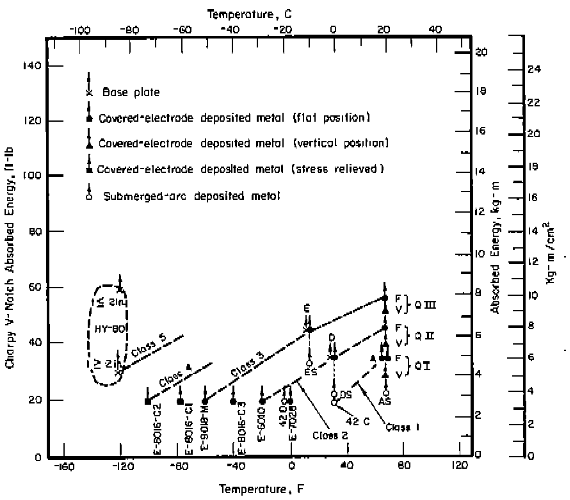


Fig. 2. Notch toughness required by various specifications.

1. *International specification for ship steel: A, D, E (AS, DS, ES are 70 percent of A, D, and E, respectively; submerged-arc welding)*
2. *AWS: E-7028, E-6010, E-8016-C3, E-9018-M, E-8016-C1, E-8016-C2*
3. *IIW, Commission II: QI, QII, QIII for flat and vertical positions*
4. *IIW, Commission XII: 42C, 42D (submerged arc-welding)*

TABLE I. NOTCH TOUGHNESS REQUIREMENTS OF VARIOUS SPECIFICATIONS.

Base Metal or Weld Metal	Specifications and Classes	Charpy V-Notch Minimum Energy Absorption, ft-lb	Charpy V-Notch Temperature, F
	International Specification for Ship Steel		
Base metal	Grade D*	35	32
	Grade E*	45	14
	U. S. Navy HY-80 Steel		
	Thickness 2 inches or less*	60	-120
	Thickness over 2 inches*	30	-120
	AWS-ASTM (1964)		
Covered-electrode-deposited metal	E6012, E6013, E6020, E7014, E7024	Not required	
	E7028*	20	0
	E6010*, E6011, E6027, E7015, E7016, E7018	20	-20
	E8016-C3*, E8018-C3	20	-40
	E9015-D1, E9018-D1, E10015-D2, E10016-D2, E10018-D2	20(a)	-60
	E9018-M*, E10018-M, E11018-M, E12018-M	20	-60
	E8016-C1*, E8018-C1	20(a)	-75
	E8016-C2*, E8018-C2	20	-100
	International Specification for Ship Steel		
	Joining Grade A steel*	35	68
	Joining Grades B, C, D steels*	35	32
	Joining Grade E steel*	45	14
	IIW Commission II		
	Tensile strength of weld metal 61,000 to 67,000 psi: Quality I*, flat position	35	63
	Quality I*, vertical position	29	68
	Quality II*, flat position	46	68
	Quality II*, vertical position	40	68
	Quality III*, flat position	57	68
	Quality III*, vertical position	52	68
	Tensile strength of weld metal 74,000 to 88,000 psi: Quality II, flat position	46	68
	Quality II, vertical position	40	68
	Quality III*, flat position	57	68
	Quality III*, vertical position	52	68
	IIW Commission XII		
Submerged-arc-deposited metal	Minimum tensile strength of weld metal 60,000 psi: 42C*	20	32
	42D*	20	-4
	Minimum tensile strength of weld metal 71,000 psi: 50C	20	32
	50D	20	-4

(a) Stress-relieved condition.

*Notch-toughness values are shown in Figure 2.

Charpy V-notch absorbed energy at certain temperatures are specified.* Figure 2 shows notch-toughness requirements for entries marked in Table 1 with asterisks. No specification covers the notch toughness of weld metals in fillet joints.

Base Metal

Low-Carbon Ship Steels. The American Bureau of Shipping requires that Class B or Class C steels be used for main structural members, depending on the thickness.[13] Requirements for chemical composition and steelmaking processes are stipulated for these steels, but there is no requirement for notch toughness.

At an international conference held in London in 1959, ship classification societies of major shipbuilding countries approved an international specification for ship steels.[14] In this specification, steels are classified into five grades, A, B, C, D, and E. Charpy V-notch values of 35 ft-lb at 32 F for Grade D and 45 ft-lb at 14 F for Grade E are specified. These requirements are represented in Figure 2 by points designated D and E. Ship-classification societies which have adopted the international specification include Lloyd's Register of Shipping, London,[15] and Nippon Kaiji Kyokai, Tokyo.[14]

High-Strength Steels. Many specifications cover the notch toughness of high-strength steels which can be used in ship structures.[4, 5, 16-19] The U. S. Navy Specification MIL-S-16216 covers notch-toughness requirements for HY-80 steel, which is a low-carbon nickel-chromium-molybdenum steel. The minimum requirements for Charpy V-notch impact-test values of steels in the quenched and tempered condition are 60 ft-lb for plates 2 inches thick or less and 30 ft-lb for plate over 2 inches thick.

Covered-Electrode-Deposited Metals

Table 1 shows requirements of various specifications for the notch toughness of weld metals deposited with covered electrodes:

(1) The AWS-ASTM specifications for mild-steel covered electrodes (AWS A5·1-64 T and ASTM A-233-64) and for low-alloy-steel covered electrodes (AWS A5·5-64 T and ASTM A316-64 T). Table 1 shows the notch-toughness requirements for weld metals made with various types of electrodes, E7028, E6010, E6011, etc.

(2) Notch-toughness values which have been proposed for weld metals made with covered electrodes used for joining Grades A through E steels of the international specification for ship steels.

(3) Notch-toughness values which have been recommended by Sub-Commission C, "Testing and Measuring of Weld Metal" of Commission II of the International Institute of Welding.[20] Notch-toughness values have been recommended depending on (1) the tensile strength of the weld metal, (2) the quality of the weld (QI, QII, QIII), and (3) the welding position (flat or vertical).

*The Charpy V-notch absorbed energy is given by ft-lb or kg-m. The specific absorbed energy per square centimeter of sectional area (0.8 cm^2), kg-m/cm^2, also is often used.

$$1 \text{ ft-lb} = 0.138 \text{ kg-m} = 0.174 \text{ kg-m/cm}^2.$$

Electrodes used for military applications are specified by MIL-E-22200/1. Electrodes MIL-9018, MIL-10018, MIL-11018, and MIL-12018 are similar to those of AWS specifications E-9018-M, E10018-M, E11018-M, and E12018-M. The U. S. Navy specification NAVSHIP 250-637-3 specifies among other processes the use of covered electrodes in the fabrication of HY-80 submarine hulls. MIL-11018 and 9018 electrodes are used most commonly.

Submerged-Arc-Deposited Metals

Sub-Commission E, "Study of Weld Metal Deposited by All Processes", of Commission XII of IIW has proposed notch-toughness requirements for submerged-arc-deposited metals in carbon steel.[21] Values shown in Table 1 are recommended, depending on (1) the minimum tensile strength (60,000 or 71,000 psi) and (2) the class of weld (C or D).

Theoretically, requirements for the notch toughness of weld metal should be the same for all welding processes. However, several ship-classification societies currently accept submerged-arc-deposited weld metals with notch toughness lower than those of covered-electrode deposited weld metals. Apparently, this is because of the difficulty in obtaining submerged-arc-deposited metals which meet the requirements for covered-electrode-deposited metals. For example, the Japanese ship-classification society currently requires the following values for submerged-arc-deposited metals:[22]

(1) 25 ft-lb at 68 F for joining Grade A steel
(2) 25 ft-lb at 32 F for joining Grades B, C, and D steels
(3) 35 ft-lb at 14 F for joining Grade E steel.

These values are shown in Figure 2 by points designated AS, DS, and ES, respectively. These values are about 70 percent of the values required for covered-electrode weld deposits used in joining steels of corresponding grades.

Comparison of Various Specifications

To facilitate discussions in later chapters of this report, the notch-toughness requirements of various specifications are divided into the following five classes, with Class 1 being the least severe and Class 5 the most severe:

Class 1: QI, flat position; 42 C (35 ft-lb at 68 F: 20 ft-lb at 32 F)

Class 2: QII, flat; Grade D; E6010 (46 ft-lb at 68 F; 35 ft-lb at 32 F; 20 ft-lb at -20 F)

Class 3: QIII, flat; Grade E; E9018-M (57 ft-lb at 68 F; 45 ft-lb at 14 F; 20 ft-lb at -60 F)

Class 4: E8016-C2 (20 ft-lb at -100 F)

Class 5: HY-80 steel base metal over 2 inches thick (30 ft-lb at -120 F).

Basis for Toughness Requirements

It is still debatable (1) whether the Charpy V-notch impact test is an adequate test for evaluating notch toughness and (2) what notch-toughness level is really needed even for base metals. Nevertheless, attempts have been made to establish realistic requirements for the notch toughness of the base metal by:

(1) Analyses of notch-toughness data obtained with specimens taken from fractured ships. The analyses include those made at the U. S. National Bureau of Standards[23, 24], the U. S. Naval Research Laboratory[25, 26], and Lloyd's Register of Shipping[27]. Analyses also were made by Audigé[28], Rühl[29], Bonhomme[30], and other investigators.

(2) Comparison of notch-toughness data obtained with the Charpy specimens and the fracture behavior of large-size specimens. Studies were made by Feely, et al.[31], Puzak and Pellini[32], and other investigators[33, 34].

However, almost no information has been obtained which can be used to establish realistic requirements for weld-metal and heat-affected-zone notch toughness. Most current specifications are apparently based on the principle that the notch toughness required for the base metal should also be required for the weld metal deposited by any welding processes used to join the steel. This basic principle, however, is not always obeyed. For example:

(1) The notch-toughness requirement for weld metals deposited with MIL-11018 electrodes, which have been used extensively for the fabrication of submarine hulls from HY-80 steel, is considerably less severe than that for the HY-80 base metal. The requirement is 20 ft-lb at -60 F for the weld metal and 60 or 30 ft-lb at -120 F for the base metal.

(2) Some ship-classification societies allow lower notch toughness for submerged-arc-deposited metals than for covered-electrode-deposited metal.

The low toughness requirements have been set in some cases because weld metals with higher notch toughness are not available at the present time, not because notch toughness is less important in the weld metal than in the base metal. Economics also plays a part in the establishment of some requirements.

CHAPTER 2. NOTCH TOUGHNESS OF WELD METALS DEPOSITED BY VARIOUS WELDING PROCESSES

This chapter is concerned with the notch toughness of weld metals deposited by several processes in mild steel and high-strength steels of various strength levels. Figure 3 shows schematically the relationship between the tensile strength of an as-deposited weld metal and the maximum attainable notch toughness. For a given strength level, T_1, several weld metals with various notch-toughness levels, N_1, N_2, N_3, ... are possible; however, there is a maximum attainable notch-toughness level, $N_{max}(T_1)$. The maximum attainable notch-toughness level decreases with an increase of the tensile strength. Figure 3 illustrates that the higher the desired strength, the more difficult it is to obtain a weld with good notch toughness. In addition, as the strength of a weld metal increases, it becomes more difficult to obtain a weld without cracks and other defects.

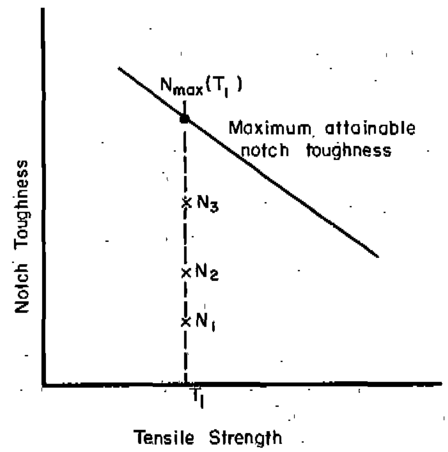


Fig. 3. Relationship between tensile strength of as-deposited weld metal and maximum attainable notch toughness.

2.1 Covered-Electrode-Deposited Metals

There are abundant data on the notch toughness of weld metals deposited with various types of electrodes from various manufacturers.[8, 9, 12, 35-45] This report discusses the general trends observed in the notch toughness of weld metals deposited by various electrode types. The electrode types important for ship-hull fabrication are (1) mild-steel electrodes and (2) low-hydrogen, low-alloy, steel electrodes.

Mild-Steel Electrodes E60XX

Figure 4 contains the following notch-toughness data:

(1) A "band", presented by Pellini[8] in an interpretive report in 1956, indicating the expected notch toughness of weld metals deposited with E6010 electrodes. A band for the notch toughness of ship steels of World War II production is also shown.

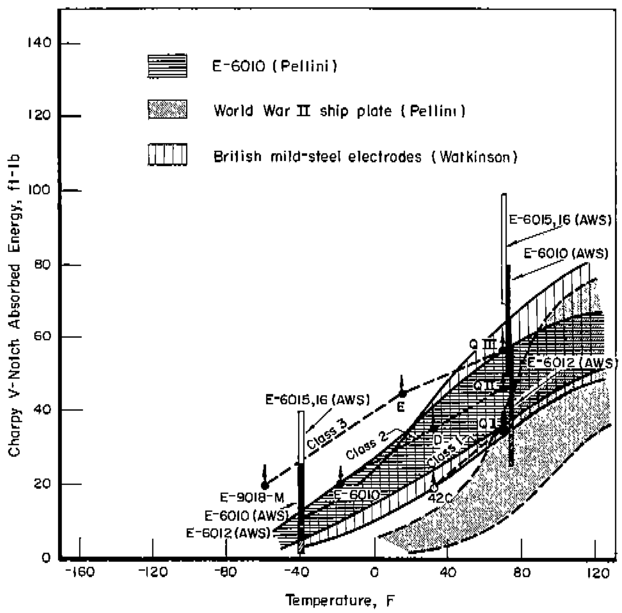


Fig. 4. Notch-toughness data of weld metals of mild-steel electrodes.

(2) A "band" which covers most of the transition curves reported by Watkinson[46] in 1959 for weld metals deposited with mild-steel electrodes from British manufacturers. Investigations were made of two brands each of three types of electrodes: rutile, cellulosic, and basic or lime-fluoride. Welds were made in four welding conditions: downhand, overhead, vertical, and horizontal-vertical.

(3) Ranges of notch-toughness values expected in the as-deposited condition at 70 F and -40 F, given in the latest AWS Welding Handbook[47], for weld metal deposited by E6010, E6012, E6015, and E6016 electrodes.

Also shown in Figure 4 are some of notch-toughness requirements illustrated in Figure 2.

Figure 4 shows the general trends in the notch toughness of weld metals deposited with mild-steel covered electrodes, as follows:

(1) E6010 electrodes: The band for Pellini's data for American E6010 electrodes and that for Watkinson's data for British mild-steel electrodes coincide. The bands for these electrodes fall at lower temperatures than the average band for ship steels for World War II production, indicating superior notch toughness.

Data given in the latest AWS Welding Handbook and the recent toughness requirement for the E6010 electrode indicate that modern E6010 electrodes provide weld metals with better notch toughness than provided by the older electrodes used by Pellini and Watkinson.

(2) Low-hydrogen electrodes: Modern E6015 and E6016 electrodes provide weld metals with notch toughness which can almost meet the Class 3 requirement.

(3) E6012 electrodes: E6012 electrodes do not meet even the Class 1 requirement. E6012 and E6013 electrodes are not approved for use in joining main structural members because of the low notch toughness of their weld metals.

Low-Hydrogen, Low-Alloy Electrodes

The EXX15, EXX16, EXX18, and EXX28 low-hydrogen electrodes are so called because their covering is low in hydrogen-forming compounds. The low-hydrogen electrodes are almost the only type used for welding high-strength notch-tough steels for the following reasons:

(1) The low-hydrogen electrodes are less likely to cause underbead cracking than are any other types of electrodes. "Difficult-to-weld" steels can be welded with less preheat than that necessary with other types of electrodes.

(2) Impact properties of weld metal deposited by low-hydrogen electrodes are much better than those of weld metal deposited by other types of electrodes.

(3) The characteristics of the basic mineral covering make it possible to add carbon, manganese, and other alloying elements to the covering to produce weld metals with various compositions and strengths.

Smith(19), in 1959, presented an interpretive report on properties of weld metal deposited with low-hydrogen electrodes. Sagan and Campbell(48), in 1960, reported impact properties of weld metals deposited with many types of electrodes under various conditions. Figure 5 shows bands which cover most of the transition curves of weld metals deposited with (1) E7016 and E7018 electrodes, and (2) E7028 electrodes. Also shown in Figure 5 are expected notch-toughness values given in the AWS Welding Handbook for weld metals deposited with E7016, E7018, and E7028 electrodes.

The E7016 and E7018 data of Smith and Sagan-Campbell, and the ranges given in the Welding Handbook indicate that the notch toughness of weld metals made with these electrodes is very good. The electrodes easily meet the Class 2 requirement; most electrodes meet even the Class 3 requirement.

With E7028 electrode deposits, however, there is considerable disagreement between Smith's data and Sagan-Campbell's data, as already mentioned by Sagan and Campbell. Values given in the Welding Handbook are somewhat lower than those given by Smith.

Figure 6 shows transition-curve bands for the following:

(1) Pellini's data for E10015, E10016, and E12015 electrode deposits.

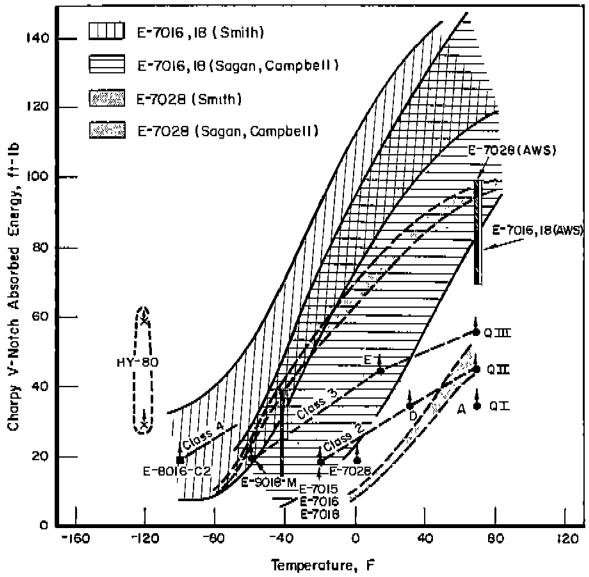


Fig. 5. Notch toughness of weld metals of low-hydrogen E-70XX electrodes.

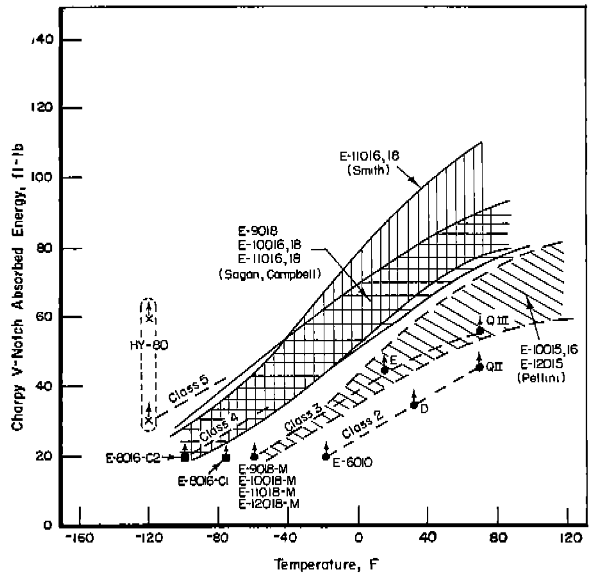


Fig. 6. Notch toughness of weld metals of low-hydrogen high-strength steel electrodes.

(2) Smith's data for E11016 and E11018 electrode deposits.

(3) Sagan-Campbell's data for E9018, E10016, E10018, E11016, and E11018 electrode deposits.

The bands for electrodes used by Smith and Sagan-Campbell agree well. Energy values for these weld deposits are considerably higher than those for weld deposits in Pellini's investigation, indicating the improvement of notch toughness in welds deposited with these electrodes between 1955 and 1959.

Figure 6 shows that the notch toughness of weld metals deposited with modern low-hydrogen, low-alloy steel electrodes is very good. Also shown in the figure are some of the notch-toughness requirements listed in Table 1. Nickel-steel electrodes E8016-C2 and E8018-C2 provide weld metals with a notch-toughness level over 20 ft-lb at -100 F in the stress-relieved condition. However, no electrode specification guarantees to provide weld metals which meet the notch-toughness requirements for HY-80 steel base metal.

2.2 Submerged-Arc-Deposited Metals

There are abundant data on the notch toughness of weld metals deposited by the submerged-arc process when using various combinations of wire, flux, and base metal.(49-64) Within the scope of this literature survey, there are two major areas of interest:

(1) Notch toughness of two-pass submerged-arc-deposited metals in heavy mild-steel ship plates.

(2) Notch toughness of submerged-arc-deposited metals in high-strength, notch-tough steels.

Heavy, Mild-Steel Ship Plates

A significant trend in the shipbuilding industry after World War II has been an increase in the size of ships, especially oil and ore carriers.[65] It has been known for some time that the notch toughness of two-pass submerged-arc-deposited metals decreases as the plate thickness increases. In the fabrication of pressure vessels in which high-quality welds of very heavy plates are required, multilayer procedures are commonly used. In the fabrication of merchant-ship hulls, there has been strong interest in reducing the number of passes, primarily for economic reasons.

Augland and Christensen[52] investigated the notch toughness of submerged-arc weld metals made with two-pass and multilayer procedures in 1-9/16-inch-thick carbon-steel plates. Welding conditions were:

(1) Two-pass welding: 1000 amperes, 4-1/2 in. /min travel speed; and
1200 amperes, 4-3/4 in. /min travel speed

(2) Multilayer welding: 600 to 750 amperes, and 10 in. /min travel speed.

Chemical composition (percent) of the base and weld metals was:

	C	Mn	Si	P	S
Base metal	0.15	0.66	0.19	0.02	0.03
Two-pass weld metal	0.10	0.73	0.46	0.04	0.02
Multilayer weld metal	0.09	1.43	0.33	0.05	0.02

Figure 7 shows transition characteristics of Charpy V-notch specimens taken from the weld metals. Specimens were prepared in the first- and the second-pass weld metal. Notches were made in the thickness direction (Type 3 in Figure 1) and parallel to the plate surface (Type 4). The location and orientation of the specimen had little effect on the transition characteristics; therefore, Figure 7 shows bands only for the two-pass and the multilayer welding. The notch toughness of the multilayer-weld metal was excellent for mild steel, passing Class 2 requirements. The notch toughness of the two-pass weld metal was poor; the weld did not meet Class 1 requirements.

Stern, et al.[53] used Charpy V-notch impact-test specimens and Navy tear-test specimens (see Figure 29a, Chapter 5) to investigate the notch toughness of submerged-arc-deposited metals in carbon and low-alloy steel plates 2 inches thick. In the first series of tests, carbon-steel welds made with many thin layers exhibited somewhat better notch toughness than did the corresponding welds made with few, heavy layers. Charpy V-notch data are shown in Figure 7. However, in further investigations on carbon- and alloy-steel welds made under various combinations of filler wire, flux, and joint design, no general rule was found relative to the relationships between weld-layer thickness and the tear-test transition temperatures.

Figure 8 shows values of absorbed energy at 32 F of Charpy V-notch impact-test specimens taken from many two-pass submerged-arc weld metals in steel plates 5/8

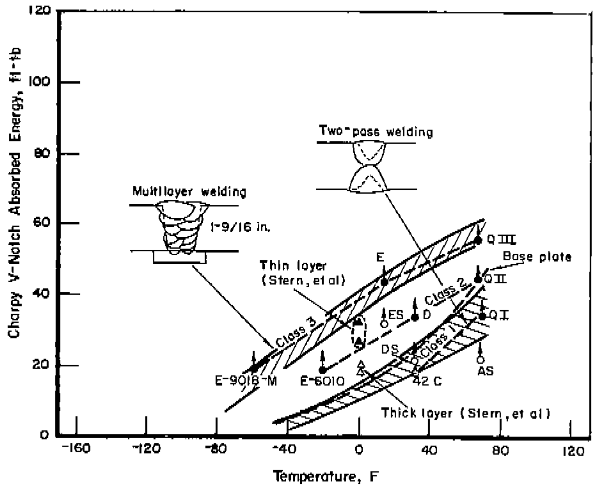


Fig. 7. *Notch toughness of submerged-arc weld metals, two-pass and multilayer welding (Augland, Christensen (52)).*

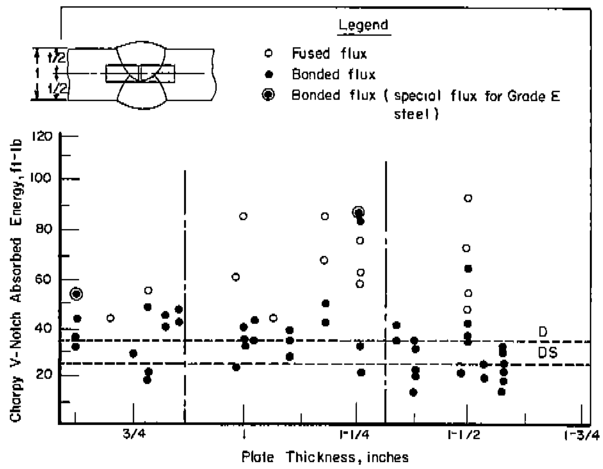


Fig. 8. *Values of absorbed energy at 32 F of Charpy V-Notch impact-test specimens taken from many two-pass submerged-arc weld metals in steels of various thickness. (Data are supplied by Mr. S. Kaku of the Nippon Kaiji Kyokai.)*

to 1-9/16 inch thick.[54] The following tabulation shows the number of welds made with conventional electrodes and fluxes (fused) which had absorbed-energy values over 25 ft-lb (the requirement DS in Figure 2) and 35 ft-lb (the requirement D):

	Range of Plate Thickness, t, inch		
	t < 7/8	7/8 < t < 1-5/16	t > 1-5/16
Total Number of Cases	11	14	20
Number of Welds Over 25 Ft-Lb	9	12	11
Number of Welds Over 35 Ft-Lb	7	8	5

Note: A case in which datum fell on the border line is counted as 0.5.

When plates were thinner than 7/8 inch, 82 and 64 percent of the welds had sufficient energy to meet the requirements DS and D, respectively. However, only 55 and 25 percent of the welds in plates thicker than 1-5/16 inches met the same requirements. The data show an apparent loss of notch toughness in two-pass submerged-arc weld metals in heavier plates.

Figure 8 also shows the improvement in weld-metal notch toughness when bonded fluxes were used instead of conventional fused fluxes.* Excellent notch toughness was obtained by using a bonded flux specially developed for welding Grade E steel.

In the "FN process", which has been developed recently in Japan, a tubular flux-cored filler wire (the "FN wire") is fed into the molten pool of a submerged-arc weld using conventional electrode and flux as shown in Figure 9.[55] The FN wire contains various materials including deoxidizing agents and alloying elements for addition to the weld metal. These additions help in obtaining the desired weld-metal mechanical properties. Figure 9 shows the notch toughness of a single-pass weld metal in Grade E steel plates 1-1/4 inch thick. The notch toughness of the weld metal is excellent, almost passing the Class 3 requirement.

*The fused flux is made by fusing all ingredients into a glasslike material at a high temperature (around 2500 F) and then crushing the fused mass into granules. The bonded flux is made by baking the mixed ingredients at temperatures around 1400 to 1800 F.

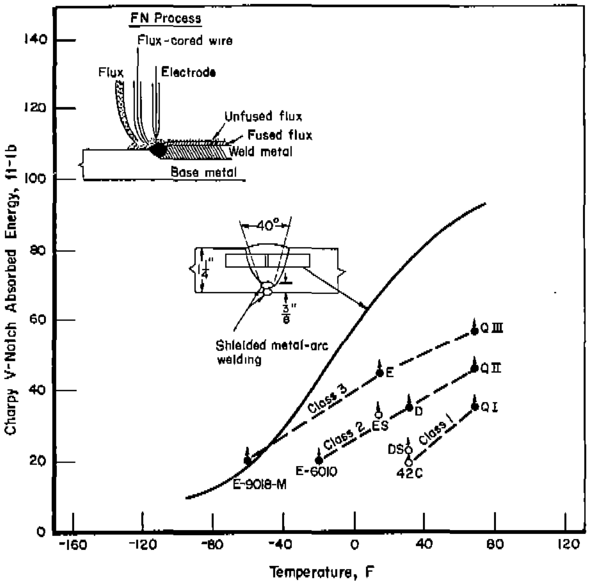


Fig. 9. *Notch toughness of single-pass "FN" process deposited metals in grade E steel plate 1-1/4 inches thick (Hotta, et al.*[55]*).*
Welding conditions: 1200 amperes; 38 volts; 7.5 ipm; feeding speed of the FN wire, 79 ipm.

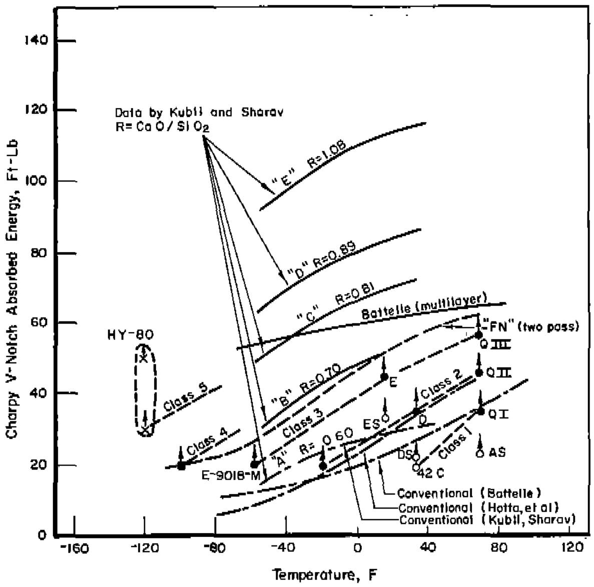


Fig. 10. Notch toughness of submerged-arc deposited metals in high-strength steels.

High-Strength Notch-Tough Steels

Many research programs have been and are being conducted for developing submerged-arc welding processes which provide weld metals with high strength and good notch toughness.[57-61]

A research program was conducted for the Bureau of Ships at Battelle Memorial Institute[62, 63] for developing fluxes and filler wires for submerged-arc welding of HY-80 steel. Figure 10 shows the Charpy V-notch transition curves of (a) the weld metal which had the best notch toughness and (b) a weld metal made with conventional wire and flux. The welds were made in 1/2-inch thick HY-80 steel plate by the multi-layer technique with heat inputs of 45,000 joules per inch of weld bead. The improvement of notch toughness is apparent. The yield strength of the experimental weld metal was over 90,000 psi.

The chemical composition (percent) of the experimental filler wire and the weld metals is given in the following tabulation:

Element	Experimental Filler Wire	Weld Metal from Experimental Filler Wire and Flux	Weld Metal from Conventional Filler Wire and Flux
Carbon	0.09	0.10	0.07
Manganese	1.12	0.62	0.81
Silicon	0.29	0.42	0.44
Nickel	2.02	2.13	2.15
Phosphorus	0.011	0.015	0.014
Sulfur	0.010	0.010	0.016
Molybdenum	0.50	0.50	0.32
Aluminum	0.085	0.027	-
Oxygen (total)	-	0.042	0.096

The oxygen content of the experimental weld metal was less than one-half that of the conventional weld metal. Microscopic investigations revealed that the experimental weld metal was significantly cleaner (with fewer inclusions) than the conventional weld metal. The investigators believed that the improvement in notch toughness was a result of the lower oxygen content and fewer inclusions in the experimental weld metal.

In addition, NRL drop-weight test specimens were taken from weld metals in the 1-inch-thick HY-80 steel plates welded in the experimental wire and flux. The nil-ductility transition temperature was -150 F.

Kubli and Sharav[64] reported the notch toughness of submerged-arc-deposited weld metals in quenched and tempered steels. Welds were made using calcium silicate fluxes A through E of the following composition:

	A, Fused	B, Bonded	C, Bonded	D, Fused	E, Fused
CaO, percent	23	30	34	40	44
SiO_2, percent	38	43	42	45	41
CaO/SiO_2, ratio	0.60	0.70	0.81	0.89	1.08

The CaO/SiO_2 ratios varied from a low of 0.60 for Flux A to 1.08 for Flux E. Flux A is a commercial, essentially "neutral", fused flux introduced for comparison purposes. Fluxes B and C were bonded fluxes. Figure 10 shows Charpy transition curves of weld metals made with these fluxes and a 0.5 percent molybdenum, 1 percent manganese, low-alloy steel wire. Impact properties improved with an increase of the CaO/SiO_2 ratio for the flux used. The yield strengths of the welds were about 60,000 psi in the stress-relieved condition. Further studies were made for developing wires providing higher strength; however, when the strength increased, notch toughness decreased.

Hotta, et al.[55] investigated the notch toughness of weld metals deposited by the "FN" submerged-arc process in HY-80 steel. Figure 10 shows Charpy curves for weld metals deposited in two passes in 1-inch-thick plates. The weld metal deposited with the FN process had notch toughness better than that deposited with a conventional flux and wire.

Figure 10 also shows that the transition curves for weld metals deposited with conventional fluxes and wires used in the three investigations discussed here coincide well, indicating that comparisons of data obtained in these investigations are valid.

2.3 Gas, Metal-Arc-Deposited Metals

Use of Gas, Metal-Arc Welding in Ship Hull Fabrication

In the gas, metal-arc welding processes, the electric arc between a metal electrode and the work is shielded by such gases as carbon dioxide and argon.[66] A bare wire is commonly used for the electrode, but flux-cored and magnetic-fluxed wires also are used. Various gas mixtures, including CO_2-O_2[67], CO_2-argon, argon-O_2, and argon-CO_2-O_2-N_2[68], also have been used for the shielding gas.

A new development in the gas, metal-arc process is the narrow-gap process being developed at Battelle Memorial Institute for the Bureau of Ships under Contract NObs-86424.[69] The distinguishing feature of the Narrow Gap welding process is the use of a very narrow, square-butt joint (with approximately 1/4 inch gap between plates) rather than conventional V- or U-groove joint preparations normally used for arc welding, as shown in Figure 11. The process is automatic and uses a mixture of argon and CO_2. Welding can be done in all positions.

The gas, metal-arc welding processes have not been widely used in the fabrication of ship hulls; however their potential use is promising. The argon-CO_2 and argon-O_2 gas, metal-arc processes appear to be quite useful for welding high-strength notch-tough steels for at least two reasons:

(1) Weld metals deposited by these processes exhibit good notch toughness.

(2) Difficulties encountered in controlling moisture in the coating of low-hydrogen-type electrodes can be avoided.

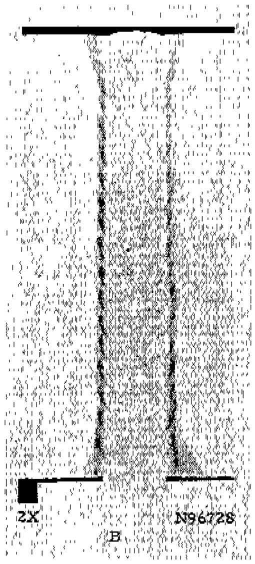


Fig. 11. The Battelle narrow-gap weld in a 2-inch thick HY-80 steel, single-wire weld, made in vertical position.

Notch Toughness of CO_2 and CO_2-O_2 Metal-Arc-Deposited Metals

Figure 12 shows the Charpy V-notch toughness behavior of weld metals deposited by the following processes:

(1) CO_2-shielded arc process using flux-cored (a) carbon-steel, and (b) alloy-steel wires[70]

(2) CO_2-O_2 metal-arc process developed by Sekiguchi, et al.[71], using low-carbon steel wires shielded by (a) 100 percent CO_2 and (b) 62 percent CO_2, 38 percent O_2.

(3) The Battelle Narrow Gap process, using 100 percent CO_2. Welds were made with A-632 filler wire in 1/2-inch thick HY-80 steel (refer also to Figure 13)[69].

The figure shows that the notch toughness of the CO_2 metal-arc-deposited weld metal is fairly good but not excellent.

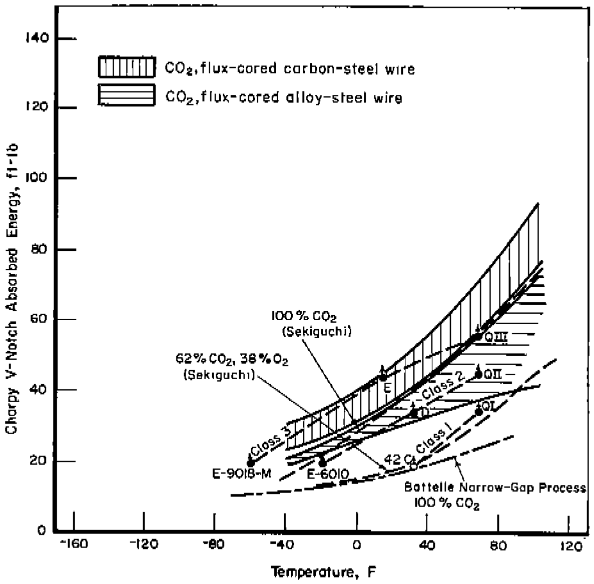


Fig. 12. Notch toughness of CO_2 and CO_2-O_2 metal-arch deposited weld metals.

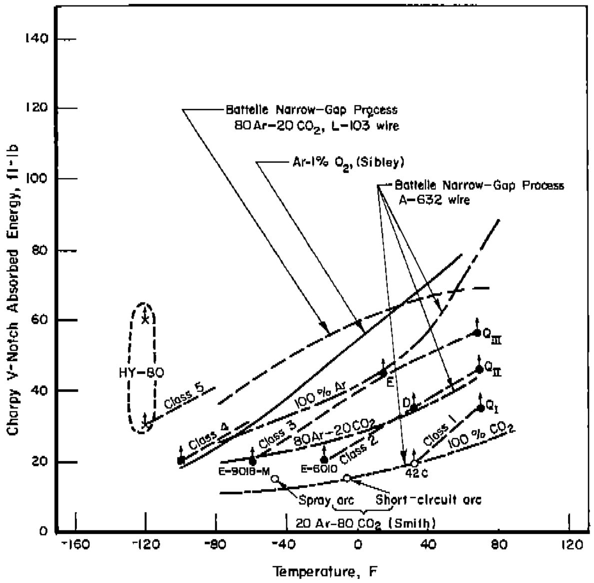


Fig. 13. Notch toughness of argon and argon-CO_2 metal-arc deposited metals.

Notch Toughness of Argon and Argon-CO_2 Metal-Arc-Deposited Metals

Figure 13 summarizes notch-toughness data for weld metals deposited by argon and argon-CO_2 metal-arc processes.[68, 69, 72-74]

Sibley[72, 73] reported that satisfactory mechanical properties were obtained in 1-inch-thick HY-80 steel welds made with a shielding-gas mixture of argon plus 1 percent oxygen and Mn-Ni-Mo-V filler metal. The chemical composition, in percent, of the filler wire and the weld metal was as follows[73]:

	C	Mn	P	S	Si	Ni	Mo	V	Cr	Cu	Ti
Filler metal[a]	0.073	1.22	0.018	0.018	0.41	1.18	0.47	0.11	0.15	0.023	0.04
Weld metal	0.093	0.96	0.016	0.023	0.32	1.41	0.43	0.17	0.25	0.15	<0.01

(a) MIL B-88 in specification MIL-E-19822A (SHIPS), electrolytically cleaned.

Notch toughness was over 20 ft-lb at -80 F. Yield strength was over 90,000 psi.

Salter[68] investigated the notch toughness of mild-steel welds made with a shielding gas of argon-20 percent CO_2-2 percent O_2-0.2 percent N_2. The Charpy V-notch, 15-ft-lb transition temperatures of as-deposited weld metals made with a short-circuiting arc and with a spray arc were -22 F and -45 F, respectively.

Figure 13 shows the notch toughness of weld metals made with the Battelle Narrow-Gap process while using the following filler wires and shielding gas mixtures[69]:

(1) A-632 filler wire and mixtures of CO_2 and argon (100, 20, and O percent argon)

(2) L-103 filler wire and a mixture of 80 percent argon and 20 percent CO_2.

The chemical composition (in percent) of the filler wires was:

	C	Si	Mn	Ni	Cr	Mo	V	Cu	Zr	Al
A-632	0.04	0.57	1.36	1.22	0.13	0.45	0.15	-	0.005	0.013
L-103	0.07	0.59	1.45	0.99	0.25	0.30	0.006	0.54	0.03	0.009

The notch toughness of weld metals made with A-632 filler wire improved as the percentage of argon increased. Excellent notch toughness was obtained when using L-103 wire and a mixture of 80 percent argon and 20 percent CO_2. Yield strengths of the weld metals were around 90,000 psi.

2.4 Electroslag- and Electrogas-Deposited Metals

Use of Electroslag and Electrogas Welding in Ship-Hull Fabrication

Electroslag welding, an automatic process for fusion welding metals in the vertical position, was introduced in the U.S.S.R.[75-78] In electrogas welding, which was developed in West Germany, flux-cored wire is fed into an arc shielded by CO_2 gas or other gases, depending on the type of base metal.[79]

Electroslag and electrogas welding processes are most suitable for the joining of plates thicker than 2 inches. The use of these processes in the fabrication of ship hulls has been negligible. However, there has been interest in the application of these processes in some particular portions of a ship hull, such as vertical butt joints between the shell plates of a large tanker.[80-82] Crosswell[80] reported the present position and attitude of classification societies toward the use of electroslag welding. Societies in some countries accepted only normalized welds for pressure vessels, while other societies accepted nonnormalized welds for some applications.

Notch Toughness of Electroslag- and Electrogas-Deposited Metals

Notch toughness data for electroslag- and electrogas-deposited metals appear in a number of articles.[76-78, 81-90] Direct comparisons of test data are difficult, since most Russian investigators used 2-mm-deep U-notch Mesnager specimens, while Charpy V-notch or keyhole specimens were used by American, Western European, and Japanese investigators.

Figure 14 summarizes notch-toughness data for electroslag-deposited metals in the as-welded condition, as follows:

(1) A region for data obtained by Thomas[77] on welds in 3-inch-thick low-carbon, 1.8 percent Mn, 0.3 percent Mo steel plates.

(2) Data obtained by Danhier[78] on killed-steel plates 1-1/4 and 5 inches thick.

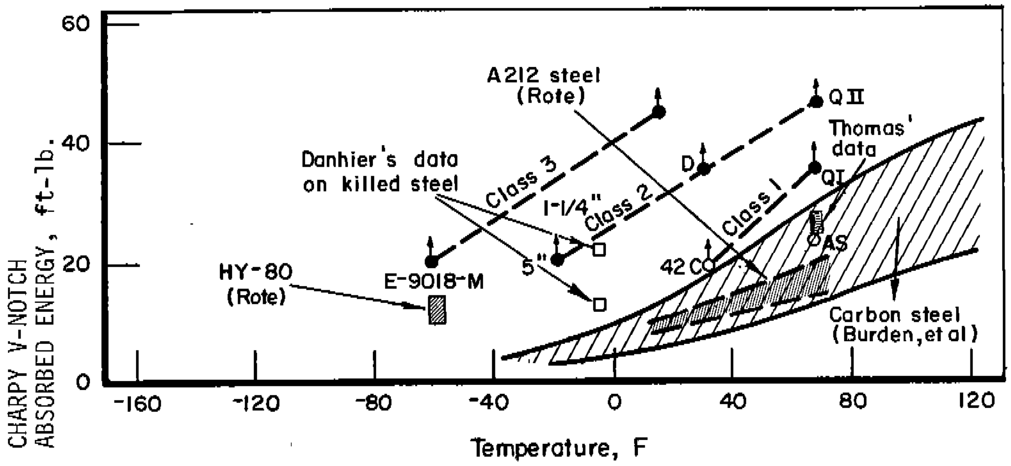


Fig. 14. Notch toughness of electroslag deposited metals in as-welded condition.

(3) A band for welds in three carbon-steel plates 5/8 inch thick, after Burden, et al.[81]

(4) Bands for data obtained by Rote[83] on welds in:
  (a) Carbon-steel A212 plates 3-3/4 inches thick
  (b) HY-80 steel plates 2-5/16 inches thick.

As shown in the figure, the notch toughness of electroslag-deposited weld metals in the as-welded condition is very poor.

Scatter of notch-toughness data for specimens taken from electroslag-deposited weld metal has been observed.[39] According to Santilhano and Hamilton[84], Charpy V-notch impact-test values at 14 F of specimens with various notch directions taken from various locations of a 7-inch-thick electroslag weld (0.11 C, 0.22 Si, 1.61 Mn, 0.021 S, 0.015 P, 0.44 Ni, 0.17 Cr, 0.19 Cu; the weld was normalized after welding) ranged between 22 and 64 ft-lb.

Efforts made to improve the notch toughness of electroslag-deposited metals have included addition of alloying elements, and applying vibration during welding to promote grain refining.[86]

It has been found that the notch toughness of electroslag-deposited metals can be improved by a proper heat treatment.[81, 83, 85] Figure 15 shows the improvement from heat treatment of the notch toughness of electroslag-deposited metals, as follows:

(1) Bands for data obtained by Burden, et al.[81] in 5/8-inch-thick carbon-steel welds in:
  (a) As-welded condition
  (b) Stress relieved for 1 hour at 1200 F
  (c) Normalized from 1740 F, then stress relieved for 1 hour at 1200 F.

(2) Bands for data obtained by Rote[83] in carbon-steel A212 welds 3-3/4 inches thick in:
  (a) As-welded condition

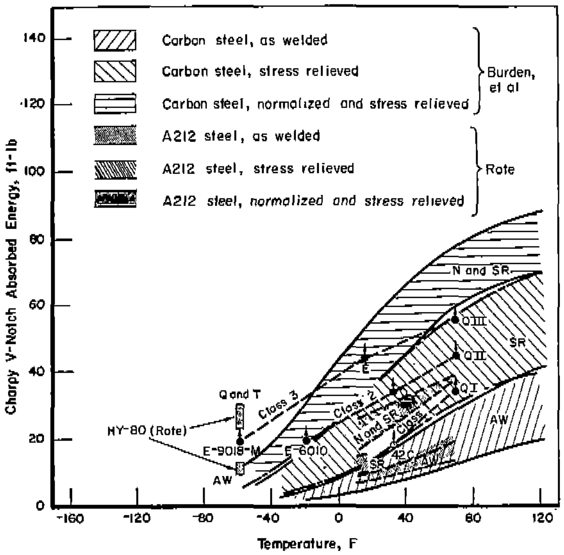


Fig. 15. Improvement through heat treatment of notch toughness of electroslag-deposited metals.

(b) Stress relieved at 1150 F and then furnace cooled
(c) Normalized from 1675 F, stress relieved at 1225 F, and air cooled.

(3) Bands for data obtained by Rote[83] in HY-80 steel welds 2-5/16 inches thick in:
(a) As-welded condition
(b) Water quenched and tempered.

2.5 Summary of Chapter 2

Table 2 illustrates the general trends in the notch toughness of weld metals deposited by various welding processes.

Weld metals which meet the Class 1 (QI-42C) requirement can be obtained with all welding processes listed except (1) when using E6012 and E6013 electrodes and (2) electroslag and electrogas processes (in the as-welded condition). Two-pass submerged-arc welding with conventional wire and flux in heavy plates may not meet the requirement unless proper procedures are used.

To meet the Class 2 (QII; Grade D; E6010) requirement, welding procedures should be selected as follows:

(1) Shielded metal-arc welding: E6010 electrodes can be used.

(2) Submerged arc welding: Multilayer procedures with conventional wire and flux may be used. For two-pass welding, special wire and flux must be used.

TABLE II. GENERAL TRENDS IN THE NOTCH TOUGHNESS OF WELD METALS DEPOSITED BY VARIOUS WELDING PROCESSES.

Classes In This Report	Class 1	Class 2	Class 3	Class 4	Class 5
Specifications	QI (35, 68 F)[(a)] 42 C (20, 32 F)[(a)]	QII (57, 68 F)[(a)] D (35, 32 F)[(a)] 6010 (20, -20 F)	QIII (57, 68 F)[(a)] E (45, 14 F)[(a)] 9018-M (20, -60 F)	8016-C2 (20, -100 F)[(a)]	HY-80 (30, -120 F)[(a)]
Shielded Metal-Arc Welding					
E6012, E6013	x	x	x	x	x
E6010	o	o	x	x	x
E9018-M, E11018-M	o	o	o	x	x
E8016-C2	o	o	o	o	x
Submerged-Arc Welding					
Conventional two pass	?	x	x	x	x
Conventional multilayer	o	o	x	x	x
Special technique	o	o	o	x	x
Gas Metal-Arc					
CO_2, CO_2-O_2	o	x	x	x	x
Argon, argon-CO_2	o	o	o	o ?	x
Electroslag, Electrogas					
As welded	x	x	x	x	x
Normalized	o	o	x	x	x

x Indicates that weld metal notch toughness does not meet the requirements of a Class.

o Indicates that weld metal notch toughness meets the requirements of a Class.

(a) Values in parentheses are charpy v-notch absorbed energy, ft-lb, at a temperature F. For example (35, 68 F) means 35 ft-lb at 68 F; refer to Table 1.

(3) Gas metal-arc welding: CO_2- and CO_2-O_2-shielded processes do not appear to meet the requirement, but argon and argon-CO_2 shielded processes will be satisfactory.

(4) Electroslag and electrogas welding: These processes may be used when welds are normalized.

Only selected welding processes deposit weld metals which meet the Class 3 (QIII; Grade E; E9018-M) requirement, as follows:

(1) Shielded metal-arc welding: Low-hydrogen low-alloy electrodes E9018-M, E10018-M, E11018-M, and E12018-M will deposit weld metals which can meet the requirement in the as-welded condition.

(2) Submerged-arc welding: Special techniques must be used.

(3) Gas metal-arc welding: Argon and argon-CO_2 (with high argon content) shielded processes must be used.

Weld metals which meet the Class 4 (E8016-C2) requirement can be deposited with only two processes at present.

(1) Shielded metal-arc welding: Low-hydrogen nickel-steel electrodes E8016-C2 and E8018-C2 will deposit weld metals which meet the Class 4 requirement in the stress-relieved condition.

(2) Gas metal-arc welding: Argon and argon-CO_2 (with high argon content)-shielded processes appear to be satisfying.

No welding process can be guaranteed to deposit weld metals as tough as HY-80 steel base metal. The most promising welding process in this respect is the inert-gas metal-arc process. The inert-gas tungsten-arc process also deposits weld metals with a high notch toughness; however, the low deposition rates involved make this process unattractive for the fabrication of ship hulls.

CHAPTER 3. EFFECTS OF VARIOUS FACTORS ON NOTCH TOUGHNESS

This chapter describes the effects on notch toughness of various factors, including (1) chemical composition and microstructure and (2) factors related to welding procedures.

3.1 Effects of Chemical Composition and Microstructure

Two major factors which determine the mechanical properties of metals are chemical composition and microstructure. The effects of chemical composition and microstructure on the notch toughness of base metals have been studied by many investigators.(91-95) Very few systematic investigations have been made of the effects of chemical composition and microstructures on the notch toughness of weld metals.

Effect of Chemical Composition

Most weld metals for joining low-carbon structural steels and low-alloy high-strength steels are low-carbon, low-alloy ferritic steels. They contain less than 0.2 percent carbon and such alloying elements as manganese, nickel, chromium, vanadium, and molybdenum in amounts less than 5 percent. Unintentional additions include sulfur, phosphorus, oxygen, and nitrogen.

Investigations of the effects of the chemical composition on notch toughness of weld metals have been made by investigators including Sakaki(96), Sagan and C Campbell(48), Dorschu and Stout(97), and Ohwa(98).*

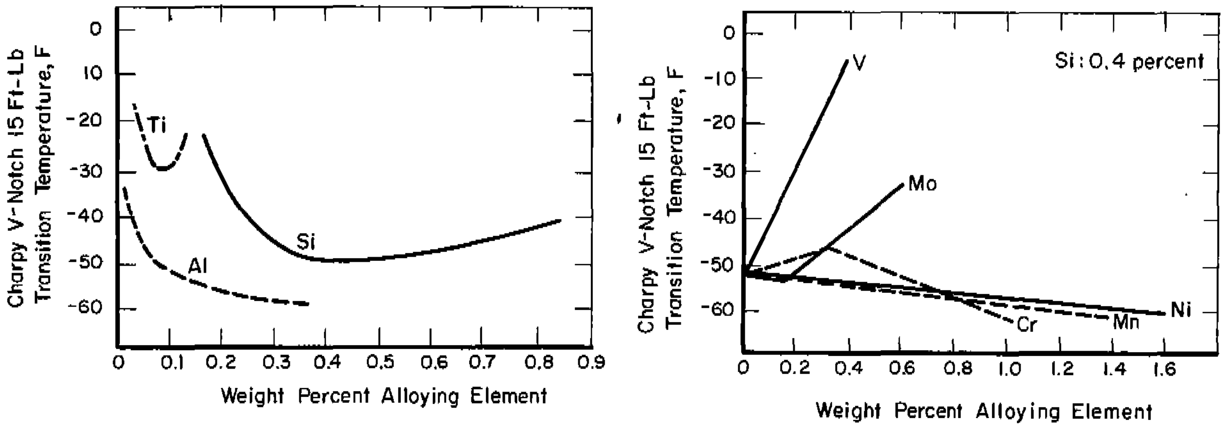
Sakaki(96) investigated the effects of alloying elements on the notch toughness of covered-electrode-deposited metals. Low-carbon, low-manganese core wires were covered with lime-fluoride-type coatings containing various amounts of alloying elements. Welds were made in the downhand position by the multilayer technique. Results are summarized in Figure 16, which shows the effects of alloying elements on the Charpy V-notch, 15-ft-lb transition temperature of the weld metal.

Ohwa(98) conducted a statistical investigation of the notch toughness of multilayer-weld metals deposited with commercial and experimental basic-type electrodes. The following formula was obtained to express the effects of alloying elements (in percent) and grain diameter on the Charpy V-notch, 15-ft-lb transition temperature, Tr_{15}:

---

*In an investigation for obtaining as-deposited weld-metals having yield strengths over 150,000 psi, Heuschkel(99) recently made an extensive study of the effects of alloying elements on the notch toughness of high-strength-steel weld metals. The results, however, are not discussed here, since the yield strengths of most weld metals studied exceeded the upper strength limit (120,000 psi) of this literature survey. Charpy V-notch energy values at 80 F were reported. These are difficult to compare with data obtained by other investigators expressed usually in terms of transition temperatures or energy values at a low temperature, say 32 F.

DMIC Report 172(100) describes background for the development of materials to be used in high-strength-steel structural weldments with a yield strength of 150,000 psi. The effects of chemical composition on the notch toughness of weld metals are discussed.



a. Silicon, Aluminum, and Titanium

b. Vanadium, Nickel, Manganese, Chromium, and Molybden um

Fig. 16. Effects of alloying elements on notch toughness of covered-electrode deposited weld metals (Sakaki [96]).

$$
\begin{aligned}
Tr_{15}(F) = {} & 436\ C - 54\ Mn + 14\ Si + 286\ P + 819\ S \\
& - 61\ Cu - 29\ Ni + 13\ Cr + 23\ Mo + 355\ V \\
& - 112\ Al + 1138\ N + 380\ O \\
& + 1.08\ (d \times 10^4) - 203 \pm 22, \qquad (1)
\end{aligned}
$$

where

d is grain diameter, inch (ranged 3.1 to 8.7 x 10^{-4} inch).
Ranges of alloying elements were: C, 0.03 to 0.11; Mn, 0.02 to 0.16; Si, 0.05 to 1.2; P, 0.004 to 0.17; S, 0.006 to 0.11; Cu, 0.05 to 0.3; Ni, 0.05 to 1.4; Cr, 0.05 to 2.6; Mo $\leq$ 1.2; V $\leq$ 0.31; Al $\leq$ 0.36; N, 0.004 to 0.02; O, 0.007 to 0.19.

Figure 17 shows a comparison between transition temperatures calculated from chemical composition by using the above formula and transition temperatures determined experimentally.

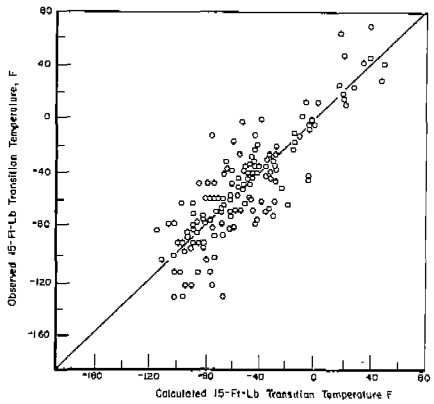
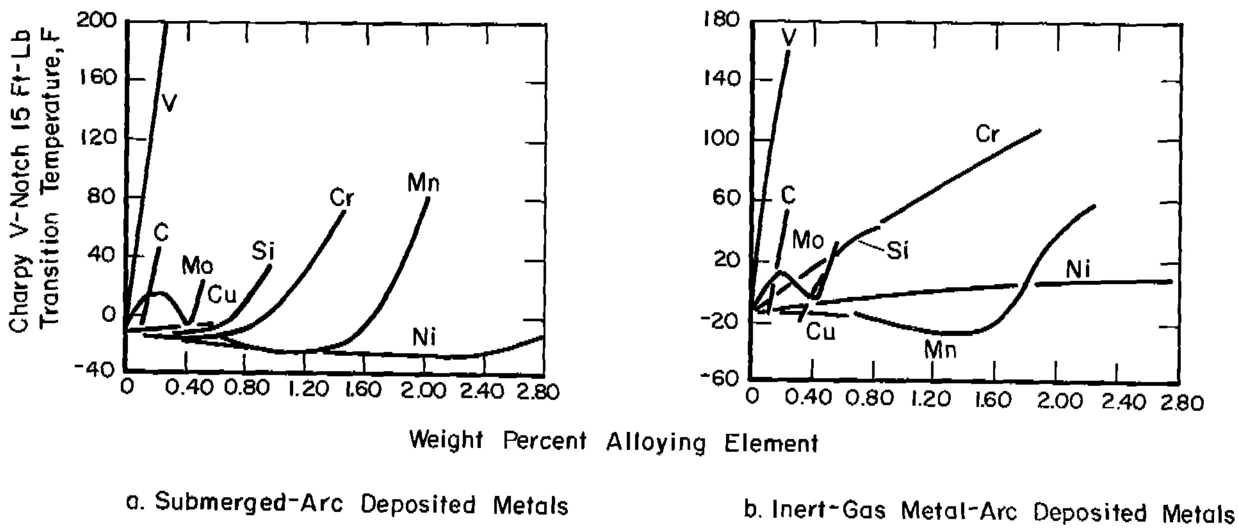


Fig. 17. Calculated versus observed Charpy V-Notch 15-ft-lb transition temperatures of multilayer weld metals (Ohwa [98]).

Dorschu and Stout(97) studied the effects of alloying elements on the notch toughness of submerged-arc- and inert-gas-deposited metals. Eight elements commonly found in weld metal were added singly to the weld deposit. Figure 18 shows the effects of these alloy additions on the Charpy V-notch, 15-ft-lb transition temperatures of submerged-arc- and inert-gas metal-arc-deposited metals.

The following paragraphs describe general trends in the notch toughness of weld metals related to individual alloying elements.

Carbon. Carbon added to weld metal is deleterious to notch toughness.(101) Equation (1) and Figure 18 indicate considerable increases in transition temperature with small increases in the carbon content of weld metals. Dorschu and Stout(97) found



Chemical composition of base metal, welding wire, and base weld metal:

	Submerged-Arc			Inert-Gas Metal-Arc		
	Base Metal	Welding Wire(a)	Base Weld Metal	Base Metal	Welding Wire(b)	Base Weld Metal
Carbon	0.16	0.10	0.12	0.16	0.09	0.12
Manganese	0.47	0.41	0.60	0.47	1.27	0.70
Silicon	0.10	0.01	0.30	0.10	0.54	0.35
Phosphorus	0.014	0.011	0.013	0.014	0.015	0.013
Sulfur	0.035	0.029	0.033	0.035	0.022	0.028
Copper	...	...	0.04	...	...	0.20

(a) Bare wire.
(b) Copper-coated wire.

Fig. 18. Effects of alloy additions on notch toughness of weld metals made with submerged-arc welding and inert-gas metal-arc welding (Dorschu and Stout(97)).

that as carbon was added a greater proportion of carbides was apparent in the structure. These findings are consistent with those of Rinebolt and Harris[102] on base metal. Sagan and Campbell[48] discussed in detail the effect of carbon on the notch toughness of covered-electrode-deposited weld metals.

Manganese. Sakaki[96] noted an improvement in the notch toughness of covered-electrode-deposited weld metals with increasing manganese up to 1.1 percent (the maximum Mn content used). Equation (1) also shows the improvement in the notch toughness of the weld metal with increasing manganese. These findings are consistent with those of Rinebolt and Harris[102] on base metal and of Zieglar, et al.[103] on cast carbon-manganese steels.

On the other hand, Dorschu and Stout[97] found no significant change in the notch toughness of the submerged-arc-deposited weld metal as manganese was increased from 0.6 to 1.6 percent, as shown in Figure 18a. Increasing manganese above 1.6 percent caused a rapid deterioration in notch toughness. Inert-gas metal-arc-deposited weld metal followed a similar trend with a deterioration in toughness when the addition increased beyond 1.80 percent.

Silicon. Sakaki found that the notch toughness of covered-electrode-deposited weld metal improved when silicon was increased from 0.2 to about 0.4 percent. An increase of silicon beyond about 0.4 percent caused a gradual decrease in notch toughness.

Dorschu and Stout found that silicon in amounts between 0.35 to 0.80 percent caused a general decrease in the notch toughness of inert-gas metal-arc deposited weld metals. In submerged-arc deposited weld metals, little effect of silicon was noted up to about 0.5 percent, but additions beyond this amount increased the transition temperature.

These results are generally similar to those reported by Rinebolt and Harris[102] and Ziegler, et al.[104]

Molybdenum. Additions of molybdenum up to about 0.5 percent increase the transition temperature of the weld metals, as shown in Figures 16 and 18. The influence of molybdenum on the notch toughness of weld metal appears to be complex when the amount exceeds about 0.5 percent.

Aluminum. Aluminum appears to improve the notch toughness of weld metals up to total aluminum contents of 0.05 to 0.1 percent. Additions above this level raise the transition temperature. The apparent effect of aluminum is probably a result of the deoxidizing effects of this metal.

Vanadium. Additions of vanadium greatly increase the transition temperature of weld metal. Similar trends on notch toughness were noted by Rinebolt and Harris[102] and Ziegler, et al.[105] Vanadium increases the susceptibility to stress-relief embrittlement of high-strength-steel weld metals.

Chromium. Available data showing the effect of chromium on the notch toughness of weld metal is conflicting. Sakaki found that the Charpy V-notch 15-ft-lb transition temperature of covered-electrode-deposited weld metal increased slightly with the addition of chromium up to 0.4 percent and then decreased as the chromium content increased to about 1 percent, as shown in Figure 16b. Dorschu and Stout, on the other hand, found that additions of chromium up to about 1.6 percent caused a progressive increase in the transition temperature of submerged-arc-deposited metals and inert-gas metal-arc-deposited metals, as shown in Figure 18.

The direct effect of chromium additions is obscured by the effect of this element on the response of the weld metals to changes in thermal cycles. The following tabulation shows this effect on a 2-1/2 percent chromium weld metal[100]:

Preheat Temperature, F	Postheat Temperature, F	Transition Temperature, F
None	None	34
300	None	34
300	1300	-30

It is probably safe to assume that if the chromium content of a weld metal is more than about 0.5 percent, the transition temperature will be greatly dependent on the thermal cycle to which the weld metal is subjected.

Nickel. Available data showing the effect of nickel on the notch toughness of weld metal is conflicting. Sakaki found that the Charpy V-notch, 15-ft-lb transition temperature of covered-electrode-deposited weld metal decreased slightly with the addition of nickel to 1.5 percent. Dorschu and Stout found that the addition of nickel up to about 2.4 percent caused a slight decrease of the transition temperature of submerged-arc-deposited metals but it caused a slight increase of the transition temperature of inert-gas metal-arc-deposited metals.

DMIC Report 172 also reports that there is confusion about the effects of nickel additions on the notch toughness of weld metals. There are useful 100,000-psi-yield-strength weld metals containing as little as 1 percent nickel and as much as 3 percent nickel. According to the AWS specification, weld metals deposited with E8016-C1 and E8016-C2 electrodes contain 2 to 2.75 and 3 to 3.75 percent nickel, respectively. As shown in Table 1, the weld metal deposited by these electrodes is tougher than weld metal deposited with any other type of electrode.

Copper. Dorschu and Stout found that the effect of copper additions up to 0.5 percent on the weld-metal notch toughness was not significant for submerged-arc and inert-gas metal-arc process. Smith[106] found that 0.4 percent copper in CO_2-gas metal-arc-deposited metals slightly reduced notch toughness.

Oxygen and Nitrogen. Both oxygen and nitrogen are known to decrease the notch toughness of weld metals. Many investigators have reported improvements in the weld-metal toughness when oxygen and nitrogen contents were reduced.[56, 63, 64, 107]

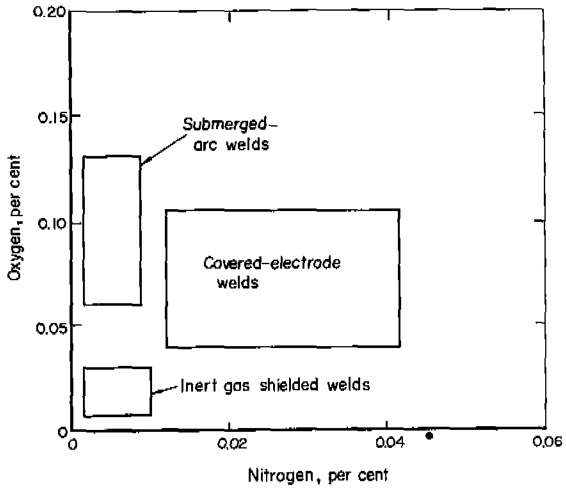


Fig. 19. Oxygen and nitrogen content of mild-steel welds made by three arc-welding processes.

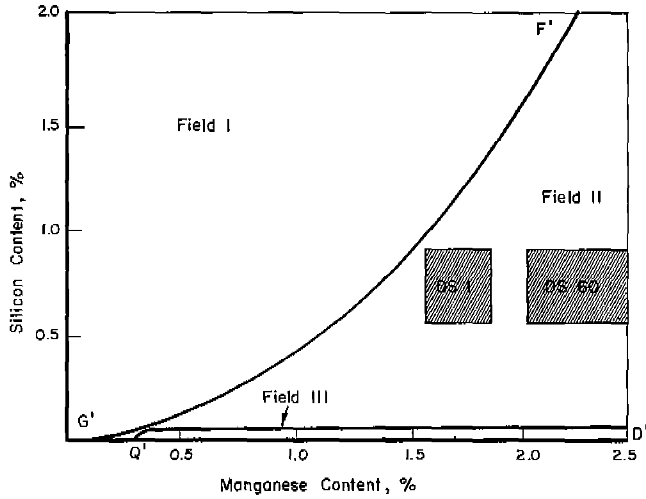


Fig. 20. Manganese and silicon contents in welding filler metal (Sekiguchi[67]).

Figure 19 shows the oxygen and nitrogen levels that can be expected in welds made with different welding processes. The figure indicates that the inert-gas metal-arc process provides the lowest oxygen and nitrogen contents. Consequently weld metals deposited by this process would be expected to exhibit better notch toughness than would weld metals deposited by other processes. Reported experience generally confirms this expectation.

Chemical Reactions in Molten Weld Metal

Many investigators have used the principles of steelmaking as a guide in developing filler wires, electrode coverings, and submerged-arc fluxes.[108, 109]

Sekiguchi[67], in an experimental and theoretical investigation, proposed that the manganese and silicon contents of a welding wire be located in Field II of Figure 20.[110, 111] When the Mn-Si contents are located in Field II, the FeO-MnO-SiO_2 liquid solution is unsaturated with SiO_2; thus, deoxidation products can float off to the surface of the molten metal and leave in clean, sound weld metal. Sekiguchi's theory has been applied in Japan to the design of filler wires for the shielded metal-arc and CO_2-O_2 metal-arc process. Figure 20 also shows the ranges of Mn and Si contents of Japanese filler wires DS 1 and DS 60.

Effect of Microstructure

Weld metals are basically cast structures. Since the rather low heat input of welding produces a high cooling rate, grains in the weld metal are rather fine if the weld is considered as a casting. In multipass welding, those structures in areas adjacent to subsequent weld passes are recrystallized to form finer and equiaxed grains. The fine-grained recrystallized structures exhibit notch toughness superior to that of coarse-grained as-cast structures. Many research programs have been carried out to establish welding procedures which would produce weld metals with a favorable microstructure. However, there has been little information published about how microstructures quantitatively affect the notch toughness of weld metals.

Effect of Grain Size. Published information is available on the effect of grain size on the notch toughness of weld metals. Equation (2) shows how the Charpy V-notch, 15-ft-lb transition temperature of covered-electrode-deposited weld metal increases with an increase in the grain diameter.

According to Petch(112), a relationship between the grain diameter and the transition temperature of a ferritic material can be expressed as follows:

$$T = A - B \log_e (d^{-1/2}) \qquad (2)$$

where

T is the transition temperature
A and B are constants
d is the mean grain diameter.

Garstone and Johnston(39) investigated the effects of grain size on the notch toughness of carbon-steel weld metals made with four types of covered electrodes. Welds were made with different preheat and interpass temperatures to produce different grain sizes in the deposited metals; some weld metals were normalized to produce further grain-size modifications. All welds were stress relieved before Charpy V-notch specimens were machined. Equation (2) was found to hold true for normalized weld metals. The weld metals made with a 68 F interpass temperature had higher transition temperatures than the values predicted by Equation (2). The investigators explained that this discrepancy was caused by excessive amounts of unrefined structures in the cross section of the Charpy specimens.*

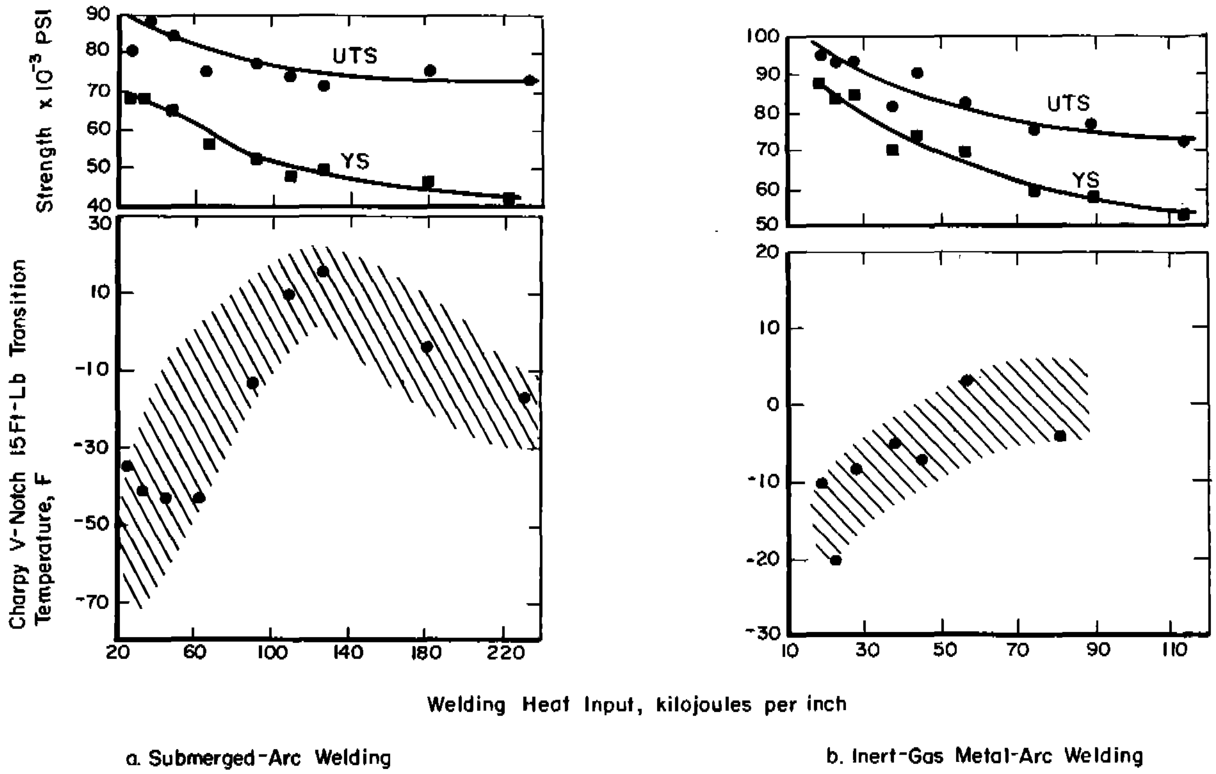
Electron Microscopic Study of Fractures in Weld Metals. In the past few years, significant information regarding the micromechanism of various types of fracture has been obtained with electron microfractography, the examination of fracture surfaces at high magnification by means of the electron microscope.(114, 118-121) It has been found that fractures produced by different mechanisms or in different ways have characteristic appearances when viewed under the electron microscope. A cleavage fracture in a metal is characterized by a pattern called the "river pattern". A ductile fracture has a characteristic appearance consisting of roughly elliptical domains which have been termed "ductile dimples". However, no systematic investigations have been reported on the electron micrographic study of fractures of weld metals.

3.2 Effect of Welding Procedures

Welding-Heat Input

Dorschu and Stout(97) investigated the effect of welding-heat input on the notch

*It has been shown by theoretical and experimental investigations that the yield stress of an annealed iron alloy increases proportionally to the inverse of the square root of the grain diameter ($\sigma_y = \sigma_o + k\, d^{-1/2}$).(113, 114) Several investigators(39, 115-117) have reported that weld metals with fine-grain structures showed greater increases in the yield stress than predicted by the above relationship.



The average chemical composition of weld metals:

	C	Mn	Si	P	S
Submerged-Arc Weld Metal[a]	0.09	1.40	0.34	0.014	0.023
Inert-Gas Metal-Arc Weld Metal[b]	0.08	0.90	0.37	0.011	0.018

(a) The base plate was A201.
(b) The base plate was A212.

Fig. 21. Effect of welding-heat input on notch toughness and strength of submerged-arc and inert-gas metal-arc weld metals (Dorschu and Stout[97]).

toughness of submerged-arc and inert-gas metal-arc welds deposited in a groove (90-degree vee, 5/8 inch deep) in low-carbon-steel plates 3/4 inch thick. Figure 21 shows the Charpy V-notch, 15-ft-lb transition temperatures of these weld metals.

In the submerged-arc-deposited metals, the transition temperature increased to a maximum at a heat input of about 120 kilojoules per inch and decreased slightly as the energy was further increased to 231 kilojoules per inch, as shown in Figure 21a. In the inert-gas metal-arc-deposited welds, the transition temperature progressively increased with an increase in the heat input up to 81 kilojoules per inch (the maximum studied), as shown in Figure 21b. With increasing heat input, the yield and ultimate tensile strengths decreased, as shown in Figures 21, and elongation and reduction of area increased. The investigators concluded that the loss in notch toughness with increasing heat input was associated with coarsening of the microstructure. The increase in heat input caused a decrease in the cooling rate resulting in coarsening of the microstructure. The investigators explained that the slight improvement in notch toughness of the submerged-arc-deposited weld metal deposited at the higher heat-input levels was due to a reduction in strain aging caused by a reduction in restraint.

Yoshida, et al.[60] investigated the effect of welding-heat input on submerged-arc-deposited metals in 1-inch-thick high-strength steel plates (ultimate tensile strength: 122,000 psi). Welds were made in two passes, using a bonded flux containing manganese, nickel, and molybdenum. Notch toughness of the deposited metal decreased slightly as the heat input increased from 13 to 36 kilojoules per inch; at the same time, the notch toughness of the fusion zone decreased significantly.

Multilayer Welding Techniques

The notch toughness of weld metal generally improves with an increase in the number of passes as shown earlier in Figure 7 for submerged-arc welding. It is believed that a stringer-bead technique generally produces weld metals with better notch toughness than that of welds produced by a weaving-bead technique. The reasons for the improvements in notch toughness are believed to be as follows:

(1) As the number of layers or passes increases, a lower heat input is usually used, resulting in finer grains

(2) As the number of layers of passes increases, the grain refining action of each subsequent pass becomes more effective in forming a network of grain-refined zones.

The extent of the effect, however, depends greatly on the chemistry of the weld metal, the welding process, welding position, and other factors.

Welding Position

Information obtained in published articles generally agrees that the notch toughness of the weld metal is subject to a degradation approximately in the following order of welding positions: flat, horizontal or overhead, and vertical.[9, 34, 46, 48]

Preheat

It has been common knowledge that increasing the preheat and interpass temperature improves the fracture behavior of many weldments, primarily due to softening of the heat-affected zone. However, as far as the notch toughness of the weld metal is concerned, preheat does not always have favorable effects.[48, 122, 123]

Sagan and Campbell[48] stated that preheating has a decidedly beneficial effect only on certain mild-steel and low-alloy-steel weld metals which are low in tensile strength (Ni-alloyed weld metals for example). They reported a case in which the transition temperature of a weld metal made with E7018 electrodes decreased as much as 75 F with the use of 300 F preheat and a favorable (in this case) full-weave welding technique.

In low-alloy, high-strength-steel weld metals, the effect of preheat varies with such factors as coating design and the weld-metal analysis. Sagan and Campbell[48] reported that an increase of preheat and interpass temperature from 100 to 300 F caused little change in notch toughness of the weld metal made with a E9018 electrode. The influence of preheat is more complex for some electrodes sensitive to stress-relief embrittlement.

Postweld Heat Treatments

Postweld heat treatments used in the fabrication of welded structures are classified as follows:

(1) Local heating employed shortly after welding

(2) Stress-relieving heat treatment made at a temperature below the A_1 temperature

(3) Normalizing and full annealing by heating above the A_1 temperature

(4) Quench-and-tempering and other special heat treatments.

This section discusses mainly the effects of a stress-relieving heat treatment on the notch toughness of the weld metal, since embrittlement due to stress relieving has been noticed on weld metals, especially on alloy-steel weld metals.

Ohwa(124) investigated the effect of stress-relieving heat treatments (including some above the A_1 temperatures) on the notch toughness of carbon- and alloy-steel weld metals. Studies were made on electrodes of seven types: ilmenite*, cellulose, iron oxide, titania, low hydrogen (Mn-Si steel wire), low hydrogen (Mn-Si-Cr-Mo steel wire), and iron powder. Butt welds 5/8 inch thick were heat treated for 1 hour at temperatures between 1110 and 1830 F and then furnace cooled. The yield strengths of the as-deposited weld metals ranged between 50,000 and 92,000 psi.

Figure 22 shows changes in the Charpy V-notch, 15-ft-lb transition temperatures of these weld metals. The heat treatments caused losses in the notch toughness of weld metals made with electrodes other than the low-hydrogen types, especially when the heating temperature exceeded the A_1 temperature. The heat treatments caused rather little change in the notch toughness of weld metals made with low-hydrogen-type electrodes; even slight improvement was observed in some cases. When the heating temperature exceeded the A_1 temperature, a marked increase in grain size was observed in the weld metals made with all types of electrodes.

Sagan and Campbell(48) investigated the stress-relief embrittlement of both carbon- and alloy-steel weld metals. They reported that weld metals which undergo secondary hardening (increasing the tensile strength) embrittle most after stress relief, whereas an improvement in notch toughness can be expected when the tensile strength decreases significantly after stress relief. Vanadium is known to promote secondary hardening and stress-relief embrittlement. Sagan and Campbell reported that the Charpy V-notch transition temperature of a weld metal made with E10016 electrodes of Ni-Mo-0.1V wire increased by about 40 F after stress relieving for 2

*The ilmenite type electrode uses flux containing ilmenite (iron titanate) as the major ingredient. Ilmenite-type electrodes are commonly used in Japan for all-position welding in ships and other structures.

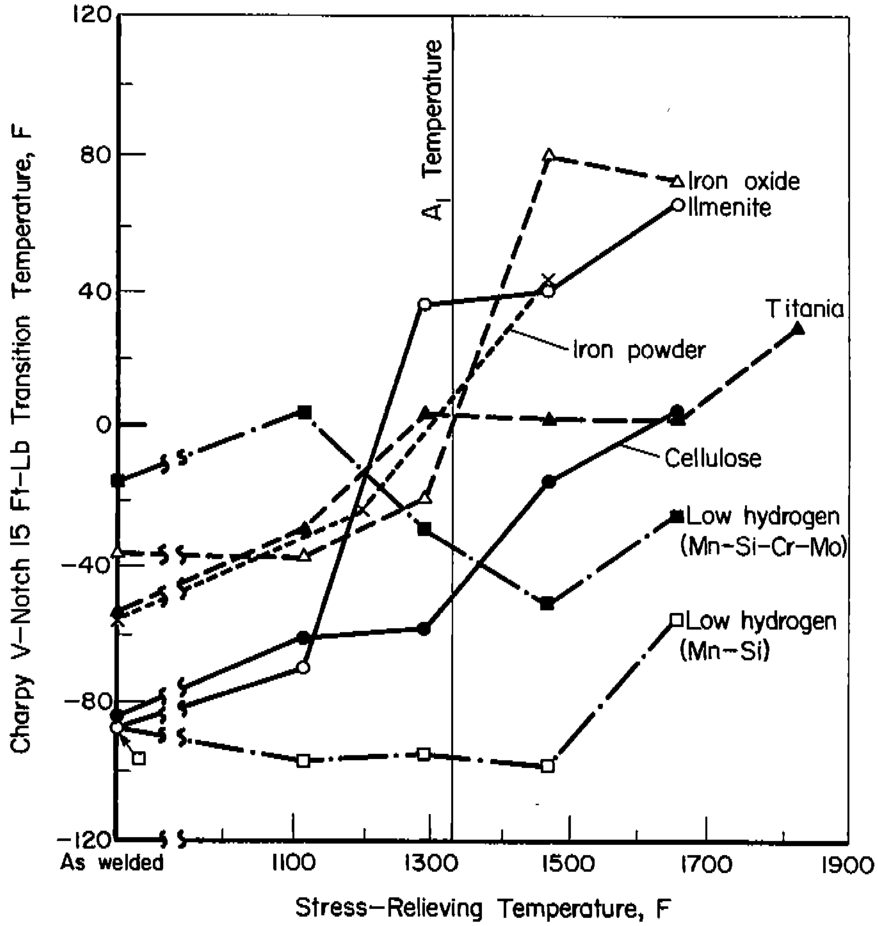


Fig. 22. Effect of stress relieving on the notch toughness of of weld metals deposited with various types of electrodes (Ohwa [124]).

hours at 1150 F, while the notch toughness of a weld metal made with similar electrodes of vanadium free wire was barely affected by the stress-relieving heat treatment.

Peening

Peening is sometimes used to minimize distortion and residual stresses due to welding. Results of investigations conducted so far generally agree that peening which involves severe plastic deformation of weld metal is detrimental to notch toughness.[3, 125].

3.3 Summary of Chapter 3

On the basis of the limited information available, it has been found that the effects of the chemical composition and the microstructure on notch toughness are roughly the same in weld metals and in base metals. Alloying elements which are generally deleterious to notch toughness include carbon, sulfur, phosphorus, molybdenum, vanadium, oxygen, and nitrogen. Additions of manganese and aluminum up to certain amounts are believed to improve notch toughness. Notch toughness is improved when grains become smaller. However, there are some differences in the ways in which the chemical composition and microstructure affect the notch toughness of base metal, which is a rolled material, and weld metal, which is a cast material. It is believed that major factors which cause observed differences in weld-metal notch toughness are differences in the distribution of nonmetallic inclusions and such minor elements as oxygen and nitrogen, which are not determined in many chemical analyses. Systematic investigations are needed on the effects of the chemical composition and the microstructure on the notch toughness of weld metals made by various welding processes.

How a change in the welding procedure affects the notch toughness of the weld metal depends on how the microstructure and the chemical composition are changed. Therefore, the effects of welding procedures on the notch toughness of weld metals depend greatly on the composition of the filler and the base metal and on the welding process. In general, weld metals deposited with a low heat input and in many passes have better notch toughness than those made with a high heat input and in few passes. Preheating has a beneficial effect on the notch toughness of weld metals in carbon steel; the effect of preheating on notch toughness is complex in weld metals in alloy steels. Stress-relieving heat treatment causes complex embrittlement effects in weld metals in some alloy steels. Peening of the weld metal is known to be detrimental to notch toughness.

CHAPTER 4. NOTCH TOUGHNESS OF THE HEAT-AFFECTED ZONE EVALUATED WITH CHARPY IMPACT-TEST SPECIMEN

Numerous research programs[4, 5, 18, 126, 127] have been carried out to study:

(1) Cracks in the heat-affected zone

(2) Hardenability of the heat-affected zone

(3) Weldment fractures initiating from the heat-affected zone and propagating into the base metal. (Fracture tests of weldments are discussed in Chapter 5.)

Only rather limited information has been obtained on the notch toughness of the heat-affected zone. This chapter describes notch-toughness evaluations with Charpy impact-test specimens from the heat-affected zone. The following subjects are covered:*

(1) Techniques for evaluating the notch toughness of the heat-affected zone

(2) Notch toughness of the heat-affected zone in mild steel

(3) Notch toughness of the heat-affected zone in high-strength steels.

4.1. Evaluation of the Notch Toughness of the Heat-Affected Zone

Since the heat-affected zone is a narrow zone composed of many areas with different structures, special techniques have been used for studying the notch toughness of the heat-affected zone.

Charpy Specimens Taken From a Weldment

A commonly used technique is to prepare Charpy V-notch specimens from a weld, locating the apex of the notch in particular microstructures. A single-J or a double-J groove weld is often used to produce a fusion line perpendicular to the plate surface, and the notch is placed parallel to the fusion line.

Evaluation of the Notch Toughness of the Weld Metal and the Heat-Affected Zone Simultaneously

Hatch and Hartbower[130, 131] conducted Charpy V-notch impact tests in which properties of the weld metal and the heat-affected zone could be evaluated simultaneously. Charpy specimens were prepared from a bead-on-plate weldment in such a

*Since electroslag and electrogas welding employ high heat inputs, the notch toughness of the heat-affected zone is sometimes damaged.[78, 79, 128, 129] However, discussion of the notch toughness of the heat-affected zone in electroslag and electrogas weldments is not included in this report, because these processes deposit weld metals with such poor notch toughness that they are not likely to be used extensively in ship-hull construction.

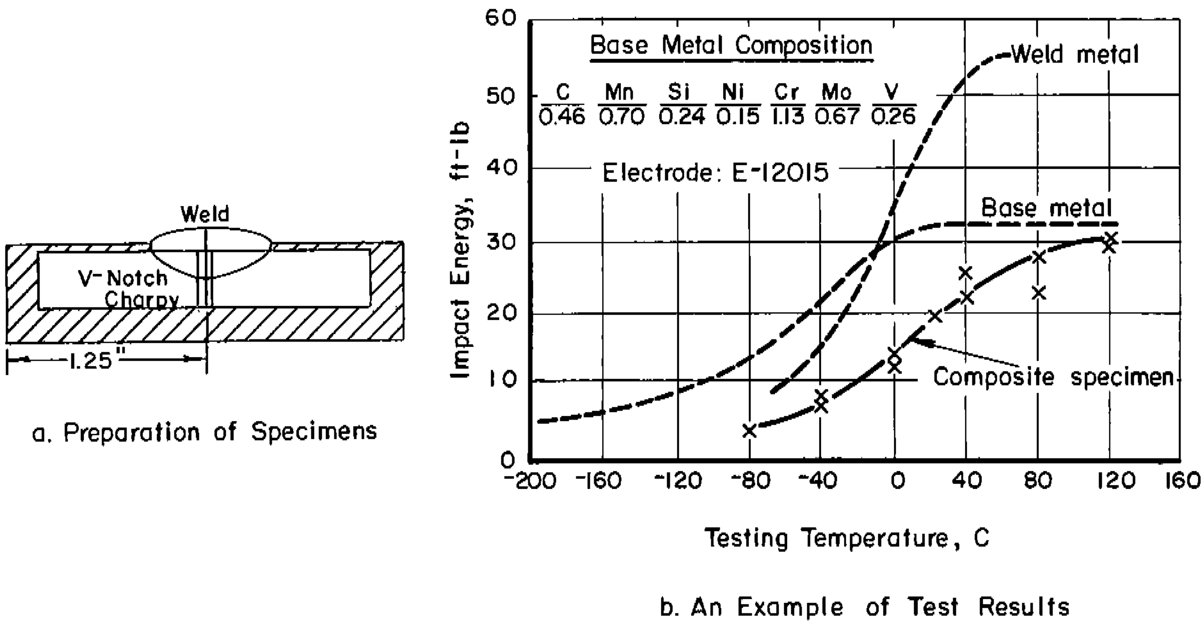
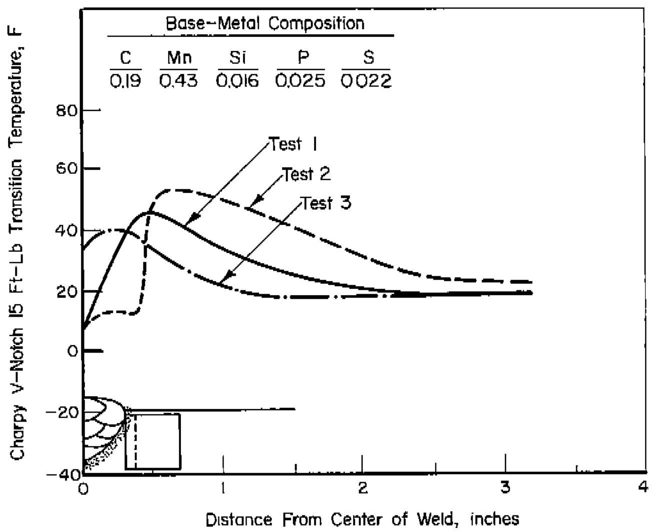


Fig. 23. V-notch Charpy impact testing of weld metal and heat-affected zone simultaneously (Hatch and Hartbower[130]).



Welding conditions:

Test	Welding Method	Shape of Groove	Welding Current, amperes	Welding Speed, in. /min
1	Shielded metal-arc	60°V, 0.35" deep	160	8.0[a]
2	Submerged-arc	60°V, 0.16" deep	600	11.5
3	Submerged-arc	60°V, 0.12" deep	500	34.0

(a) For each pass.

Fig. 24. Distribution of Charpy V-notch 15-ft-lb transition temperatures in groove welds in 1/2-inch-thick mild-steel plates made with shielded-metal-arc and submerged-arc processes (Kihara, et. al.[137]).

way that the path of fracture traversed equal portions of weld metal and heat-affected base metal, as shown in Figure 23a. Figure 23b shows results for a weld made with E12015 electrodes on a quenched and tempered steel(130); the composite specimens showed notch toughness inferior to that of the weld metal and the unwelded base metal. Relative locations of the three transition curves varied as the properties of the weld metal, base metal, and the heat-affected zone changed.

Synthetic-Specimen Technique

The synthetic-specimen technique, which was originated by Nippes and associates(132, 133) at the Rensselaer Polytechnic Institute, has been used for evaluating the notch toughness of specific heat-affected structures. A specially designed temperature-control device is used to reproduce in Charpy blanks the thermal cycle associated with the microstructure at any desired location in a weld-heat-affected zone. Several sets of such specimens, each set containing a single heat-affected-zone structure, are then tested over a range of temperature to obtain transition curves of the several structures under investigation.

Toughness Requirements of Specifications

No ship-classification-society specification covers explicitly the notch toughness of the heat-affected zone, but several specifications cover the following factors to secure a heat-affected zone with acceptable properties(5, 126):

(1) Maximum welding-heat input

(2) Maximum hardness of the heat-affected zone of a weldment made under certain welding conditions

(3) Maximum value of carbon equivalent of the base metal.

For example, the U. S. Navy specifies in NAVSHIPS 250-637-3 a maximum heat input of 45, 000 joules per inch for welding HY-80 steel plates less than 1/2 inch thick, and 55, 000 joules per inch for thicknesses 1/2 inch and greater. The requirements for the maximum hardness and carbon equivalent are aimed at preventing weld cracking rather than obtaining a heat-affected zone with desirable notch toughness.

4.2 Heat-Affected Zone in Mild-Steel Weldments

Many investigators (4, 5, 134-140) studied the notch toughness at various locations of a welded joint. In most cases Charpy-impact specimens were used; however, other specimens, including notched-bar tensile or bending specimens, also have been used. Figure 24 shows distributions of the Charpy V-notch 15-ft-lb transition temperatures in 1/2-inch-thick mild steel welds made by shielded metal-arc and submerged-arc processes.(137) Transition temperatures were high in areas 0.4 to 0.6 inch from the weld center, somewhat outside the heat-affected zone. The maximum temperature of the embrittled zone attained during welding was 750 to 930 F.

Nippes and Savage(132) first used the synthetic-specimen technique to investigate the notch toughness of the heat-affected zone. Bars (0.4 by 0.4 by 3 inches) which were machined from aluminum-killed steel plates were heated and then cooled to duplicate several of the heat-affected structures in a 1/2-inch-thick butt joint. Fracture tests were made on Charpy V-notch specimens prepared from the bars. Specimens which exhibited low impact properties were those which represented a region well outside the zone normally considered the heat-affected zone. The investigators suggested that the embrittlement was attributable to a strain-aging reaction.

The above investigations show that notch toughness is the lowest in areas well outside the zone usually considered the heat-affected zone. This embrittled zone, however, has not been considered important in the brittle fracture of welded structures. Brittle fractures do not initiate from the embrittled zone, nor do they propagate through the embrittled zone.

4.3 Heat-Affected Zone in High-Strength-Steel Weldments

Research programs have been carried out to study the notch toughness of the weld-heat-affected zone in various high-strength steels.(5, 141-145) In general, the loss of notch toughness has been noted in two regions: (a) the fusion zone and (b) the coarse-grained heat-affected zone. However, the extent of losses in notch toughness varies greatly, depending on the type of steel (composition and heat-treatment conditions) and the welding thermal cycle. There has been much interest during the last decade in heat-treated high-strength steels such as quenched and tempered steels. Since the high-strength and excellent notch toughness of these steels are obtained by heat treatments, the welding thermal cycle may cause losses in both strength and notch toughness in areas adjacent to the weld. The effects become greater with increased welding-heat input.

Kobler(146) investigated the notch toughness of the heat-affected zone of butt welds in quenched-and-tempered steel plates 1/2 inch thick. The chemical composition (percent) of the base metal was:

C	Mn	Si	S	P	Ni	Cr	Mo	V	B
0.13	0.69	0.14	0.04	0.017	0.87	0.50	0.48	0.06	0.0046

The minimum required yield strength of the steel was 90,000 psi. Welds were made with five electrodes of E11015, E11018, and E12016 types. The joints were restrained during welding with a 2-inch-thick plate. The welds were subsequently stress relieved at 1100 F for 2 hours. Figure 25 shows bands for the transition curves of (1) the weld metals, (2) heat-affected zones, and (3) fusion zones. The transition curve for the base metal also is shown. Figure 25 shows the following:

(1) Notch toughness of the heat-affected zone was comparable with that of the base metal

(2) Notch toughness of the fusion zone was considerably below that of the base metal.

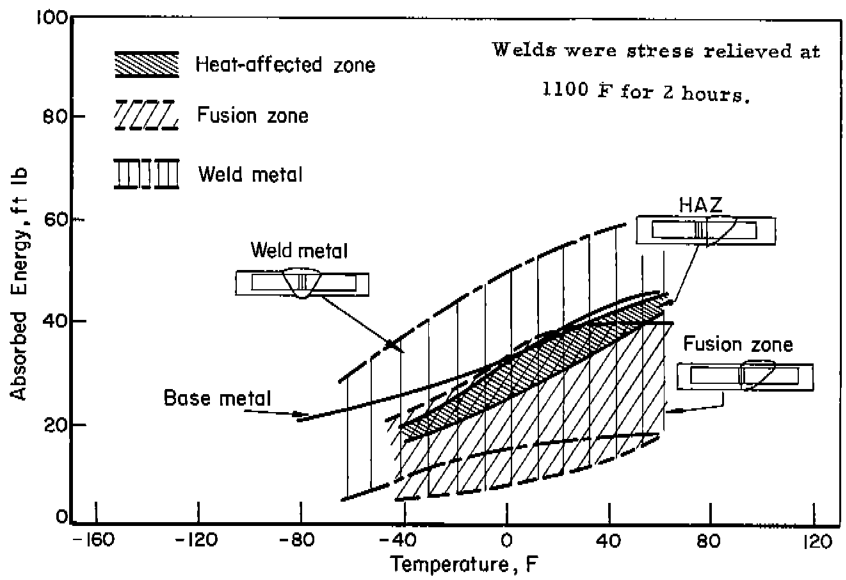


Fig. 25. Notch toughness of heat-affected zone, fusion zone, and weld metal in 1/2-inch-thick quenched-and-tempered steel joints made with various electrodes (Kobler[146]).

(3) Notch toughness of the weld metal and the fusion zone varied greatly, depending on the type of electrodes used.

The investigator concluded that the dilution between the base and the weld metal caused the loss of notch toughness in the fusion zone. He theorized that liquid dilution and partial solid-state diffusion set up discontinuous, intermetallic compounds and other single-phase constituents in the extremely narrow interface defined as the fusion zone.

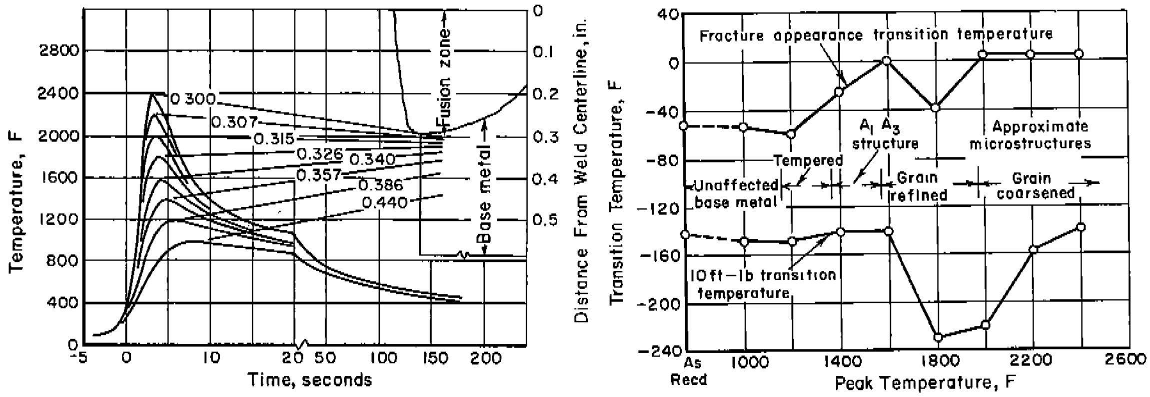
The synthetic-specimen technique has been found to be very useful for studying the notch toughness of the heat-affected zone in high-strength steels which undergo complex transformations during cooling.[131, 147-153]

Nippes and Sibley[147] investigated the notch toughness of the heat-affected zone in a quenched and tempered steel with the following chemical composition (per cent):

C	Mn	Si	S	P	Ni	Cr	Mo	V	B	Cu
0.15	1.00	0.23	0.022	0.014	0.94	0.53	0.45	0.05	0.0014	0.34

The yield strength of the base metal was about 110,000 psi. Samples were subjected to thermal cycles representing various locations in a butt weld made under normal welding conditions in 1/2-inch-thick plate. Figure 26a illustrates the time-temperature cycles employed and indicates the relative locations of the equivalent portions in the heat-affected zone of a weld. Figure 26b shows the relationships between the peak temperature attained during the thermal cycles and Charpy V-notch transition temperatures as follows:

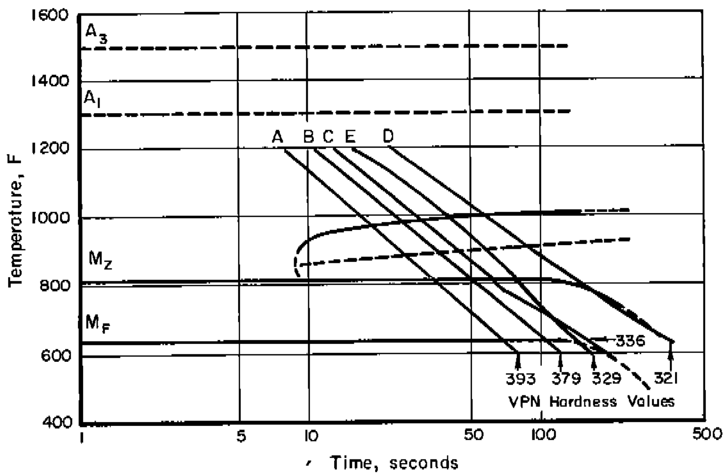
(1) The fracture-appearance transition temperature determined by 50 percent shear fracture



a. Time – Temperature Cycles Employed

b. Charpy V-Notch Transition Temperatures vs Peak Temperature

Fig. 26. Synthetic-specimen technique to study notch toughness of weld heat-affected zone in quenched-and-tempered high-strength steel (Nippes and Sibley [147]*).*



Results obtained with synthetic thermal-cycle specimens:

Thermal Cycle	Energy Input, j/in.	Initial Plate Temp, F	Peak Temp, F	Hard-ness, VPN	Weld Cooling Rate at 900 F, F/sec	Charpy V-Notch Transition Temp, F: 10 Ft-Lb	Fracture Appearance
A	47,000	72	2400	393	12.8	-138	+ 5
B	47,000	200	2400	379	8.7	-100	+ 25
C	47,000	300	2400	336	6.3	- 47	+ 68
D	47,000	500	2400	321	2.5	+ 26	+152
E	75,600	72	2400	329	4.5	- 16	+ 71

Fig. 27. Weld thermal cycles indicated on continuous-cooling transformation diagram of quenched and tempered high-strength steel.
(Nippes, et. al. [133,148]*).*

(2) The 10-ft-lb transition temperature (the temperature which corresponds to 10 ft-lb of absorbed energy).

The fracture appearance transition temperature increased steadily as the location of the structure approached the fusion zone, with an exception for the fine-grained structure obtained by heating to 1800 F. The 10-ft-lb transition temperature was also low at the peak temperature of 1800 F. Metallographic studies showed that specimens exposed to thermal cycles which exceeded the effective A_3 temperature exhibited a low-carbon martensitic structure. The impact properties of these low-carbon martinsites are outstanding.

The effect of cooling rate on microstructure and notch toughness can be investigated systematically with the combined use of the synthetic-specimen technique and the continuous-cooling transformation (CCT) diagram. Figure 27 shows the CCT-diagram of the steel used in the experiment for which results are shown in Figure 26. Also shown in the figure are weld thermal cycles as follows:

(1) Thermal Cycles A, B, C, and D, which represent cooling curves for the heat-affected zone structures with a 2400 F peak temperature in 1/2-inch-thick butt welds (heat input: 47,000 joules per inch) with various preheating temperatures up to 500 F.

(2) Thermal Cycle E, which represents a cooling curve of the heat-affected zone in a weld made with a 75,000 joules per inch heat input.

The notch toughness of synthetic specimens which underwent Thermal Cycles A through E is shown in the note of Figure 27. Notch toughness decreased markedly with either increasing initial plate temperature or increasing energy input. A 500 F preheat, for example, raised the Charpy V-notch, 10-ft-lb transition temperature from -138 to +26 F. The investigators explained that the poor behavior of the heat-affected zone of weldments made with high preheat temperature or high heat input is due to the fact that low-carbon martensite, which has excellent notch toughness, is gradually replaced by a mixture of ferrite and high-carbon martensite or bainite.

It must be mentioned that the effects of welding thermal cycle on notch toughness of the heat-affected zone depend greatly on the composition and the microstructure of the base metal. In the example shown in Figure 27, slower cooling caused a loss of notch toughness. However, the reverse may be true in other types of steel. In the case of hardenable steels containing moderate amounts of carbon, rapid cooling rates generally cause formation of brittle martensite.

4.4 Summary of Chapter 4

The notch toughness of the heat-affected zone is not a serious problem in mild-steel welds. Transition temperatures are high in areas somewhat outside the zone normally considered the heat-affected zone. However, brittle fractures do not initiate or propagate in the embrittled zone.

Loss of notch toughness in some portions of the heat-affected zone has been noted in some high-strength alloy steels, especially in heat-treated steels. The extent of the loss depends greatly on the composition and the microstructure of the base metal and on variations in the welding procedure. More information is needed on this subject.

CHAPTER 5. EVALUATION OF WELD-METAL TOUGHNESS BY VARIOUS TESTS

This chapter discusses the evaluation of weld-metal toughness by tests other than the standard charpy tests. Details of test procedures are not given here, since they are available in other literature.(1-5, 154,155)

5.1 Impact Tests With Small Specimens

Modified Charpy Tests and Other Impact Tests

Many investigators have used various types of modified Charpy tests. Specimens larger or smaller than the standard size have been used to study the notch toughness of weld metals.(52,53) Kihara(157) reported notch-toughness data of weld metals evaluated with the pressed-notch Charpy specimen in which a notch was made by pressing a sharp knife edge into the specimen.(158,159) Results on stress-relieved weld metals are shown in Table 3, which also contains data obtained with other tests.*

Hatch and Hartbower(130,131) used the "double-blow" or "low-blow" technique in their study of evaluating the notch toughness of the weld metal and the heat-affected zone simultaneously. In the double-blow technique,(160,161) a blow with the pendulum is applied twice in an attempt to evaluate separately the energy to initiate a crack and that required to propagate the crack.

Fichte(162) investigated the notch toughness of fillet-weld metals by preparing Charpy V-notch specimens from fillet joints.

Shorshorov and Kodolov(163) used the Schnadt test(164-166) to study the notch toughness of the heat-affected zone in welds in carbon and low-alloy steels. Schnadt specimens having the notch root at the heat-affected zone were taken from bead-welded specimens.

NRL Drop-Weight Test

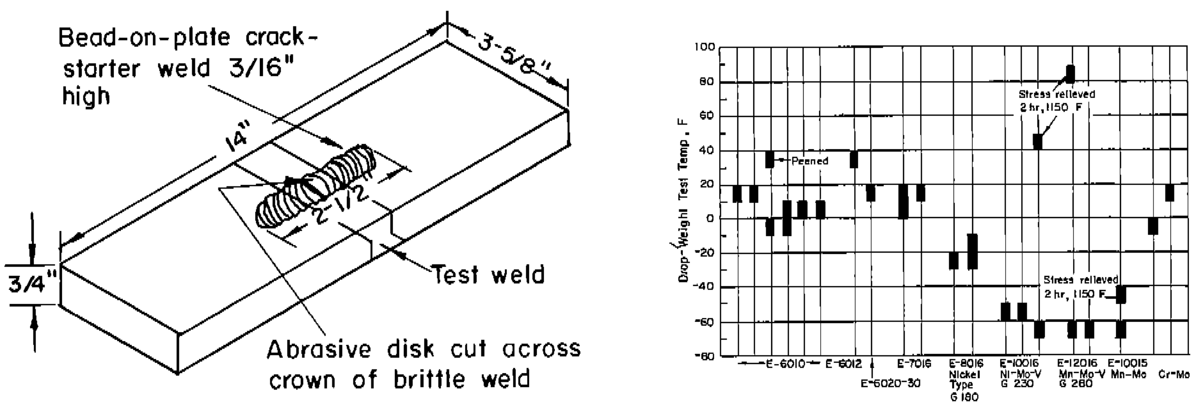
The drop-weight test was developed by Pellini and Puzak(167-169) at the U. S. Naval Research Laboratory. Pellini and Eschbacher(8, 170) used the drop-weight test to investigate the notch toughness of weld metal. Drop-weight test specimens, as shown in Figure 28a, were taken from butt welds made with electrodes of various types. A bead-on-plate crack-starter weld was laid on the butt weld so that the initiation and propagation of fracture was restricted to the butt weld. Figure 28b summarizes the test results. The bands indicate the scatter of the NDT (nil-ductility transition) temperature. No fracture occurred at temperatures above the band, and all specimens fractured at temperatures below the band.

* Kihara(157) reported an extensive investigation made by the Research Committee on Deposited Metals of the Japan Welding Engineering Society on the notch toughness of weld metals. The notch toughness of 12 types of weld metals was evaluated with various tests. The welds were made by the shielded metal-arc and the submerged-arc processes in 3/4-inch-thick steel plates with various strength levels. Small-size industrial test specimens were prepared in the as-welded and the stress-relieved conditions. Large-size specimens were prepared only in the stress-relieved condition, since it had been found that a brittle crack did not propagate through the weld metal (as shown in Figure 38) unless the specimen was stress relieved. Table 3 contains only data on the stress-relieved weld metals.

TABLE 3. SUMMARY OF NOTCH-TOUGHNESS DATA OBTAINED IN VARIOUS TESTS ON STRESS-RELIEVED WELD METALS (KIHARA)[157].

Test	Method	Criteria	PA	PB	PC	PD(a)	QA	QD(a)	RA	RD(a)	SA	SD(a)	TA	TD(a)
		Ultimate Tensile Strength, 1000 psi:	78.4	75.4	83.2	62.1	92.2	82.6	108.0	106.0	115.5	121.5	80.2	77.4
		Yield Strength, 1000 psi:	70.0	64.1	71.2	41.7	84.2	66.1	96.5	93.0	101.6	105.8	68.8	58.8
			Industrial Tests With Small Specimens											
(1)	Charpy standard V-notch	Tr_{15}(b), F	-182	-54	32	-31					-69	-8	-159	-78
		E_{32}(c), ft-lb	157	72	14.5	64					59	20	145	55
(2)	Charpy pressed notch	T_s(d), F	-58	50	140	73	3	99			68	172	-13	3
(3)	Mesnager	E_{32}(c), ft-lb	137	84	103	84	149	58			126	38	171	93
(4)	NRL drop weight	NDT(e), F	-126			-36	-76	-4	-31	5	-100	-49	-112	-82
(5)	Van der Veen	T_s(d), F	-63	-4	104	81	-10	75	14	158	14	109	-31	64
			Laboratory Tests With Large Specimens											
(6)	ESSO test	T_a(f), F	-103	-4	54	68					-37	95	-55	-6
(7)	Double-tension test	T_{ag}(g), F	-6	25	77	34	-13	41			39		-18	5
(8)	Welded-and-notched wide-plate tension test	T_i(h), F	-274	-205	5						-60	9	-202	-227

(a) Submerged-arc welding; other welds were made with covered electrodes.
(b) 15 ft-lb transition temperature.
(c) Energy absorption at 32 F.
(d) Fracture-appearance transition temperature.
(e) Nil-ductility transition temperature.
(f) Arresting temperature.
(g) Arresting temperature with gradient-temperature specimens.
(h) Initiation transition.



a. Specimen

b. Summary of Test Results

Fig. 28. Use of the Naval Research Laboratories Drop-Weight Test to Evaluate Notch Toughness of Weld Metals made with Electrodes of Various Types (Pellini and Eschbacher[170]).

Table 3 contains NDT temperatures of weld metals reported by Kihara.[157]

5.2 Static Tests With Small Specimens

Static tests using small specimens include:

(A) Static fracture tests on notched specimens*

(1) Notched-specimen tension tests, such as the Tipper test[171] and the Noren nominal cleavage (N-C) strength test[172]

(2) Tear tests, such as the Navy tear test[177]

(3) Notched-specimen bend tests, such as the Van der Veen test[178,179]

(B) Bend tests on welded specimens

(4) Longitudinal-bead-weld notched-bend tests, such as the Lehigh test[180,181] and the Kinzel test[182-184]

(5) Longitudinal-bead-weld bend tests, such as the Kommerell test.[185-187]

Tests in Group (A) have been developed primarily for evaluating the notch toughness of unwelded base plates. These tests can be used for evaluating weld metals by preparing a specimen in such a way that fracture propagates through the weld metal.

Tests in Group (B) have been developed for evaluating the fracture characteristics of weldments or the effects of welding on the base plate, i.e., the weldability of steel. Research has been conducted to study the effects of weld-metal toughness on results obtained in the Lehigh, Kinzel, and Kommerell tests.

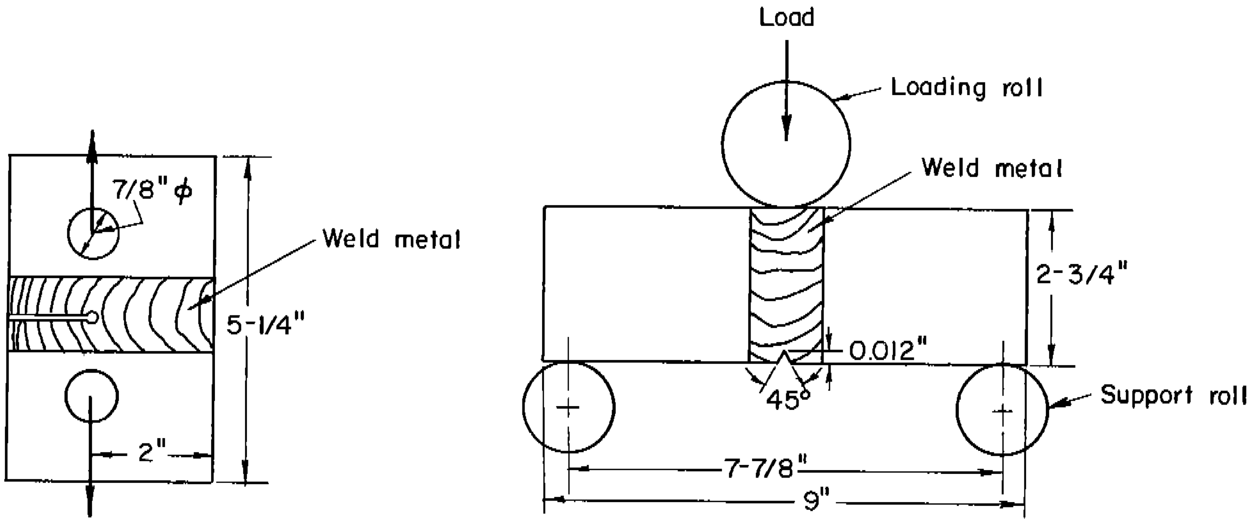
Evaluation of Weld-Metal Toughness By Static Fracture Tests on Notched Specimens

Several investigators have used notched-tension, tear, and notched-bend tests to evaluate notch toughness of weld metals.

Stern, et al.[53] used the Navy tear test to evaluate notch toughness of submerged-arc weld metals. Tear-test specimens were taken from welded joints in such a way that the notches were located at (1) the center of the weld metal, as shown in Figure 29a, and (2) the fusion zone. Otani and Ota[188, 189] also used the Navy tear test to study notch toughness of the weld heat-affected zone.

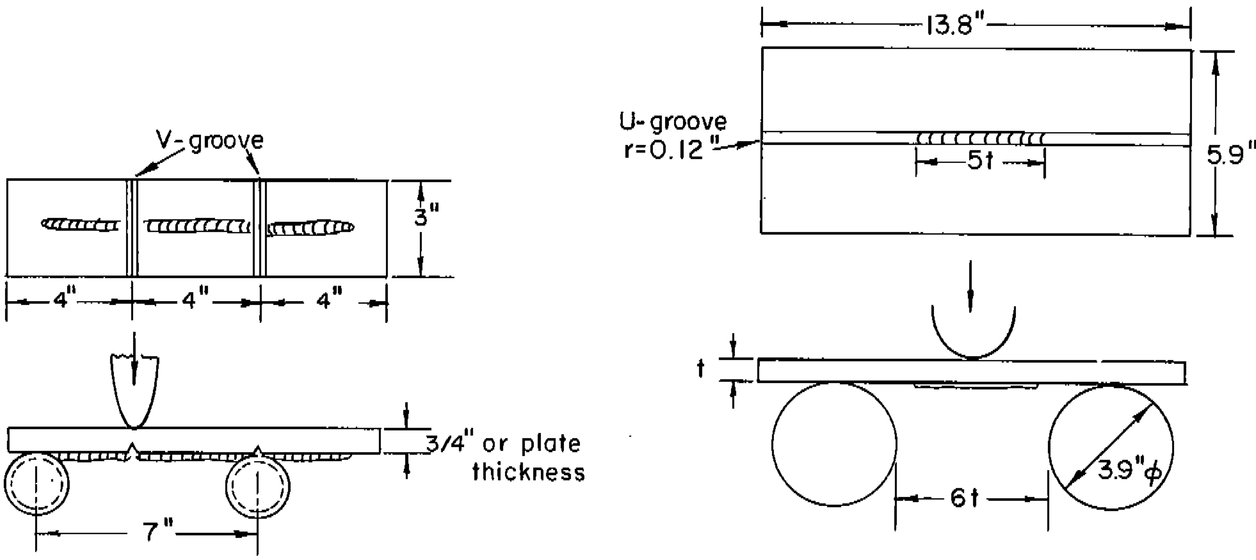
Kihara[157] used the Van der Veen test to study the notch toughness of weld metals. The notch was located in the center of the weld metal of a butt joint, as shown in Figure 29b. Test results were shown earlier in Table 3.

* The ASTM Committee on Fracture Testing of High-Strength Sheet Materials[173] has described techniques of notched-specimens tension tests for determining fracture toughness of high-strength materials, primarily those with over 700,000 psi per cubic inch strength-to-density ratio (for steel over 200,000-psi ultimate tensile strength).[127] Fracture toughness, K_c is used to characterize the toughness of the material. The analysis is based on the Griffith-Irwin theory of brittle fracture.[174-176]



a. Navy Tear Test   b. Van der Veen Test

Fig. 29. Evaluation of Weld-Metal Toughness with the Navy Tear Test and the van der Veen Test.



a. Lehigh Test   b. Kommerell Test

Dimensions of the Kommerell test change depending upon the plate thickness. Dimensions shown in this figure are for plates less than 1 inch thick.

Fig. 30. Lehigh and Kommerell Tests.

Effects of Weld-Metal Toughness on the Results of Bend Tests on Welded Specimens

In the Lehigh and the Kinzel test, a bending load is applied to a specimen having a transverse notch cut across the weld metal deposited on the specimen. Figure 30a shows the specimen and manner of conducting the Lehigh test.

In the Lehigh and the Kinzel test, fracture usually initiates from the heat-affected zone and propagates into the base metal.[190, 191] Consequently, the behavior of a specimen is governed primarily by:

(1) The fracture-initiation characteristics of the heat-affected zone

(2) The fracture-propagation characteristics of the base metal.

The toughness of the weld metal is believed to have little effect on the behavior of the specimen. Murphy and Stout[192] reported that the type of electrode had little effect on the transition temperature determined by Kinzel specimens made in carbon steel and low carbon Mn-Si high-strength steel with the exception of the 25Cr-20Ni electrode, which resulted in a definite improvement in toughness.

In the Kommerell test, which was originated in Germany, a single-pass weld bead is deposited along a test plate, and it is bent with the weld on the tension side, as shown in Figure 30b.[185-187] Small cracks appear in the weld metal or in the heat-affected zone; as the crack proceeds, these cracks extend into the base metal. Brittle steel is unable to stop the progress of the cracks, and the specimen breaks suddenly at a small bend angle. Ductile steel, on the other hand, stops the advance of the cracks, and the specimen breaks only after considerable deformation.

Figure 31 shows the effects of electrode type on transition behaviors of a low-alloy high-strength steel evaluated with the Kommerell-type test.[5, 193] Specimens were welded with two types of electrode: low-hydrogen Type E7016, and ilmenite Type JIS D4301 (refer to Figure 22). At high temperatures, the bend angle for crack initiation was affected by the electrode type. However, the crack initiated from the brittle weld did not extend to the notch-tough base plate; consequently, the electrode type did not affect the maximum bend angle. At low temperatures, on the other hand, the bend angle was affected by the electrode type. The results indicate that when the base metal is brittle, complete fracture occurs as soon as a crack initiates from the weld zone. The transition temperature determined by the maximum bend angle was not affected by the electrode type.

5.3 Fracture Tests of Weldments by Dynamic Loading

Dynamic loadings such as those created by explosives and projectiles have been utilized as simple means of fracturing full-size weldments. Various tests have been proposed and used, as follows:

(1) Explosion bulge test developed by Hartbower and Pellini[194, 195]

(2) Crack-starter explosion test developed by Pellini and associates[167, 196]

(3) Direct explosion test proposed by Mikhalapov, et al.[197-199]

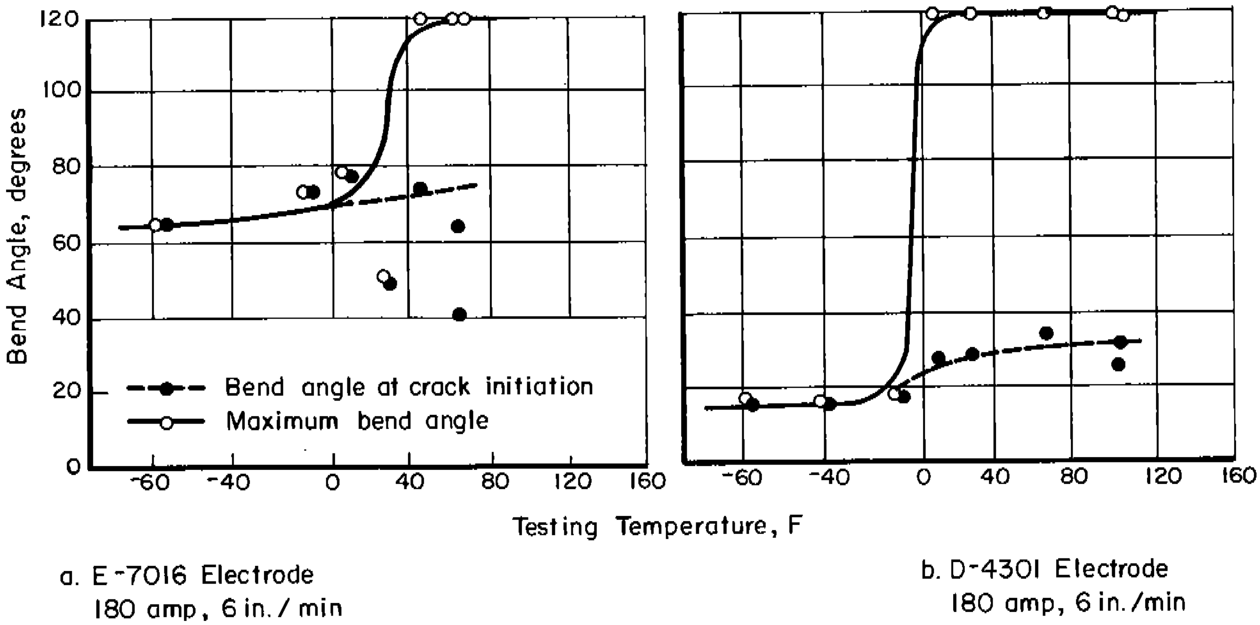
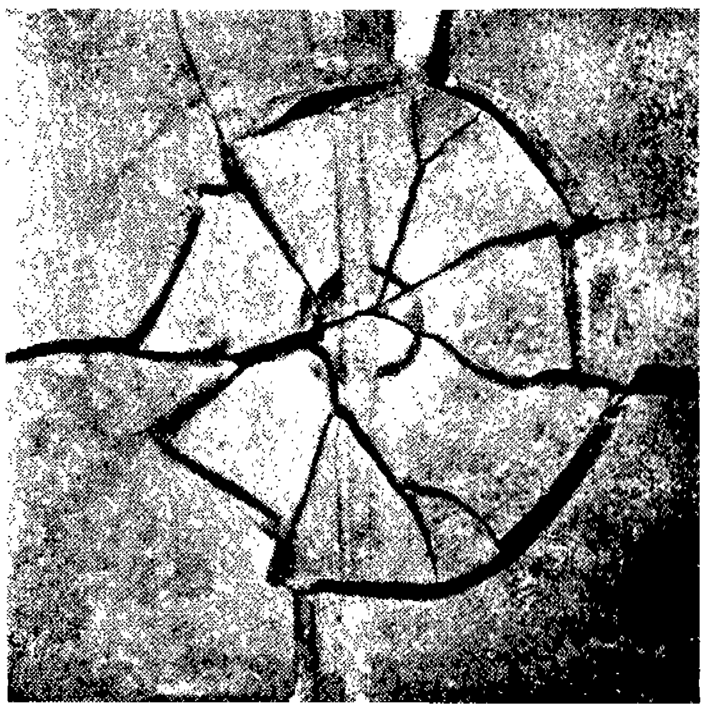


Plate thickness, 3/4-in.; steel composition, %: C 0.18, Mn 1.21, Si 0.43, Cu 0.25.

Fig. 31. Effect of Electrode Type on Transition Characteristics of a High-Strength Steel as Revealed by the Kommerell Test (Otake, et al.[193]).



2X

Fig. 32. Plate Fracture Paths Developed in E-6010 Weldments of 1-in. Carbon-Steel Ship Plate Tested at 20 to 40 F (Pellini[8]).

Source: Welding J., 35 (5), 227-s (1956).

(4) H-plate shock test used by the Ordnance Corps, U. S. Army[200,201]

(5) Explosion tests of welded tubes conducted by Folkland,[202] Hauttmann[187], and Kihara, et al.[203,204]

These tests have been used to study (1) behavior of a weldment as a whole under impact loading and (2) the role of weld-metal toughness on the over-all behavior of a weldment. The following sections describe results related to weld-metal toughness obtained with the explosion bulge test and the crack-starter explosion test.

Explosion Bulge Test

In the NRL explosion bulge test, two plates, usually 10 by 20 inches, are butt welded to form a square and are then placed over a circular die and explosion-loaded by successive shots to the point of failure or to the development of a full-hemispherical bulge. Explosion bulge tests of weldments made with various type of base metals and electrodes have been conducted.[8,205-210]

According to Pellini,[8] Figure 32 illustrates fracture paths which are typical of E6010 carbon-steel weldments of the type used in World War II vintage ships. At 20 to 60 F test temperatures, the fractures propagate only via a plate path, i.e., in the same fashion as observed in service failures.[23] There is no tendency for propagation via weld, heat-affected zone, or fusion-line paths. Fractures which cut across the weld in the 40 F to 60 F tests show a distinct change in fracture appearance in the weld region, characterized by readily visible shear lips. This indicates that the material least resistant to brittle fracture is the base metal. As the temperature is lowered to the 0 F to -20 F range, brittle fractures are propagated extensively also along the weld and in the heat-affected zone. Pellini and Eschbacher[212] reported that:

(1) Fractures often initiated from cracklike flaws such as those introduced by arc strikes

(2) Shot peening of the base metal and the weld metal was found to be detrimental with respect to the resistance of weldments to initiation and propagation of brittle fractures.

Various types of fracture have been observed in high-strength-steel weldments. In some cases fractures have occurred along a certain zone of a butt weld (not in many directions as shown in Figure 32), either along the weld metal, the heat-affected zone, or the fusion zone. It is generally believed that the unidirectional fracture path along a certain zone occurs when either one or both of the following conditions are satisfied:

(1) The strength of the particular zone is lower than that of other areas of the weld. Concentration of plastic deformation takes place in the zone.

(2) The notch toughness of the particular zone is inferior to that of other areas of the weld. The fracture propagates along the zone with the least resistance.

However, it has not been determined quantitatively how great a loss in the strength or the notch toughness of the particular zone is necessary for the occurrence of the unidirectional fracture along the zone.

Crack-Starter Explosion Test

In the NRL crack-starter explosion test, a specimen (14 by 14 inches) is prepared for testing by depositing a short bead of brittle weld metal which is then notched by a disk abrasive wheel. The specimen is placed over a circular die and explosion loaded. The NDT (nil-ductility transition) temperature can be determined as the highest temperature at which a specimen fractures with no evidence of ductility as illustrated by a "flat break" in many pieces.

Puzak and Pellini[211] used crack-starter explosion tests to demonstrate the feasibility of using overlays of notch-tough welds to prevent the initiation and propagation of brittle fracture in otherwise brittle, structural mild steels. Circular weld beads 2 inches wide were overlaid on both surfaces of the plate around the periphery of the explosion-test specimens. Weld beads were laid with ferritic E12016 electrodes and 25Cr-20Ni austenitic stainless steel electrodes. In explosion tests conducted at 20 F and 40 F, fragmentation of the prime plate was obtained, but brittle fractures did not propagate through the overlaid welds. It also was demonstrated, in another series of tests, that the cladding of a brittle steel with notch-tough weld metal increases resistance to the initiation of brittle fracture.

5.4 Wide-Plate Tension Tests

This section describes results obtained with (1) fracture-propagation tests and (2) welded-and-notched wide-plate tension tests.

Fracture-Propagation Tests

Many investigators[212-217] have established that a brittle crack, if it once begins to extend, can propagate under a low average stress when (1) the temperature is below some critical temperature and (2) stress is higher than the critical stress for crack propagation. Tests that have been used in the study of fracture propagation include (1) the Robertson test[212], (2) the ESSO (or SOD) test developed by Feely, et al.[31,213], and (3) the double-tension test developed by Yoshiki and Kanazawa[214]. Although these tests have been used primarily for evaluating fracture-propagation characteristics of base metals, they can be used for studying fractures which propagate through weld metals and the heat-affected zone.

Yamauchi and Nakai[156] investigated fracture-propagation characteristics of weld metals by means of the ESSO test, as shown in Figure 33a. Specimens 18 inches wide were prepared from butt-welded joints of quenched-and-tempered high-strength-steel plates 3/4-inch thick. The joints were welded by the shielded metal-arc process and the submerged-arc process. Notches for fracture initiation were placed at the center of the weld and at the heat-affected zone. A crack initiated from the notch by impact was introduced into the specimen, which was at a predetermined uniform temperature and under uniform stress.

Figure 34 summarizes the test results. Test results on the unwelded quenched-and-tempered steel and a mild steel also are shown. For the mild-steel base metal, original data are shown. When the test temperature was low and the stress was high, the specimen fractured as indicated by cross marks; when the temperature was high and the stress was low, the fracture did not propagate, as indicated by circles. Thus, a curve which shows the critical stress and the critical temperature was determined as a dividing line between data for propagation and nonpropagation. As shown in the figure, the weld metals (both covered-electrode and submerged-arc deposited) had fracture-propagation characteristics superior to those of unwelded plate i.e., lower arresting temperatures and higher critical stresses.

Figure 35 shows the results obtained with large-scale Charpy impact specimens (twice as large as the standard Charpy specimen) taken from (1) the weld metal, (2) the heat-affected zone, and (3) the base metal. Data for the mild-steel base metal also are shown. Transition temperatures of the weld metals were considerably higher than that of the quenched-and-tempered base metal. Yamauchi and Nakai[156] suggested that the discrepancy between results obtained with the two different tests might have been caused by residual welding stresses which existed in the ESSO test specimens. In the ESSO test specimens, fractures did not always propagate straight; some deviated from the weld zone.

Kihara[157] reported fracture-propagation characteristics of weld metals evaluated with the ESSO test and the double-tension test. The ESSO test specimens were similar to those used by Yamauchi and Nakai. Figure 33b shows the double-tension test specimen. The specimen was composed of two parts, the crack-initiation part and the main part, which were connected by a narrow passage and loaded independently. A cleavage crack was initiated in the crack-initiation part and introduced into the main part through the passage. Results were summarized earlier in Table 3.

Welded-and-Notched Wide-Plate Tension Tests

A characteristic of brittle fracture is that actual failures usually occur at stresses well below the yield stress of the material. In many cases, fractures have occurred without any repeated or impact loading, and fractures have frequently started from a weld-joint flaw. However, low-stress fracture does not occur in most laboratory tests. Even in a specimen which contains very sharp notches and fractures with low energy absorption and with brittle-fracture appearance, the fracture stress is as high as the yield stress. In fracture-propagation tests the fracture propagates at a low stress; however, such expedients as the impact loading in the Robertson and the SOD tests or high-tensile stress applied at the auxiliary part of a specimen in the double-tension test are necessary to initiate a brittle crack.

Following the work done by Greene[226] and Wells[219,220], extensive research on low-applied-stress fracture of weldments has been conducted during the last several years.[221-229] It has been found that a low-applied-stress fracture can be obtained experimentally from a notch located in an area containing high residual tensile stress.

Kihara, et al.[228] investigated fractures along the weld metal and the heat-affected zone using welded-and-notched wide-plate tension-test specimen, as shown in Figure 36. The specimen size was 1 by 40 by 40 inches. The transverse test weld was first made and the weld reinforcement was removed, then the longitudinal weld was made. A short transverse notch was cut at various locations of the transverse test weld, including (1) the center of the weld metal, (2) the coarse-grained heat-affected zone (which was vertical to the plate surface), (3) the embrittled zone determined by Charpy V-notch specimens (refer to Figure 25 for definition)*, and (4) the base metal. Tensile fracture tests were conducted over a range of temperatures. Since the longitudinal weld produced high residual tensile stresses in the direction of loading, complete fracture of the specimen occurred, under certain test conditions, when the applied stress was well below the yield stress.

* As it turned out, the notch toughness of this zone was only slightly lower than that of the base metal.

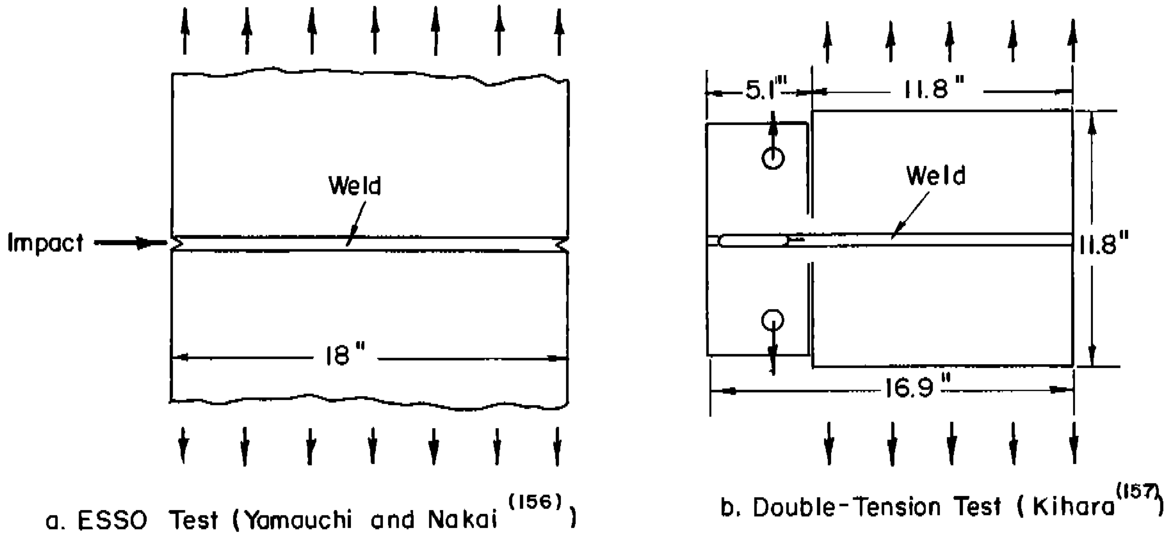


Fig. 33. Use of Esso Test and Double-Tension Test for Evaluating Fracture-Propagation Characteristics of Weld Metal.

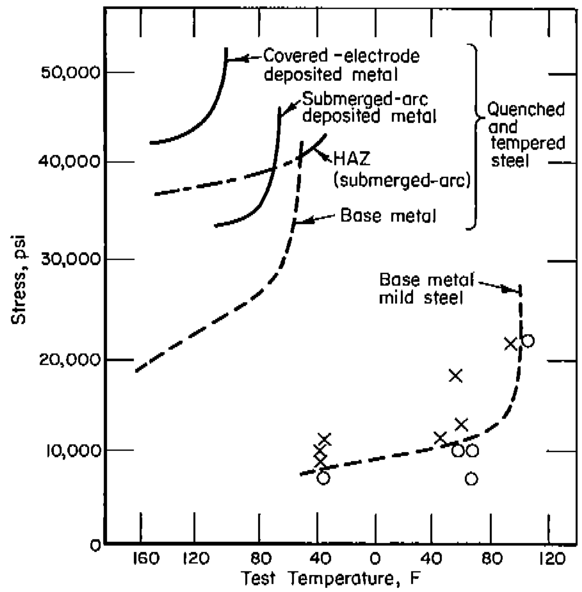


Fig. 34. Evaluation of Toughness of Weld Metal and Heat-Affected Zone with the Esso Test (Yamauchi and Nakai[156]).

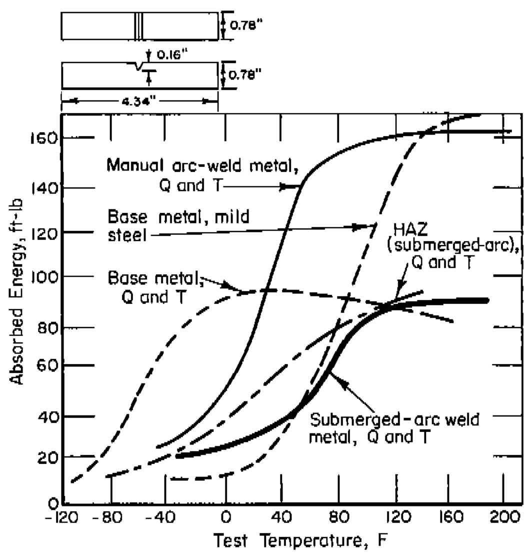


Fig. 35. Transition Curves Determined by Large-Scale Impact-Test Specimens of Weld Metals, Heat-Affected Zone, and Base Metals (Yamauchi and Nakai[156]).

Figure 37 summarizes test results on semikilled-carbon-steel welds. The transverse test weld was made by the submerged-arc process. The chemical composition (in percent) of the base and the weld metal was as follows:

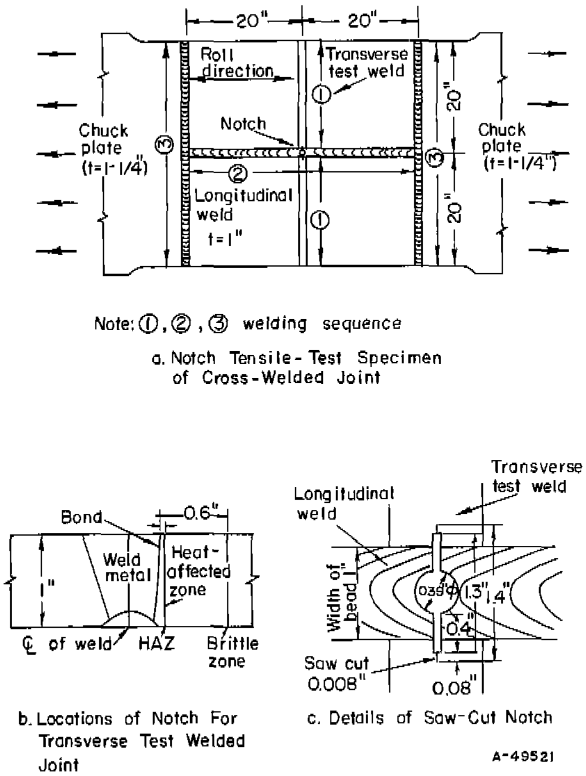


Fig. 36. Welded-and-Notched Wide-Plate Tension-Test Specimen for Studying Fracture Characteristics of Weld Zone (Kihara, et al.[228]).

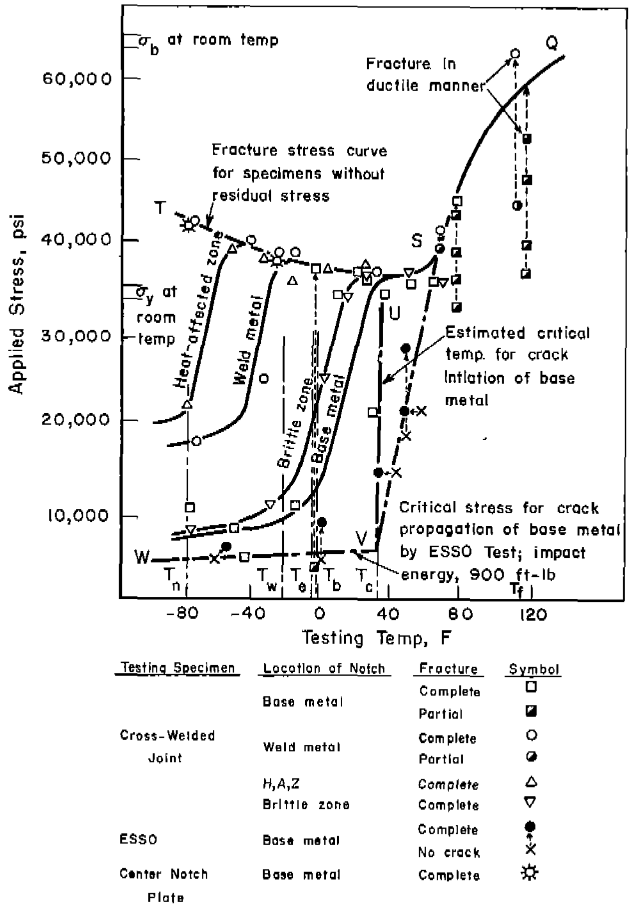


Fig. 37. Results of Welded-and-Notched Wide-Plate Tension Tests on Weld Zone (Kihara, et al.[228]).

	C	Mn	Si	P	S
Base metal	0.16	0.45	0.10	0.035	0.021
Weld metal	0.14	0.88	0.19	0.033	0.017

The ultimate tensile strength and the yield strength of the base metal were 76,000 psi and 52,000 psi, respectively.

The figure also contains the following data:

(1) The fracture stress curve for specimens without residual stress, ST. The curve was determined by tensile fracture tests of center-notched specimens (unwelded).

(2) The fracture-propagation characteristics of the base metal determined with the ESSO test, as follows:

(a) The critical stress for crack propagation, VW

(b) The critical temperature for crack initiation**, T_c.

** The temperature below which a crack initiates from the notch.

(3) Transition temperatures determined with Mesnager 2-mm U-notch specimens prepared from various portions of the weld. T_h, T_w, T_e, and T_b represent the transition temperatures of the heat-affected zone, the weld metal, the embrittled zone, and the base metal, respectively.

Figure 37 shows the following:

(1) When the test temperature was higher than T_f, fracture occurred at a stress close to the ultimate tensile strength. The fracture stress was not affected by the location of the notch, and residual stress had no effect on the fracture stress.

(2) Low-applied-stress fractures occurred in welded specimens when the test temperature was below a certain value, depending on the location of the notch. The heat-affected zone and the weld metal exhibited better toughness (lower critical temperatures and higher critical stresses) than the base metal.

(3) There was a good correlation between the critical temperatures determined with the wide-plate test of these zones and the Mesnager transition temperatures, T_h, T_w, T_e, and T_b. (This finding was quite different from the results obtained by Yamauchi and Nakai, Figures 34 and 35).

(4) Fracture stresses for unwelded specimens (Curve ST) were as high as the yield stress, indicating that residual stresses produced by the longitudinal weld were essential for causing the low-stress fracture.

Kihara, et al.[228] reported that fractures tended to deviate from the weld metal. In specimens without transverse welds, fractures propagated rather straight in the direction perpendicular to the loading direction, as shown in Figure 38a. In specimens with transverse welds, fracture tended to deviate from the weld, as shown in Figures 38b and 38c; the deviation was less pronounced when the fracture stress was higher. It was believed that residual welding stresses in the transverse weld caused the deviation.

In a later series of tests, a specimen was stress relieved after the transverse test weld was made, then the longitudinal weld was made. In this type of test, the deviation of fracture from the test weld became minimum (results were summarized earlier in Table 3).

5.5 Correlation of Test Results

Correlations of notch-toughness data for base metals evaluated by means of various tests have been studied by many investigators.[31-34] However, only a few investigations have been made to correlate notch-toughness data from weld metals evaluated with various tests.

For weld metals, Pellini[8] investigated the correlation between Charpy V-notch impact-test results and the NDT temperatures determined by the drop-weight test, as shown in Figure 28. The NDT temperatures generally coincided with the 15 to 25-ft-lb transition temperatures in the Charpy V-notch impact tests. Pellini concluded that the

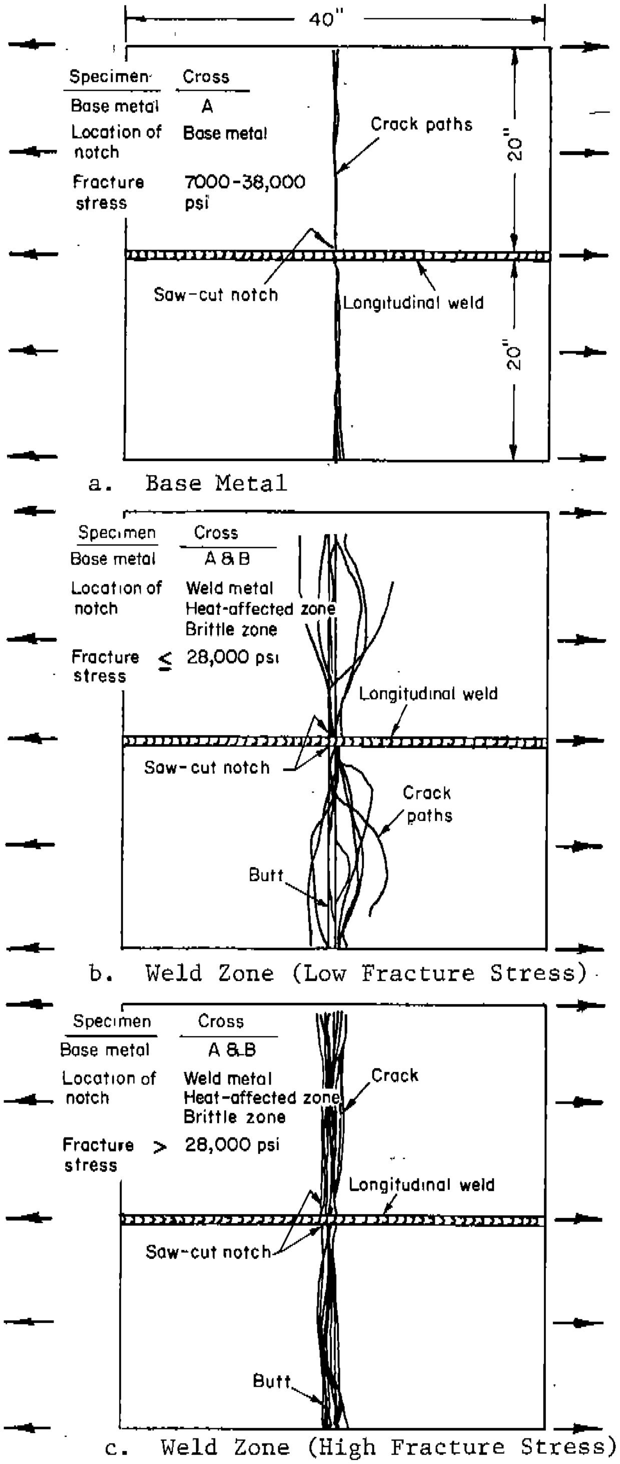


Fig. 38. Fracture Paths in Welded-and Notched Wide-Plate Tension-Test Specimens (Kihara, et al.[228]).

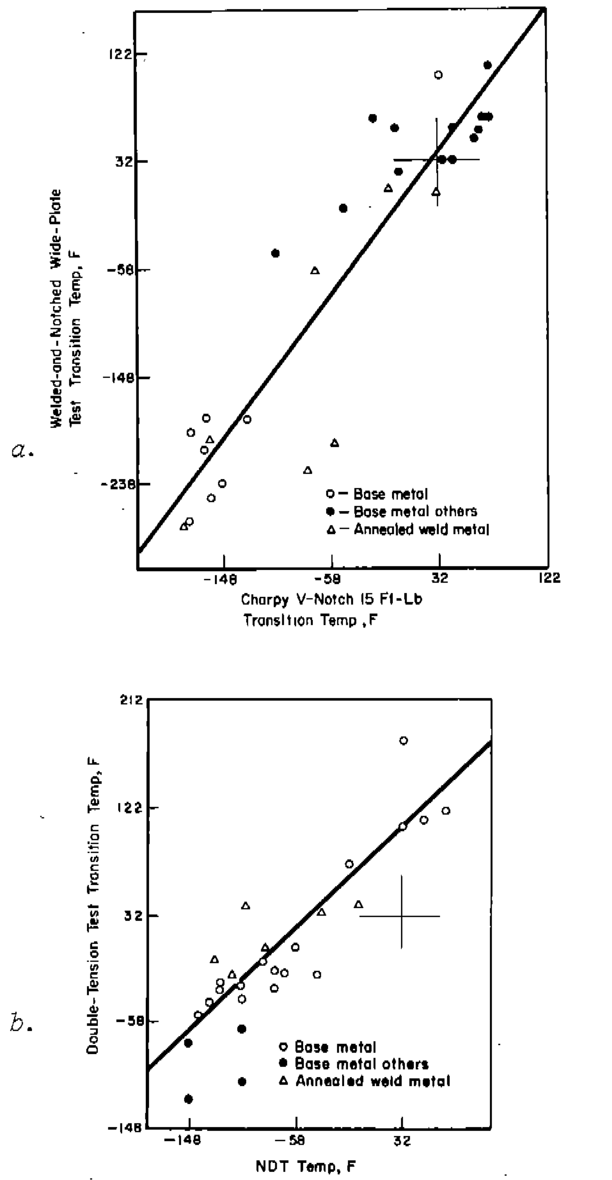


Fig. 39. Correlations Among Test Results Obtained with Various Tests (Kihara, et al.[157]). a. Charpy V-Notch 15-ft-lb Transition Temperature Versus the Transition Temperature Obtained with the Welded-and-Notched Wide-Plate Tension Test. b. Naval Research Laboratory Drop-Weight Test NDT Temperature Versus the Arrest Temperature Determined with the Double-Tension Test (with Temperature Gradient).

20-ft-lb transition temperature can be used as an average "fix" point for correlating the NDT temperature with the Charpy V-notch impact-test data for covered-electrode-deposited metals.

Kihara[157] investigated correlations among notch-toughness data of weld metals evaluated by various tests, as shown in Table 3. Figure 39 shows the following:

Figure 39a: Correlation between the Charpy V-notch 15-ft-lb transition temperature and the transition temperature obtained with the welded-and-notched wide-plate tension test

Figure 39b: Correlation between the NRL drop-weight test, NDT temperature, and the arrest temperature determined with the double-tension test (with temperature gradient).

Included in these figures are data on the base plates. Figure 39 indicates that the weld metal and the base metal behave the same as far as the correlation among transition temperatures determined by different tests is concerned.

5.6 Summary of Chapter 5

Various tests have been used to evaluate:

(1) The notch toughness of weld metals and the heat-affected zone

(2) The effects of the notch toughness of the weld metals and the heat-affected zone on the fracture behavior of weldments.

Notch Toughness of the Weld Metal and the Heat-Affected Zone

The notch toughness of the weld metal and the heat-affected zone has been evaluated by means of various industrial tests, including (1) modified Charpy tests and other impact tests, (2) the NRL drop-weight test, and (3) static fracture tests on notched specimens such as the Navy tear test and the Van der Veen test. Laboratory tests on large-size specimens including the ESSO test, the double-tension test, and the welded-and-notched wide-plate tension test also have been used to evaluate brittle-fracture characteristics of the weld metal and the heat-affected zone.

Generally, the same correlations exist among data obtained with various tests in the weld metal and those obtained in the base metal, as shown in Figure 39. In other words, the weld metal and the base metal behave the same way when the test methods are changed. Cases, however, have been observed in which results obtained with small specimens do not agree with those obtained with large specimens, as shown in Figures 34 and 35. Results shown in Figures 34 and 35 indicate that despite the lower notch toughness exhibited in Charpy V-notch impact tests of the weld metal and the heat-affected zone (compared with that of the base metal) brittle fracture does not necessarily occur along these zones. Adequate information is lacking on this subject.

Effects of the Notch Toughness of the Weld Metal and the Heat-Affected Zone on the Fracture Behavior of Weldments

The effects of the notch toughness of the weld metal and the heat-affected zone on the fracture behavior of weldments have been investigated with various tests, including (1) bend tests on welded specimens such as the Lehigh test and the Kommerell test and (2) fracture tests of weldments by dynamic loading such as the explosion bulge test and the crack-starter explosion test.

In brittle fractures which propagate transverse to the weld, such as those in the Lehigh and the Kommerell tests, the properties of the weld metal and/or the heat-affected zone affect the fracture initiation; however whether the fracture propagates or not depends primarily on the properties of the base metal. In the Kommerell test, for example, the bend angle for crack initiation is affected by the type of weld metal, but the maximum bend angle is little affected by the type of weld metal, as shown in Figure 31.

In brittle fractures which propagate parallel to the weld, it has been found that:

(1) In carbon-steel weldments in which the weld-metal notch toughness is as good as or better than the base metal and the yield strength of the weld metal is as high as or even higher than the base metal, brittle fracture does not usually propagate along the weld metal or the heat-affected zone.

(2) In high-strength alloy-steel weldments, brittle fracture may or may not propagate along the weld metal or the heat-affected zone, depending on the relative notch-toughness and yield strength of the weld metal or the heat-affected zone with respect to the base metal. Fracture propagation along the weld metal or the heat-affected zone is a serious problem in high-strength heat-treated steels in which the high strength and excellent notch toughness of the base metal can be damaged by welding thermal cycles. More research is needed on this subject.

CHAPTER 6. AREAS OF NEEDED RESEARCH

One of the most important observations made during this literature survey has been the relatively limited information available on the notch toughness of weld metals and the heat-affected zone. Although much work has been done in this general area to avoid brittle fracture, much of it has been done on welded plates or assemblies, and only limited charpy impact-type data were obtained for specific weldment zones. However, to have a common basis for comparison the notch-toughness values of the weld metal and the heat-affected zone should be determined on the same basis as for the base metal. It would then be possible to set up a realistic relationship that should exist between the three zones for satisfactory service in steels of different strength levels.

It was also observed that there has been relatively little correlation of such factors as chemical composition, microstructure, and welding variables with the notch toughness of weld metals and the heat-affected zones. If the desired relationships of notch-toughness values referred to above are determined, then it would be in order to conduct extensive investigations to determine how the notch toughness of the weld metal and the heat-affected zone can be improved by modifying the numerous variables involved.

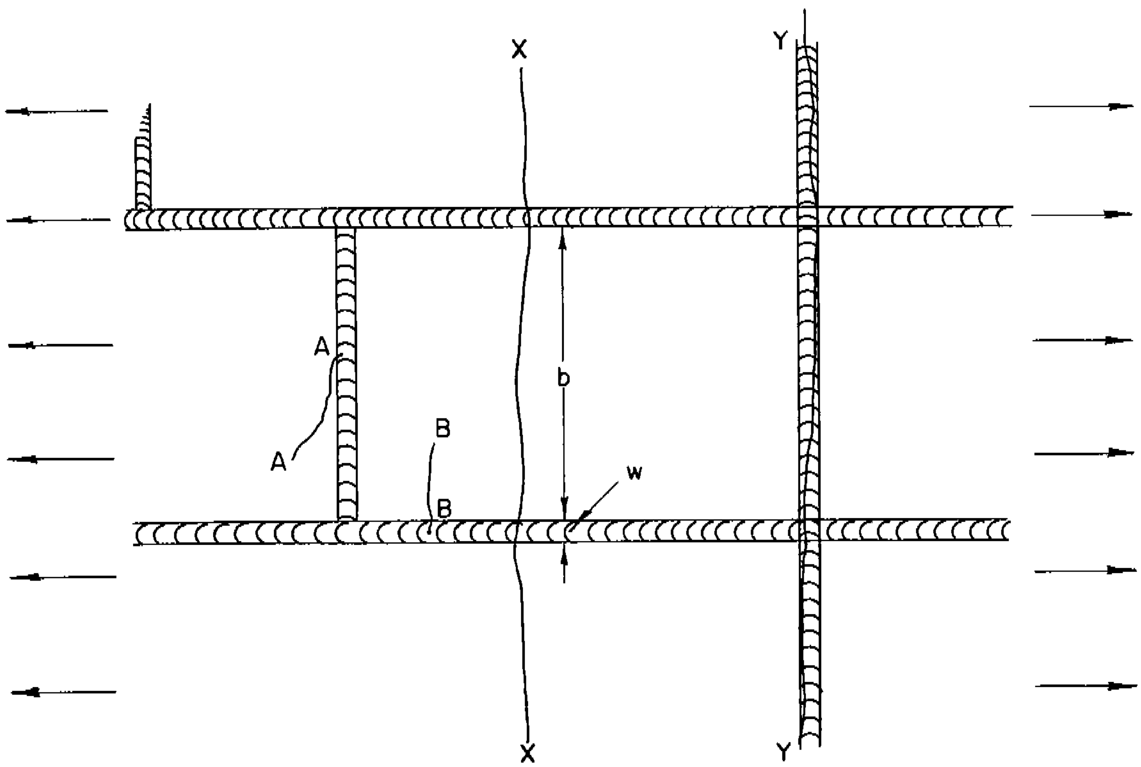


Fig. 40. Initiation and Propagation of Fracture in Ship Structure.

6.1 Realistic Requirements for Notch Toughness of the Weld Metal and the Heat-Affected Zone

Research should be conducted to determine on a more rational basis the notch toughness needed in the weld metal and the heat-affected zone compared with the notch toughness of the base metal. To do this would require a study wherein weld metals of different notch-toughness levels were produced and welding techniques changed so that the heat-affected-zone notch-toughness level also changed. Charpy impact tests should be used to determine the notch-toughness levels. Then full size welded plates should be tested under standard conditions to determine their performance. This test could be one of fracture tests of weldments such as the explosion bulge test or the welded-and-notched wide-plate tension test. The results of such work would provide a correlation between the notch toughness of the weld metal, the heat-affected zone, and the base metal, as measured by charpy impact properties, with performance as a welded assembly in service.

The following discussion relates to the establishment of realistic requirements for the notch toughness of the weld metal and the heat-affected zone. Discussions will cover the following, with reference to Figure 40:

(1) Initiation of brittle fracture from the weld metal and/or the heat-affected zone, as shown by AA and BB

(2) Propagation of brittle fracture through the weld metal and/or the heat-affected zone, as shown by YY.

This discussion is presented using fracture initiation and propagation criteria, since these are the criteria most influenced by variations in notch toughness.

Fracture Initiation

Evidence obtained in the investigations of brittle failures in welded ships and other structures has shown that in many cases fractures initiated from welds containing cracks and other defects. Since there always is a chance that the weld metal may contain defects, the weld metal should have enough resistance against fracture initiation (by subcritical crack growth) that the defects do not grow to an unstable fracture.

Importance of the heat-affected zone for the initiation of brittle fracture has been recognized. It has been known that brittle failures in welded structures also have initiated from heat-affected zones, especially from those with cracks and other flaws. Studies of brittle fractures which initiate from the heat-affected zone and propagate into the base metal have been made by many investigators using various tests including the Lehigh longitudinal-bead-weld notched-bend test, the Kommerell longitudinal-bead-weld bend test, the explosion bulge test, and explosion tests on welded tubes.

Fracture Propagation

Paths of fracture propagation relative to the weld are classified into the following two basic types:

Type 1 path: A fracture propagates mostly in the base metal and traverses the weld metal, as shown by XX in Figure 40.

Type 2 path: A fracture propagates along the weld metal and/or the heat-affected zone, as shown by YY.

Fracture Propagation Transverse to the Weld. In a Type 1 path, notch toughness of the weld metal and the heat-affected zone does not have a significant effect on the fracture behavior of the welded structure, since the width of the weld, w, is negligible compared with the width of the base plate, b (in most structures the ratio, w/b, is much less than 0.01).

In ship structures major stresses are in the longitudinal direction of the ship, and brittle fractures have occurred in almost all cases in the transverse direction. From the viewpoint of fracture propagation, consequently, the toughness requirement for the longitudinal-seam-weld metal may be reduced. The Japanese ship-classification society allows a lower notch toughness for longitudinal-seam-weld metals than for transverse-butt-weld metals.[14]

Fracture Propagation Along the Weld Metal and the Heat-Affected Zone. Three major factors determine whether or not Type 2 fracture occurs:

(1) The relationship of the notch toughness of the weld metal, the heat-affected zone, and the base metal

(2) The relationship of the yield strengths of the weld metal, the heat-affected zone, and the base metal

(3) The widths of the weld metal and the heat-affected zone.

If the notch toughness of the weld metal and the heat-affected zone is superior to that of the base metal, Type 2 fracture will not occur. If the yield strengths of the weld metal and the heat-affected zone are higher than that of the base metal, Type 2 fracture will not occur, even when the notch toughness of the weld metal and the heat-affected zone is slightly inferior to that of the base metal. If the widths of the weld metal and the heat-affected zone are very narrow, Type 2 fracture will not occur unless the strength and the notch toughness are considerably lower than those of the base metal. It is important to determine quantitatively the conditions which govern the occurrence of Type 2 fracture.

6.2 Effects of Chemical Composition and Microstructure on Notch Toughness of the Weld Metal and the Heat-Affected Zone

Two basic factors which determine mechanical properties of a metal are the chemical composition and the microstructure. Many investigators have studied effects of chemical composition and microstructure on the notch toughness of base metals. However, very few systematic investigations have been made of the effects of chemical composition and microstructure on the notch toughness of weld metal and the heat-affected zone.

On the basis of limited information obtained so far, the effects of the chemical composition and the microstructure on notch toughness are roughly the same in base metals and in weld metals. However, there are some differences in the ways the chemical composition and the microstructure affect the notch toughness of base metals and weld metals. It is believed that major factors which cause the difference in notch toughness are nonmetallic inclusions and such minor elements as oxygen and nitrogen. More research is needed on the effects of the chemical composition and the microstructure on the notch toughness of the weld metal and the heat-affected zone, particularly in high-strength alloy-steel welds in which the effects are more complex and drastic than in carbon-steel welds.

Electron-microscope fractography should be very useful in studying the effects of nonmetallic inclusions and minor elements on the notch toughness of weld metal. It has been useful for studying the micromechanisms of fracture of metals. However, no extensive investigation of brittle fracture in weld metals and heat-affected zones has been made by electron microfractographic methods.

6.3 Effects of Welding Variables on Chemical Composition and Microstructure of Weld Metals and the Heat-Affected Zone

An inherent difficulty in obtaining weld metals and heat-affected zones with desired mechanical properties is that chemical composition and microstructures differ from those of the filler and base metal. Complicated chemical reactions take place in the molten metal. Such metallurgical changes as solidification and transformation also take place during cooling.

In many research programs conducted for developing welding processes and procedures, investigators studied to some extent the effect of welding variables, including the chemical composition of the filler and the base metal, chemistry of flux, and welding conditions, on the chemical composition and the microstructures of the weld metal and the heat-affected zone of welds made in their investigations. However, rather few investigations have been made:

(1) To better understand effects of welding variables on the chemical composition and the microstructures of the weld metal and the heat-affected zone.

(2) To improve means of predicting and controlling the chemical composition and the microstructure of the weld metal and the heat-affected zone.

Research is particularly needed on welding of high-strength alloy steels.

CONCLUSIONS

A review has been made of presently available information on the notch toughness of weld metal and the heat-affected zone produced by the use of various welding processes in carbon steel and low-alloy high-strength steels up to 120,000-psi yield strength.

On the basis of data collected in this literature survey, the following conclusions can be drawn:

(1) Weld metals with various degrees of strength and notch toughness are available with various welding processes:

(a) For joining carbon-steel ship plates, weld metals which have notch toughness as good as the base metal joined can be obtained with welding processes including shielded metal-arc welding, submerged-arc welding, and gas metal-arc welding. As-deposited metals made with electroslag and electrogas processes do not meet most of ship-classification-society requirements. Rather poor notch toughness is noted for weld metals made with two-pass submerged-arc welding in heavy plates.

(b) For joining high-strength alloy steels, it becomes increasingly difficult to obtain weld metals with good notch toughness as the required strength increases. Welding processes which produce weld metals with high strength and good notch toughness include:

(i) The shielded metal-arc process, using properly designed low-hydrogen-type electrodes

(ii) The gas metal-arc process, using shielding gas containing a high percentage of inert gas.

However, no welding process can be guaranteed to produce weld metals as tough as HY-80 base metal.

(2) The effects of chemical composition and microstructure on notch toughness are roughly the same in base metals, and in weld metals. However, there are some differences in the ways in which chemical composition and microstructure affect the notch toughness of the base metal and the weld metal. It is believed that major factors which cause the difference in notch toughness are nonmetallic inclusions and such minor elements as oxygen and nitrogen.

(3) The effects of welding procedures on the notch toughness of the weld metal depend greatly on the composition of the filler and the base metal and on the welding processes. In general, weld metals made with low heat input and in many passes have better notch toughness than do those made with high heat input and in few passes. Preheating has a beneficial effect on the notch toughness of weld metals in carbon steel; the

effect of preheating on notch toughness is complex in weld metals in alloy steels. Stress-relieving heat treatments cause complex embrittlement effects on weld metals in some alloy steels.

(4) In mild-steel welds, the notch toughness of the heat-affected zone is not a serious problem. However, loss of notch toughness in some portions of the heat-affected zone is noted in some high-strength alloy steels, especially in heat-treated steels. More information is needed on this subject.

(5) The notch toughness of the weld metal and the heat-affected zone has been evaluated by means of various industrial tests with small specimens. Laboratory tests with large specimens also have been used to evaluate brittle-fracture characteristics of the weld metal and the heat-affected zone. Generally speaking, weld metals and base metals behave the same way (correlate) when test methods are changed. However, cases have been observed in which the results for weld metals obtained with small specimens do not correlate with those obtained with large specimens when such a correlation is found for base metals. It is apparent from these observations that factors sometimes influence the behavior of weld-metal test specimens that do not influence the behavior of base-metal test specimens. Residual stress is one factor that appears to sometimes cause the observed differences.

(6) The effects of the notch toughness of the weld metal and the heat-affected zone on the behavior of weldments have been investigated. With regard to brittle fractures which propagate transverse to the weld, properties of the weld metal and/or the heat-affected zone affect the fracture initiation; however, whether the fracture propagates or not depends primarily on the base metal. With regard to brittle fractures which propagate parallel to the weld, the following have been found:

(a) In carbon-steel weldments in which the weld metal has notch toughness as good as or better than the base metal and the yield strength of the weld metal is as high as or even higher than the base metal, brittle fracture does not usually propagate along the weld metal or the heat-affected zone.

(b) Brittle fractures along the weld metal or the heat-affected zone can be a serious problem in weldments made in certain high-strength alloy steels, especially in heat-treated steels.

One of the most important observations made during this literature survey has been that relatively limited information is available on the notch toughness of weld metals and the heat-affected zone. Information is especially lacking on the realistic requirements for the notch toughness of these zones compared with that of the base metal. It was also observed that there has been relatively little correlation of such factors as chemical composition, microstructure, and welding variables with weld metal and heat-affected-zone notch toughness.

ACKNOWLEDGMENT

The authors are grateful for the cooperation and support of Lt. Commander R. Nielsen, Jr., U. S. Coast Guard, Secretary, Ship Structure Committee, and Mr. A. R. Lytle and Mr. R. W. Rumke of the National Academy of Sciences. The authors also are grateful for the advice given by the members of the Project Advisory Committee, Mr. J. J. Chyle, Chairman; Mr. R. D. Bradway; Dr. W. D. Doty; Commander E. M. Henry, USN; and Dr. D. C. Smith.

REFERENCES

(1) Parker, E. R., Brittle Behavior of Engineering Structures, John Wiley and Sons, Inc., New York (1957).

(2) Shank, M. E., Control of Steel Construction to Avoid Brittle Failure, Welding Research Council Publication (1957).

(3) Biggs, W. D., The Brittle Fracture of Steel, Pitman Publishing Corporation, New York (1960).

(4) Stout, R. D., and Doty, W. D., Weldability of Steel, Welding Research Council (1953).

(5) Kihara, H., Suzuki, H., and Tamura, H., Researches on Weldable High Strength Steels, Society of Naval Architects of Japan, 60th Anniversary Series, Vol I (1957).

(6) Averbach, B. L., "Where We Stand in Design With Brittle Fracture", Interpretive Report, SSC-114, Ship Structures Committee; also "Physical Metallurgy and Mechanical Properties of Materials: Brittle Fracture", Journal of the Engineering Mechanics Division, Proc. American Soc. of Civil Engineers, 86 (EM6), Part 1, 29-43 (1960).

(7) "Selected References on Brittle Fracture", DMIC Memorandum 55, Defense Metals Information Center, Battelle Memorial Institute (May, 1960).

(8) Pellini, W. S., "Notch Ductility of Weld Metal", The Welding Journal, 35 (5), Research Supplement, 217s-233s (1956).

(9) Smith, D. C., "Development, Properties and Usability of Low Hydrogen Electrodes", The Welding Journal, 38 (9), Research Supplement, 377s-392s (1959).

(10) "Standard Methods for Notched Bar Impact Testing of Metallic Materials", ASTM Designation E23-60, ASTM Standards, Part 3 (1961), pp 79-93.

(11) Vidrma, J., "The Influence of Notch Depth on the Notch Toughness Values of the Weld Metal", Zvaranie, 11 (1), 10-12 (1962).

(12) Yoshida, T., and Kumabe, H., "Automatic Welding in Hull Construction", Journal of the Japan Welding Society, 32 (7), 562-580 (1963).

(13) "Rules for the Classification and Construction of Steel Vessels", American Bureau of Shipping, New York (1963).

(14) Kaku, S., "Unified Requirements for Hull Structural Steels and Some Problems on their Welding Procedures", Journal of the Japan Welding Society, 33 (4), 11-16 (1964).

(15) "Rules and Regulations for the Construction and Classification of Steel Ships", Lloyd's Register of Shipping, London (1961).

(16) Dawson, T. J., "Quenched and Tempered Steels in Ship Structure", Welding Journal, 40 (4), 175s (1961).

(17) Lorentz, R. E., Jr., "Utilization of Quenching and Tempering for Improvement in Properties of Low Alloy Steels in Heavy Thicknesses for Welded Construction", Welding Journal, 41 (10), Research Supplement, 433s-447s (1962).

(18) "Steels to Match Your Imagination", Design and Engineering Seminar - 1964, United States Steel Corporation ADUSS 91-1008 (1964).

(19) "Evaluation Criterion of Structural Steels for Low Temperature Application" Japan Welding Engineering Society, WES (March 1964).

(20) "Method of Testing and Approval of Electrodes for Welding Mild and Low Alloy High Tensile Steel", Welding in the World, 1 (1), 2-17 (1963).

(21) "Tentative Methods for Testing Weld Metal Deposited by Submerged-Arc Welding (Mild Steel)", Welding in the World, 1 (1), 28-37 (1963).

(22) Private communication with Mr. S. Kaku of the Nippon Kaiji Kyokai.

(23) Williams, M. L., and Ellinger, G. A., "Investigations of Structural Failures of Welded Ships", The Welding Journal, 32 (10) Research Supplement, 498s-527s (1953).

(24) Williams, M. L., "Correlation of Metallurgical Properties and Service Performance of Steel Plates from Fractured Ships", The Welding Journal, Research Supplement, 37 (10), 445s-454s (1958).

(25) Puzak, P. P., Schuster, M. E., and Pellini, W. S., "Applicability of Charpy Test Data", The Welding Journal, 33 (9), Research Supplement, 433s-441s (1954).

(26) Puzak, P. P., Schuster, M. E., and Pellini, W. S., "Correlations of Brittle Fracture Service Failures With Laboratory Notch-Ductility Tests", The Welding Journal, Research Supplement, 37 (9), 391s-410s (1958).

(27) Hodgson, J., and Boyd, G. M., "Brittle Fracture in Welded Ships; An Empirical Approach from Recent Experience", Transactions Institute of Naval Architects, 100 (3), 141-180 (July 1958).

(28) "Recommendations of Commission IX: Behavior of Metals Subjected to Welding – Recommendations Regarding the Minimum Requirements to be Met by Ordinary Carbon or Low-Alloy Carbon-Manganese Structural Rolled or Forged Steel so That They May be Suitable for Electric Arc Welding", British Welding Journal, 3 (6), 254-257 (1956).

(29) Rühl, K., "State of Brittle Fracture Problems with Reference to Classification of Steels", Schweissen und Schweiden, 8 (4), 107-115 (1956).

(30) Bonhomme, W., "Considerations on the Classification of Steels in Relation to Their Suitability for Welded Metal Construction", Revue de la Soudure, Lastijdschrift, 14 (2), 112-116 (1958).

(31) Feely, F. J., Jr., Northup, M. S., Kleppe, S. R., and Gensamer, M., "Studies on the Brittle Behavior of Tankage Steel Plates", The Welding Journal, 34 (12), Research Supplement, 596s-607s (1955).

(32) Puzak, P. P., and Pellini, W. S., "Evaluation of the Significance of Charpy Tests for Quenched and Tempered Steels", The Welding Journal, 35 (6), Research Supplement, 275s-290s (1956).

(33) Johnson, H. H., and Stout, R. D., "Comparison and Analysis of Notch-Toughness Tests for Welded Steel", The Welding Journal, 39 (11), Research Supplement, 493s-501s (1960).

(34) "Brittle Fracture and Weldability of Structural Steels", Commission 9 of the Japan Institute of Welding (1959).

(35) Smith, D. C., "Evolution of High-Tensile Weld Metal With Low-Hydrogen Electrodes", The Welding Journal, 36 (7), 677-692 (1957).

(36) Cowan, A., "Electrodes for Welding Higher Strength Reactor Pressure Vessel Steels", Welding and Metal Fabrication, 30 (10), 386-394 (1962).

(37) Roberts, D.F.T., Prince, A., Blore, M.H.D., and Ridgway, W. F., "Impact Strength of Butt Welds in Thick Plate", British Welding Journal, 9 (16), 346-361 (1962).

(38) Roberts, D.F.T., and Ridgway, W. F., "A Further Note on the Impact Strength of Butt Welds in Thick Plate", British Welding Journal, 10 (7), 341-343 (1963).

(39) Garstone, J., and Johnson, F. A., "Impact Properties of Mild Steel Weld Metals", British Welding Journal, 10 (5), 224-230 (1963).

(40) Doneux, G., "Constatations et remarques au sujet de l'essai Charpy V dans le domaine du soudage - Part 1 Facteurs d'influence sur la Résilience Charpy V du Metal Deposé par les Electrodes Basiques", Revue de la Soudure: Lastijdschrift (Brussels), 19 (4), 169-185 (1963).

(41) Desguin, H., "Constatations et remarques au sujet de l'essai Charpy V dans le domaine du soudage – Part 2 Quelques Difficultés d'utilisation du Charpy V aux Fins d'étude et aux Fins de Reception", Revue de la Soudure: Lastijdschrift (Brussels), 19 (4), 186-200 (1963).

(42) Kasatkine, B. S., "Brittle Failure of Low-Carbon Steel Welds", Avtomaticheskaya Svarka, 11 (11), 71-80 (1958); Henry Brutcher Translation No. 4786.

(43) Matsuhara, T., "Mechanical Properties of Weld Metal (Report 1)", Journal of the Japan Welding Society, 26 (9), 563-573 (1957).

(44) Matsuhara, T., and Nakayama, H., "Mechanical Properties of Weld Metal (Report 2)", Journal of the Japan Welding Society, 26 (11), 694-702 (1957).

(45) Ohwa, T., "Notch Toughness of Weld Metals", Journal of the Japan Welding Society, 31 (1, 2, and 4), 4-10, 87-92, 256-261 (1962).

(46) Watkinson, F., "Notch Ductility of Mild-Steel Weld Metal", British Welding Journal, 6 (4), 162-74 (1959).

(47) Welding Handbook, Fourth Edition, Section V, The American Welding Society (1961).

(48) Sagan, S. S., and Campbell, H. C., "Factors Which Affect Low-Alloy Weld-Metal Notch-Toughness", Welding Research Council Bulletin, Series No. 59 (April 1960).

(49) Kraichik, M. M., "Properties of Welded Joints in 10KhGN Steel", Svarochnoye Proizvodstvo, 5 (6), 41-50 (1959).

(50) Kolago, M., "Mechanical Tests of Automatically Submerged Welded Butt Joints in Hull and Boiler Grade Steels", Przeglad Spawabnictwa, 14 (6), 157-161 (1962).

(51) Libra, O., and Podhova, J., "Application of Material 11483.1 for Pressure Vessels", Zváranie (Technical Journal of the Czechoslovak Welders), 12 (9), 245-252 (1963).

(52) Augland, B., and Christensen, N., "Some Observations on the Notch Toughness of Submerged Arc Weld Deposits", British Welding Journal, 8 (10), 473-476 (1961).

(53) Stern, I. L., Kahn, N. A., and Nagler, H., "Notch-Toughness Characteristics of Submerged-Arc Weld Deposits", The Welding Journal, 36 (5), Research Supplement, 226s-234s (1957).

(54) Private communication with Mr. S. Kaku of the Nippon Kaiji Kyokai.

(55) Hotta, T., Sakai, T., Bada, T., Tanaka, H., Morimoto, I., and Nakayama, H., "Application of the FN Process to Mild and High-Tensile-Strength Steels and Hard-Facing in Submerged Arc Welding", Document No. XII-217-64, Commission XII of the International Institute of Welding (1964).

(56) Okada, K., Saruwatari, S., Tokura, M., Miura, T., "Cut Wire Submerged Arc Welding Process — New Automatic Arc Welding Process Using 'Cut Wire' as an Auxiliary Filler Metal", Document XII-219-64, Commission XII of the International Institute of Welding (1964).

(57) "Submerged Arc Welding of High Strength Steel", Document XII-198-63, Commission XII of the International Institute of Welding (1963).

(58) Makara, A. M., Slutskaya, T. M., and Mosendz, N. A., "Submerged Arc Welding of High-Tensile Steels with Fused Fluxes", Autom. Svarka (Automatic Welding), 12 (10), 1-9 (1959).

(59) Takagi, O., Nishi, S., and Suzuki, K., "Notch Toughness of the Metal Deposited by Automatic Arc Welding", Journal of the Japan Welding Society, 31 (9 and 10), 767-774 and 821-833 (1962).

(60) Yoshida, T., Onoe, H., Kumabe, H., and Tsukui, H., "Study on Submerged Arc Welding of HT-80 Steel", Journal of the Japan Welding Society, 32 (12), 1134-1142 (1963).

(61) Nakane, K., and Muramoto, T., "Submerged Arc Welding of High-Strength Steels", Railway Technical Research Report No. 414, the Railway Research Institute of the Japanese National Railways (June 1964).

(62) Lewis, W. J., Faulkner, G. E., Martin, D. C., and Rieppel, P. J., "Submerged-Arc Welding HY-80 Steel", The Welding Journal, 39 (6), Research Supplement, 266s-272s (1960).

(63) Lewis, W. J., Faulkner, G. E., and Rieppel, P. J., "Flux and Filler Wire Developments for Submerged-Arc Welding of HY-80 Steel", The Welding Journal, 40 (8), Research Supplement, 337s-345s (1961).

(64) Kubli, R. A., and Sharav, W. B., "Advancements in Submerged-Arc Welding of High-Impact Steels", Welding Journal, 40 (11), Research Supplement, 497s-502s (1961).

(65) Yoshiki, M., "Design and Construction of Large Tankers in Japan", Welding and Metal Fabrication, 31 (3), 95-99 (1963).

(66) Christopher, G., and Becker, R. C., "Gas Metal-Arc Welding of Low-Carbon Steels", Welding Journal, 39 (5), Research Supplement, 478s-487s (1960).

(67) Sekiguchi, H., "Recent Advancement of CO_2-O_2 Arc Welding Process in Japan", Document No. XII-127-62, Commission XII of the International Institute of Welding (1962).

(68) Salter, G. R., "Argon-CO_2-O_2 Mixtures for the Welding of Mild Steel", British Welding Journal, 11 (2), 63-78 (1964).

(69) Nelson, J. W., Randall, M. D., and Martin, D. C., "Development of Methods of Making Narrow Welds in Thick Steel Plates by Automatic Arc Welding Processes", Final Report to Bureau of Ships, Department of the Navy on Contract NObs-86424, Battelle Memorial Institute (March, 1964).

(70) Inagaki, M., "Carbon Dioxide Arc Welding of High-Strength Steels", Journal of the Japan Welding Society, 33 (8), 629-653 (1964).

(71) Sekiguchi, H., Masumoto, I., Tamaoki, K., and Asai, Y., "Impact Properties of Weld Metals Deposited With the CO_2-O_2 Gas Shielded Arc Welding Process - Part 1", Journal of the Japan Welding Society, 32 (9), 732 (1963); abstract of a paper presented at the National Fall Meeting, 1963.

(72) Sibley, C. R., "All-Position Welding of HY-80 Steel With the Gas-Shielded Process", The Welding Journal, 39 (10), Research Supplement, 433s-437s (1960).

(73) Sibley, C. R., "Welding of HY-80 Steel with the Gas-Shielded Metal Arc Process", The Welding Journal, 42 (5), Research Supplement, 219s-232s (1963).

(74) Silverstein, S. M., Sopher, R. P., and Rieppel, P. J., "Filler Wire for Welding Army Ordnance Armor", The Welding Journal, 38 (5), Research Supplement, 232s-240s (1959).

(75) Volochkevich, G. Z., "Electric Slag Welding", Avtomaticheskaya Svarka, 6 (6), 3-10 (1953).

(76) Paton, B. E., "Electroslag Welding of Very Thick Material", The Welding Journal, 41 (12), 1115-1123 (1962).

(77) Thomas, R. D., Jr., "Electroslag Welding – A New Process for Heavy Fabrication", The Welding Journal, 39 (2), 111-117 (1960).

(78) Danhier, F. G., "Western European Techniques in Electroslag Welding", The Welding Journal, 41 (1), 17-23 (1962).

(79) Franz, R. J., and Wooding, W. H., "Automatic Vertical Welding and Its Industrial Applications", The Welding Journal, 42 (6), 489-494 (1963).

(80) Cresswell, R. A., "Electroslag Welding: Present Position and the Attitude of Classification Societies", Document XII-184-63, Commission XII of the International Institute of Welding (1963).

(81) Burden, C. A., Garstone, J., and Lucey, J. A., "Electro-Slag Welding of Relatively Thin Plate", British Welding Journal, 11 (4), 148-155 (1964).

(82) "A New Conception in Shipbuilding Construction", ESAB News, No. 10 (1964).

(83) Rote, R. S., "Investigation of the Properties of Electroslag Welds", The Welding Journal, 43 (5), 421-426 (1964).

(84) Santilhano, P. D., and Hamilton, I. G., "Experience in Electro-Slag Welding", British Welding Journal, 11 (6), 256-257 (1964).

(85) Frondeville, B., "Contribution a l'étude des Assemblages Soudés Verticalement sous Laitier", Soudage et Techniques Connexes, 16 (2), 103-115 (March-April 1962).

(86) Erdmann-Jesnitzer, F., Schubert, J., and Marschner, M., "Verbesserung von Gefügeausbildung und Mechanichen Eigenschaften von Elektro-Schlache-Schweissnähten", Schweisstechnik (East Germany), 11 (10), 441-448 (1961).

(87) Ostrovskaya, S. A., "Some Data for the Mechanical Properties of the Weld Metal Produced When Carbon and Low-Alloy Constructional Steels are Electroslag Welded", Avtomaticheskaya Svarka, 15 (2), 1-10 (1962).

(88) Makara, A. M., Novikov, I. V., and Lutsyuk, V. A., "The Development of a Technique for the Electro-Slag Welding of Boiler Shells Made of Type AK Medium Alloy Steel", Avtomaticheskaya Svarka, 12 (4), 66-76 (1959).

(89) Pokataev, S. V., Novitskii, V. K., and Kryanin, I. R., "Effects of the Steel-melting Conditions on the Impact Strength of Electroslag Welded Joints at Low Temperatures", Svarchnoe Proizvodatvo, 9 (6), 22-26 (1963).

(90) Ujiie, A., Sato, S., and Nagaoka, T., "Procedure Condition of Electroslag Welding on Application for Pressure Vessel", Document XII-178-63, Commission XII of the International Institute of Welding (1963).

(91) Boulger, F. W., Frazier, R. H., and Lorig, C. H., "Investigation of the Influence of Deoxidation and Chemical Composition on Notched-Bar Properties of Ship Plate Steels", Welding Research Council, Bulletin No. 26 (April 1956).

(92) Van der Veen, J. H., "Influence of Steel-Making Variables on Notch Toughness", Ship Structure Committee Report, Serial No. SSC-128 (June 1960).

(93) Boulger, F. W., and Hansen, W. R., "The Effect of Metallurgical Variables in Ship-Plate Steels on the Transition Temperatures in the Drop-Weight and Charpy V-Notch Tests", SSC-145, Ship Structures Committee (December 1962).

(94) Gross, J. H., and Stout, R. D., "The Effect of Microstructure on Notch Toughness - Parts II and III", The Welding Journal, 34 (3), Research Supplement, 117s-122s (1955), and 35 (2), 72s-76s (1956).

(95) Kottcamp, E. H., Jr., and Stout, R. D., "Effect of Microstructure on Notch Toughness - Part IV", The Welding Journal, 38 (11), Research Supplement, 435s-440s (1959).

(96) Sakaki, H., "Effect of Alloying Elements on Notch Toughness of Basic Weld Metals", Reports 1 through 7, Journal of the Japan Welding Society, 28 (12), 858-863; 29 (2), 102-105; 29 (6), 474-484; 29 (7), 539-544; 29 (12), 940-945; 30 (4), 32-37; 30 (6), 22-25 (1959-61).

(97) Dorschu, K. E., and Stout, R. D., "Some Factors Affecting the Notch Toughness of Steel Weld Metal", Welding Journal, 40 (3), 97s (1961).

(98) Ohwa, T., "Statistical Investigation on the Effect of Alloying Elements for the Notch-Toughness of Weld Metals", Document II-221-62, Commission II of the International Institute of Welding (1962).

(99) Heuschkel, J., "Composition Controlled, High-Strength, Ductile, Tough, Steel Weld Metals", The Welding Journal, 43 (8), Research Supplement, 361s-384s (1964).

(100) "Background for the Development of Materials to be Used in High-Strength-Steel Structural Weldments", DMIC Report 172, Defense Metals Information Center, Battelle Memorial Institute (July 31, 1962).

(101) Kolisnyh, V. N., and Podgaetskii, V. V., "The Effect of Carbon and Phosphorus on the Cold-Shortness of Submerged Arc Welds in Carbon Steel", Avtomatichiskaya Svarka, 14 (3), 18-25 (1961).

(102) Rinebolt, J. A., and Harris, W. J., "Effects of Alloying Elements on Notch Toughness of Pearlitic Steels", Trans. ASM, 43, 1175-1214 (1951).

(103) Ziegler, N. A., Meinhart, W. L., and Goldsmith, J. R., "Effects of Manganese on the Properties of Cast Carbon and Carbon-Molybdenum Steels", Trans. Am. Soc. Metals, 38, 398 (1947).

(104) Ziegler, N. A., Meinhart, W. L., and Goldsmith, J. R., "Effect of Silicon on the Properties of Cast Carbon and Carbon-Molybdenum Steels", Trans. Am. Soc. Metals, 40, 617 (1948).

(105) Ziegler, N. A., Meinhart, W. L., and Goldsmith, J. R., "Effect of Vanadium on the Properties of Cast Carbon and Carbon-Molybdenum Steels", Trans. Am. Soc. Metals, 41, 565-608 (1949).

(106) Smith, A. A., "The Effect of Wire Copper Coating on the Mechanical Properties of CO_2 Weld Metal", Document XII-B-6-64, Commission XII of the International Institute of Welding (1964).

(107) Ohwa, T., "A Study on Oxygen and Nitrogen in Multilayer Mild-Steel Weld Metals, Part III. Notch Toughness", Kobe Steel Works, Welding Laboratory Report No. 35-5, 1-189 (1960).

(108) Sakaki, H., "Metallurgical Aspects of Lime-Fluoride-Silica Electrode Weld Metal", Document No. II-297-64, Commission II of the International Institute of Welding (1964).

(109) "Spatial Distribution of Manganese, Silicon, Chromium, and Oxygen in Submerged-Arc Weld Deposits", Contract DA-91-591-EUC-2797, Report to the U. S. Department of Army, European Research Office from SINTEF The Engineering Research Foundation at the Technical University of Norway (March 1964).

(110) Sekiguchi, H., "A New Proposal for Steel Filler Wire for Welding", The Welding Journal, 30 (12), Research Supplement, 622s-624s (1951).

(111) Körber, F., and Oelsen, W., "Die Grundlagen der Deoxydation mit Mangan und Silizium", Mitt. Kaizer Wilhelm Inst. Eisenforsch., 15, 271-309 (1933).

(112) Petch, N. J., "The Ductile-Cleavage Transition in Alpha-Iron", Fracture, proceedings of an international conference on the Atomic Mechanisms of Fracture, held in Swampscott, Massachusetts, April 12-16, 1959, The Technology Press of MIT and John Wiley and Sons, Inc., New York (1959), pp 54-67.

(113) Averbach, B. L., Felbeck, D. K., Hahn, G. T., and Thomas, D. A., editors, Fracture - proceedings of an international conference on the Atomic Mechanisms of Fracture, held in Swampscott, Massachusetts, April 12-16, 1959, The Technology Press of MIT and John Wiley and Sons, Inc., New York (1959).

(114) Low, J. R., Jr., "The Fracture of Metals", Progress in Materials Science, Pergamon Press, 12 (1), 1-96 (1963).

(115) Irvine, K. J., and Pickering, F. B., "Relationship Between Microstructure and Mechanical Properties of Mild Steel Weld Deposits", British Welding Journal, 7 (5), 353-364 (1960).

(116) Tremlett, H. F., Baker, R. G., and Wheatley, J. M., "Mechanical Properties and Metallurgical Features of Mild Steel Weld Metals, Part I - Properties of Multi-Run Specimens", British Welding Journal, 8 (9), 437-447 (1961).

(117) Tremlett, H. F., and Baker, R. G., "Mechanical Properties and Metallurgical Features of Mild Steel Weld Metals, Part II - Metallographic Examination of Double-Run Specimens", British Welding Journal, 8 (9), 447-454 (1961).

(118) Warke, W. R., and McCall, J. L., "Using Electron Microscopy to Study Metal Fracture", SAE Preprint No. 828D, Society of Automotive Engineers, Inc., New York, 13 pp (1964).

(119) Beachem, C. D., and Pelloux, R.M.N., "Electron Fractography - A Tool for the Study of Micro Mechanisms of Fracturing Processes", text used for Workshop in Fracture Mechanics, held August 16-28, 1964, at Denver Research Institute by Universal Technology Corporation, Dayton, Ohio.

(120) McMahon, C. J., Jr., "Micromechanisms of Cleavage Fracture in Polycrystalline Iron", Ship Structures Committee, SSC-161 (1964).

(121) Malevskii, Y. B., "A Method of Electron Microfractography", Avt. Svarka, 13 (11), 10-12 (1960).

(122) Armstrong, T. N., and Warner, W. L., "Effect of Preheating and Postheating on Toughness of Weld Metal", The Welding Journal, 37 (1), Research Supplement, 27s-29s (1958).

(123) De Garmo, E. P., "A Theory for Preheating of Plain, Low-Carbon Steels", The Welding Journal, 37 (3), Research Supplement, 93s-96s (1958).

(124) Ohwa, T., "Effect of Stress-Relieving Heat-Treatment on Notch Toughness of Weld Metals, Parts 1 Through 8", Welding World (a Japanese publication), 11, 12 (1959-1960).

(125) Kihara, H., and Masubuchi, K., Distortions and Residual Stresses Due to Welding, The Sampo Publishing Co., Tokyo (1955).

(126) "Welding in Shipbuilding", British Welding Journal, 8, 477-481 (1961).

(127) Kammer, P. A., Masubuchi, K., and Monroe, R. E., "Cracking in High-Strength Steel Weldments", DMIC Report 197, Defense Metals Information Center, Battelle Memorial Institute (February 7, 1964).

(128) Ostrovskaya, S. A., "Investigation of the Properties and Weldability of 70-160 mm Thick Type M Steel", Avtomaticheskaya Svarka, 12 (5), 1-20 (1959).

(129) Pokataev, S. V., Novitskii, V. K., and Kryanin, I. R., "Effects of the Melting Process on the Impact Strength of Electro-Slag Weld Heat Affected Zones", Savchnoe Proizvodatvo, 9 (1), 3-8 (1963).

(130) Hatch, W. P., Jr., and Hartbower, C. E., "V Notch Charpy Impact Testing of Weld Metal and Heat-Affected Zone Simultaneously", The Welding Journal, 35 (3), Research Supplement, 120s-126s (1956).

(131) Hatch, W. P., and Hartbower, C. H., "Toughness of Welds Evaluated Separately and in Composite", The Welding Journal, 37 (10), Research Supplement, 455s-462s (1958).

(132) Nippes, E. F., and Savage, W. F., "Tests of Specimens Simulating Weld Heat-Affected Zone", The Welding Journal, Research Supplement, 28 (12), 599s-616s (1949).

(133) Nippes, E. F., "The Weld Heat-Affected Zone", The Welding Journal, 38 (1), Research Supplement, 1s-18s (1959).

(134) Brown, W. F., Jr., Ebert, L. J., and Sachs, G., "Distribution of Strength and Ductility in Welded Steel Plate as Revealed by the Static Notch Bar Tensile Test", The Welding Journal, 26 (10), Research Supplement, 545s-554s (1947).

(135) Grossman, N., and McGregor, C. W., "The Brittle Transition Temperature of Various Low-Carbon Steels Welded by the Same Method", The Welding Journal, 27 (5), Research Supplement, 267s-271s (1948).

(136) Masubuchi, K., Kusuda, T., and Tamura, H., "Effect of Welding on the Notch Sensitivity of Ship Steels", Journal of the Japan Welding Society, 21 (1), 2-9 (1952).

(137) Kihara, H., Masubuchi, K., and Tamura, H., "Effect of Welding on the Notch Sensitivity of Steel – Especially on the Embrittled Zone Due to Welding", Brittle Fracture in Mild Steel and Their Welded Joints, The Welding Research Committee of the Society of Naval Architects of Japan (1953), pp 144-152.

(138) Ando, Y., Yamaguchi, I., Iida, K., Imai, Y., "Effect of Welding When Superposed Upon Prestrained Steel", Report of Institute of Industrial Science, University of Tokyo, Japan, 283-318 (March 1955).

(139) Kihara, H., Kusuda, T., and Iida, K., "Experimental Studies on the Weld Heat-Affected Embrittled Zone in Mn-Si High Tensile Strength Steels", Journal of the Japan Welding Society, 25 (5), 264-266 (1956).

(140) Roberts, D.F.T., Prince, A., Billington, S. R., and Ridgway, W. F., "Note on the Notch-Ductility Damage Zone Adjacent to Thick Plate Butt Welds", British Welding Journal, 9 (5), 280-283 (1962).

(141) Doty, W. D., "Properties and Characteristics of a Quenched and Tempered Steel for Pressure Vessels", The Welding Journal, 34 (9), Research Supplement, 425s-441s (1955).

(142) Bruckner, W. H., and Robertson, C. A., "Energy Absorption Studies of Welds in Tempered Martensitic Base Metal", The Welding Journal, 37 (3), Research Supplement, 97s-100s (1958).

(143) Nippes, E. F., Savage, W. F., and Paez, J. M., "Impact Characteristics of Heat-Affected Zones in Mn-Mo Armor Steels", The Welding Journal, 39 (1), Research Supplement, 31s-39s (1960).

(144) Grotke, G. E., "Weldability and Heat-Affected-Zone Toughness of HY-150 Steels", The Welding Journal, 43 (6), Research Supplement, 265s-281s (1964).

(145) Sekiguchi, H., and Suzuki, T., "Distribution of Ductility in Welded High-Strength Steel Plates as Revealed by the Notched Bar Impact Tensile Test", Journal of the Japan Welding Society, 33 (3), 233-234 (1964); summary only.

(146) Kobler, J. S., "Notch-Ductile Weld Metal for Dynamically Loaded T-1 Steel Structures", The Welding Journal, 39 (4), 160s-171s (1960).

(147) Nippes, E. F., and Sibley, C. R., "Impact Performance of Synthetically Reproduced Heat-Affected Zone Microstructures in 'T-1' Steel", The Welding Journal, 35 (10), Research Supplement, 473s-480s (1956).

(148) Nippes, E. F., Savage, W. F., and Allio, R. J., "Studies of the Weld Heat-Affected Zone of T-1 Steel", The Welding Journal, 36 (12), Research Supplement, 531s-540s (1957).

(149) Sekiguchi, H., Inagaki, M., and Hikino, K., "Cooling Time and Brittleness of Various Steels Submitted to Welding", Journal of the Japan Welding Society, Report 1: 27 (8), 457-460 (1958); Report 2: 27 (8), 461-465 (1958); Report 3: 27 (9), 526-530 (1958); Report 4: 29 (7), 552-558 (1960).

(150) Suzuki, H., and Tamura, H., "Notch Toughness and Mechanical Properties of Synthetic Heat-Affected Zone Microstructures of Quenched and Tempered Steels", Journal of the Japan Welding Society, 29 (1), 21-29 (1960).

(151) Suzuki, H., and Tamura, H., "Notch Toughness of the Synthetic Heat-Affected-Zone Microstructures of High Strength Steels", Journal of the Japan Welding Society, 30 (11), 820-830 (1961).

(152) Suzuki, H., and Tamura, H., "Evaluation of Notch Toughness of Weld Heat-Affected Zone in High Strength Steels Using a Synthetic Apparatus for Weld Thermal Cycles", Transactions National Research Institute for Metals, Japan, 5 (3), 96-106 (1963).

(153) Nishi, S., Suzuki, K., and Shimoyama, J., "Notch Toughness of Weld Heat-Affected Zone in High-Strength Steels", Mitsubishi Heavy Industries Technical Review, 1 (1), 72-97 (1964).

(154) McClure, G. M., Eiber, R. J., Hahn, G. T., Boulger, F. W., and Masubuchi, K., "Research on the Properties of Line Pipe", Summary Report from Battelle Memorial Institute to American Gas Association, New York (May 1962).

(155) Koshiga, F., "Brittle Fracture Testing Methods", Journal of the Japan Welding Society, 32 (3 and 4), 162-168 and 314-325 (1963).

(156) Yamauchi, S., and Nakai, T., "Propagation Characteristics of Cracks in the Welded Zone of Quenched-and-Tempered High-Tensile Steel", Document X-264-61, Commission X of the International Institute of Welding (1961).

(157) Kihara, H., "Evaluation of Ductility for Steels and Deposited Metals in Wide Plate and Industrial Tests", Document IX-368-63, Commission IX of the International Institute of Welding (1963).

(158) Christensen, N., and Augland, B., "Methods of Notch-Toughness Testing of Ship Plate Steel", British Welding Journal, 4 (2), 69-87 (1957).

(159) Koshiga, F., "On the Pressed-Notch Charpy Test", Journal of the Society of Naval Architects of Japan, 104, 111-118 (1958).

(160) Orner, G. M., and Hartbower, C. E., "The Low-Blow Transition Temperature", ASTM Proceedings, 58, 623-634 (1958).

(161) Orner, G. M., and Hartbower, C. E., "Effect of Specimen Geometry on Charpy Low-Blow Transition Temperature", The Welding Journal, 36 (12), Research Supplement, 521s-527s (1958).

(162) Fichte, A., "UP-Schweissung von vollen Steganschlüsen bei dicken Materialguerschnitten", Schweisstechnik, 11 (7), 312-316 (1961).

(163) Shorshorov, M. Kh., and Kodolov, V. D., "Notch Sensitivity of Low Alloy and Carbon Steels in Arc Welding", Svarochnoe Proizvodstvo, 7 (8), 1-7 (1961).

(164) Schnadt, H. M., "Test Piece Used for the Control of Steel Brittleness", Schweissmitt., 13 (22), 35-38 (1955).

(165) Schnadt, H. M., "A New Approach to the Solution of Brittle Fracture Problems in Modern Steel Construction", Document IX-292-61, Commission IX of the International Institute of Welding (1961).

(166) Weck, R., "An Account of M. Henri M. Schnadt's Ideas on the Strength of Materials, and His Testing Methods", Transactions of the Institute of Welding, 41-56 (April 1950).

(167) Puzak, P. P., Eschbacher, E. W., and Pellini, W. S., "Initiation and Propagation of Brittle Fracture in Structural Steels", The Welding Journal, 31 (12), Research Supplement, 561s-581s (1952).

(168) Puzak, P. P., and Pellini, W. S., "Evaluation of Notch-Bend Specimens", The Welding Journal, Research Supplement, 187s-192s (April 1954).

(169) Puzak, P. P., and Babech, A. J., "Normalisation Procedures for NRL Drop-Weight Test", The Welding Journal, 38 (5), Research Supplement, 209s-218s (1959).

(170) Pellini, W. S., and Eschbacher, E. W., "Ductility Transition of Weld Metal", The Welding Journal, 33 (1), Research Supplement, 16s-20s (1954).

(171) Baker, J. F., and Tipper, C. F., "The Value of the Notch Tensile Test", Proceedings of the Institution of Mechanical Engineers, 170, 65-75 (1956).

(172) Norén, T. M., "The Nominal Cleavage Strength of Steel and Its Importance for Welded Structures", Transactions North East Coast Institution of Engineers and Shipbuilders, 73, 87-112 (1956-57).

(173) "Fracture Testing of High Strength Sheet Materials: A Report of a Special ASTM Committee", ASTM Bulletin No. 243, 29-40 (June 1960); No. 244, 18-28 (February 1960); and "Materials Research and Standards", 1 (11), 877-885 (November 1961).

(174) Griffith, A. A., "The Phenomena of Rupture and Flow in Solids", Phil. Trans. Roy. Soc., 221, 163-198 (1921); and "The Theory of Rupture", Proc. First International Congress Appl. Mech., 55-63 (1924).

(175) Irwin, G. R., "Fracture", Encyclopedia of Physics, Vol VI, Elasticity and Plasticity, Springer-Verlag, Berlin, Goettingen, Heidelberg, 551-590 (1958).

(176) Irwin, G. R., "Structural Aspects of Brittle Fracture", Applied Materials Research, 3 (2), 65-81 (April 1964).

(177) Kahn, N. A., and Imbembo, E. A., "A Method of Evaluating Transition From Shear to Cleavage Failure in Ship Plate and Its Correlation With Large-Scale Plate Tests", The Welding Journal, 27 (4), Research Supplement, 169s-182s (1948).

(178) de Graaf, J. E., and Van der Veen, J. H., "The Notched Slow-Bend Test as a Brittle-Fracture Test", Journal of Iron and Steel Institute, 173, 19-30 (1953).

(179) Imbembo, E. A., and Ginsberg, F., "Notch-Toughness Properties of Ship-Plate Steel as Evaluated by the Van der Veen Notched Slow-Bend Test", SSC-108, Ship Structures Committee (August 1959).

(180) Stout, R. D., McGeady, L. J., Sund, C. P., Libech, J. F., and Doan, G. E., "Effect of Welding on Ductility and Notch Sensitivity of Some Ship Steel", The Welding Journal, 26 (6), Research Supplement, 335s-357s (1947).

(181) Stout, R. D., and McGeady, L. J., "Notch Sensitivity of Welded Steel Plate", The Welding Journal, 28 (1), Research Supplement, 1s-9s (1949).

(182) Kinzel, A. B., "Ductility of Steel for Welded Structures", The Welding Journal, 27 (5), Research Supplement, 217s-234s (1948); and Transactions of ASM, 40, 27-82 (1948).

(183) Offenhauer, C. M., and Koopman, K. H., "Factors Affecting the Weldability of Carbon and Alloy Steels - Development of Test Procedure and Effect of Carbon, Part 1", The Welding Journal, 27 (5), Research Supplement, 234s-252s (1948).

(184) Jackson, C. E., and Goodwin, W. J., "Effect of Variations in Welding Techniques on the Transition Behavior of Welded Specimens", The Welding Journal, 27 (5), Research Supplement, 253s-266s (1948).

(185) Kommerell, O., Stahlbau-Technik, 2, 51-52 (1938).

(186) Melhardt, H., "New Austrian Welding Standards", The Welding Journal, 31 (7), 592-595 (1952).

(187) Hauttmann, H., "Erprobung Trennbruchsicherer Baustähle in Berstversuchen", Schweisstechnik (Austria), 13 (2), 13-19 (1959).

(188) Otani, M., "Notch Sensitivity of Welded Mild Steel Plates", Brittle Fracture in Mild Steels and Their Welded Joints, The Welding Research Committee of the Society of Naval Architects of Japan (1953), pp 126-143.

(189) Otani, M., and Ota, S., "Effect of Welding on the Notch Sensitivity of Mild Steel", Journal of the Japan Welding Society, 1st Report: 22 (8), 12-20 (1953); 2nd Report: 22 (9), 19-24 (1953); 3rd Report: 22 (10, 11, 12), 25-33 (1953); 4th Report: 23 (1-2), 35-40 (1954).

(190) Murphy, W. J., and Stout, R. D., "Fracture Behavior in the Notch Slow-Bend Test", The Welding Journal, 35 (4), Research Supplement, 169s-180s (1956).

(191) Stout, R. D., Murphy, W. J., and Westgren, R. C., "Evaluation of the Kinzel Test From Its Fracture Characteristics", The Welding Journal, 37 (3), Research Supplement, 107s-113s (1958).

(192) Murphy, W. J., and Stout, R. D., "Effect of Electrode Type in the Notch Slow-Bend Test", The Welding Journal, 33 (7), Research Supplement, 305s-310s (1954).

(193) Otake, T., Morita, S., and Goda, S., private communication.

(194) Hartbower, C. E., and Pellini, W. S., "Explosion Bulge Test Studies of the Deformation of Weldments", The Welding Journal, 30 (6), Research Supplement, 307s-318s (1951).

(195) Hartbower, C. E., "Mechanics of the Explosion Bulge Test", The Welding Journal, 32 (7), Research Supplement, 333s-341s (1953).

(196) Puzak, P. P., Schuster, M. E., and Pellini, W. S., "Crack-Starter Tests of Ship Fracture and Project Steels", The Welding Journal, 33 (10), Research Supplement, 481s-495s (1954).

(197) Mikhalapov, G. S., "Direct Explosion Tests of Welded Joints", The Welding Journal, 29 (3), Research Supplement, 109s-122s (1950).

(198) Mikhalapov, G. S., "Evaluation of Welded Ship Plate by Direct Explosion Testing", The Welding Journal, 30 (4), Research Supplement, 195s-201s (1951).

(199) Mikhalapov, G. S., and Snelling, W. A., "Direct Explosion Tests of Welding Procedures in Ship Plate", The Welding Journal, 34 (2), Research Supplement, 97s-104s (1955).

(200) Warner, W. L., "The Toughness of Weldability", The Welding Journal, 34 (1), Research Supplement, 9s-22s (1955).

(201) Fabrykowski, Z. J., "Ferritic Welding of Steel Armor", The Welding Journal, 40 (4), 339-342 (1961).

(202) Folkhard, E., "Le Comportment de Tuyaux pour Conduites Forcées, Soudés à l'arc, lors Déssais par Éclatement", Revue de la Soudure: Lastijdschrift (Brussels), 12 (1), 15-27 (1956).

(203) Kihara, H., Ichikawa, S., Masubuchi, K., Ogura, Y., Iida, K., Yoshida, T., and Oba, H., "Explosion Tests on Arc-Welded Tubes With and Without Stress Annealing", Journal of the Society of Naval Architects of Japan, 100, 179-187 (1956).

(204) Kihara, H. , Ichikawa, S. , Masubuchi, K. , Iida, K. , Yoshida, T. , Oba, H. , and Ogura, Y. , "Explosion Tests on Arc Welded Tubes With Various Welding Procedures", Journal of the Society of Naval Architects of Japan, 104, 119-129 (1958).

(205) Hartbower, C. E. , and Pellini, W. S. , "Investigation of Factors Which Determine the Performance of Weldments", The Welding Journal, 30 (10), Research Supplement, 499s-511s (1951).

(206) Puzak, P. P. , and Pellini, W. S. , "Embrittlement of High Strength Ferritic Welds", The Welding Journal, 31 (11), Research Supplement, 521s (1952).

(207) Pellini, W. S. , and Eschbacher, E. , "Effects of Peening Last Pass of Welds", The Welding Journal, 33 (2), Research Supplement, 71s-76s (1954).

(208) Pellini, W. S. , and Eschbacher, E. W. , "Performance of Weldments and Prime Plate of ABS-B Steel", The Welding Journal, 33 (10), Research Supplement, 524s-531s (1954).

(209) Arnold, P. C. , "Problems Associated With the Welding of T-1 Material", The Welding Journal, 36 (8), Research Supplement, 373s-381s (1957).

(210) Silverstein, S. M. , Sopher, R. P. , and Rieppel, P. J. , "Explosion-Bulge Tests of Armor Weldments", The Welding Journal, 39 (7), Research Supplement, 309s-314s (1960).

(211) Puzak, P. P. , and Pellini, W. S. , "Crack Arresting by Overlays of Notch-Tough Weld Metal", The Welding Journal, 34 (12), Research Supplement, 577s-581s (1955).

(212) Robertson, T. S. , "Propagation of Brittle Fracture in Steel", Journal of the Iron and Steel Institute, 175, 361-374 (December 1953).

(213) Feely, F. J. , Jr. , Hrkto, D. , Kleppe, S. R. , and Northrup, M. S. , "Report on Brittle Fracture Studies", The Welding Journal, 33 (2), Research Supplement, 99s-111s (1954).

(214) Yoshiki, M. , and Kanazawa, T. , "A New Testing Method to Obtain Critical Stress and Limiting Temperature for the Propagation of Brittle Crack", Proceedings of the First Japan Congress on Testing Materials - Metallic Materials, 66-68 (1958).

(215) Yoshiki, M. , Kanazawa, T. , and Koshiga, F. , "Recent Studies on Brittle Fracture Propagation-Arrest in Japan", a paper contributed to Joint Colloquium of Commissions IX and X of the International Institute of Welding, in Prague, Czechoslovakia, July 1964.

(216) Hall, W. J. , Mosborg, R. J. , and McDonald, V. J. , "Brittle Fracture Propagation in Wide Steel Plates", The Welding Journal, 36 (1), Research Supplement, 1s-8s (1957).

(217) Hall, W. J. , and Barton, F. W. , "Summary of Some Studies of Brittle-Fracture Propagation", SSC-149, Ship Structures Committee (September 4, 1963).

(218) Greene, T. W., "Evaluation of Effect of Residual Stresses", The Welding Journal, 28 (5), Research Supplement, 193s-204s (1949).

(219) Wells, A. A., "The Brittle Fracture Strength of Welded Steel Plates", Quarterly Trans. Inst. Naval Arch., 48 (3), 296-326 (July 1956).

(220) Wells, A. A., "Influence of Residual Stresses and Metallurgical Changes on Low-Stress Brittle Fracture in Welded Steel Plates", The Welding Journal, 40 (4), Research Supplement, 182s-192s (April 1961).

(221) Martin, D. C., Ryan, R. S., and Rieppel, P. J., "Evaluation of Weld-Joint Flaws as Initiating Points of Brittle Fracture", The Welding Journal, 37 (5), Research Supplement, 244s-251s (1957).

(222) Sopher, R. P., Lowe, A. L., Martin, D. C., and Rieppel, P. J., "Evaluation of Weld-Joint Flaws as Initiating Points of Brittle Fracture, Part II", Battelle Memorial Institute, Welding Journal Research Supplement (November 1959).

(223) McGeady, L. J., "Effect of Preheat on Brittle Failure of Carbon Steel in Pressure Vessels", The Welding Journal, 41 (8), Research Supplement, 355s-367s (1962).

(224) Hall, W. J., Nordell, W. J., and Munse, W. H., "Studies of Welding Procedures", The Welding Journal, 41 (11), Research Supplement, 505s-518s (1962).

(225) Pellini, W. S., and Puzak, P. P., "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures", NRL Report 5920, U. S. Naval Research Laboratory (March 1963).

(226) Dechaene, R., Soete, W., and Vinckier, A., "Low-Stress Brittle Fracture in Mild Steel", SSC-158, Ship Structure Committee (August 30, 1963).

(227) Kihara, H., and Masubuchi, K., "Effect of Residual Stress on Brittle Fracture", The Welding Journal, 38 (4), Research Supplement, 159s-168s (1959).

(228) Kihara, H., Yoshida, T., and Oba, H., "Initiation and Propagation of Brittle Fracture in Welded Steel Plate", Document No. X-217-59, Commission X of the International Institute of Welding (1959).

(229) Kihara, H., "Recent Studies in Japan on Brittle Fracture of Welded Structures Under Low Applied Stress", Document No. X-291-62, Commission X of the International Institute of Welding (1962).

NONE

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Ship Structure Committee	2a. REPORT SECURITY CLASSIFICATION NONE 2b. GROUP

3. REPORT TITLE

Interpretative Report on Weld-Metal Toughness

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

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

K. Masubuchi, R. E. Monroe, and D. C. Martin

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1965	78	229

8a. CONTRACT OR GRANT NO. NObs-90504	9a. ORIGINATOR'S REPORT NUMBER(S) SSC-169
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. AVAILABILITY/LIMITATION NOTICES
All distribution of this report is controlled. Qualified DDC users shall request through Ship Structure Committee, U. S. Coast Guard Headquarters, Washington, D. C.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Bureau of Ships, Dept. of the Navy Washington, D. C.

13. ABSTRACT A literature survey was made to review presently available information on the notch toughness of weld metals and the heat-affected zone as they are affected by welding procedures. The base metals discussed in this report include mild steel and low-alloy, high-strength steels with up to 120,000-psi yield strength, such as may be used for merchant-ship construction. Welding processes considered include (1) shielded metal-arc welding, (2) submerged-arc welding, (3) gas metal-arc welding, and (4) electroslag and electrogas welding.

DD FORM 1 JAN 64 1473

NONE

Security Classification

NONE

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Ship Structure Committee	2a. REPORT SECURITY CLASSIFICATION NONE
	2b GROUP

3. REPORT TITLE

Interpretative Report on Weld-Metal Toughness

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

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

K. Masubuchi, R. E. Monroe, and D. C. Martin

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1965	78	229

8a. CONTRACT OR GRANT NO. NObs-90504	9a. ORIGINATOR'S REPORT NUMBER(S) SSC-169
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. AVAILABILITY/LIMITATION NOTICES
All distribution of this report is controlled. Qualified DDC users shall request through Ship Structure Committee, U. S. Coast Guard Headquarters, Washington, D. C.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Bureau of Ships, Dept. of the Navy Washington, D. C.

13. ABSTRACT A literature survey was made to review presently available information on the notch toughness of weld metals and the heat-affected zone as they are affected by welding procedures. The base metals discussed in this report include mild steel and low-alloy, high-strength steels with up to 120,000-psi yield strength, such as may be used for merchant-ship construction. Welding processes considered include (1) shielded metal-arc welding, (2) submerged-arc welding, (3) gas metal-arc welding, and (4) electroslag and electrogas welding.

DD FORM 1 JAN 64 1473

NONE

Security Classification

NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

The Ship Hull Research Committee undertakes research service activities in the general fields of materials, design, and fabrication, as relating to improved ship hull structure, when such activities are accepted by the Academy as part of its functions. The Committee recommends research objectives and projects; provides liaison and technical guidance to such studies; reviews project reports; and stimulates productive avenues of research.

SHIP HULL RESEARCH COMMITTEE

Chairman: RADM A. G. Mumma, USN (Ret.)
Executive Vice President
Worthington Corporation

Members:

Prof. R. B. Couch, Chairman
Dept. of Naval Architecture & Marine Engineering
University of Michigan

Mr. Hollinshead de Luce
Asst. to Vice President
Bethlehem Steel Co.

Dr. C. O. Dohrenwend
Vice President & Provost
Rensselaer Polytechnic Inst.

Prof. J. Harvey Evans
Prof. of Naval Architecture
Mass. Institute of Technology

Professor J. E. Goldberg
Prof. of Civil Engineering
Purdue University

Mr. James Goodrich
Exec. Vice President
Bath Iron Works

Mr. D. C. MacMillan
President
George G. Sharp, Inc.

Arthur R. Lytle
Director

R. W. Rumke
Executive Secretary

SR-170 PROJECT ADVISORY COMMITTEE
"Weld Metal Toughness"

Chairman: Mr. John J. Chyle
Director of Welding Research
A. O. Smith Corporation

Members:

Mr. R. D. Bradway
Manager of Welding Engineering
New York Shipbuilding Corp.

Dr. W. D. Doty
Division Chief
Bar, Plate & Forge Products
U. S. Steel Corporation

CDR E. M. Henry, USN
U. S. Naval Postgraduate School

Mr. D. C. Smith
Director of Research
Harnischfeger Corp.

SHIP STRUCTURE COMMITTEE PUBLICATIONS

SSC-159, Acquisition and Analysis of Acceleration Data by F. C. Bailey, D. J. Fritch and N. S. Wise. February 17, 1964

SSC-160, Geometric Effects of Plate Thickness by R. D. Stout, C. R. Roper and D. A. Magee. February 7, 1964.

SSC-161, Micromechanisms of Cleavage Fracture in Polycrystalline Iron by Charles J. McMahon, Jr. May 1964

SSC-162, Exhaustion of Ductility and Brittle Fracture of E-Steel Caused by Prestrain and Aging by C. Mylonas. July 1964.

SSC-163, Investigation of Bending Moments within the Midships Half Length of a Mariner Model in Extreme Waves by N. M. Maniar. June 1964.

SSC-164, Results from Full-Scale Measurements of Midship Bending Stresses on Two C4-S-B5 Dry-Cargo Ships Operating in North Atlantic Service by D. J. Fritch, F. C. Bailey and N. S. Wise. September 1964.

SSC-165, Local Yielding and Extension of a Crack Under Plane Stress by G. T. Hahn and A. R. Rosenfield. December 1964.

SSC-166, Reversed-Bend Tests of ABS-C Steel with As-Rolled and Machined Surfaces by K. Satoh and C. Mylonas. April 1965.

SSC-167, Restoration of Ductility of Hot or Cold Strained ABS-B Steel by Treatment at 700 to 1150 F by C. Mylonas and R. J. Beaulieu. April 1965.

SSC-168, Rolling History in Relation to the Toughness of Ship Plate by B. M. Kapadia and W. A. Backofen. May 1965.