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Underwater Welding of Low-Carbon and High-Strength (HY-80) Steel

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ABSTRACT

This paper covers two subjects, the first being multipass welding of low-carbon steel, and the second, a feasibility study of underwater welding of HY-80, a quenched-and-tempered steel with a minimum yield strength of 80,000 psi. Shielded metal-arc process was used for welding these metals.

An experimental study was made of properties of multipass underwater weldments of low-carbon steel.

A study also was made into the feasibility of welding HY-80 steel underwater. Lap and tee joints were fabricated, and tests were conducted to determine joint strength, ductility, and overall weld quality.

INTRODUCTION AND BACKGROUND

Shielded metal-arc underwater welding has been the most studied underwater welding process to date; however, the depth of knowledge of this process has proven satisfactory for the underwater repair and salvage of ships since World War II. With the

References and illustrations at end of paper.

expansion of various ocean engineering activities, industry now needs the capability to fabricate steel structures underwater, as well as maintain them.

Tremendous savings could be made if undersea pipelines, offshore oil towers and other ocean structures could be fabricated in place by a wet welding process. This current commercial need has spurred great interest, not only in developing such a wet welding process, but in understanding the physical processes and phenomena of underwater welding in general.

During the last several years, a series of studies have been conducted on underwater welding at the Department of Ocean Engineering of the Massachusetts Institute of Technology (1). For example, the National Sea Grant Office of the National Oceanic and Atmospheric Administration has sponsored a three-year program since July 1, 1971 entitled "Fundamental Research on Underwater Welding and Cutting" (2,3). This program covers the following phases:

Phase 1: Survey of fundamental information on underwater welding and cutting

Phase 2: Study of heat flow during underwater welding and cutting

Phase 3: Mechanisms of metal transfer in underwater arc welding

Phase 4: Effects of water environment on metallurgical structures and properties of welds

Phase 5: Development of improved underwater welding methods

A final report of this program will be published in the summer of 1974.

As a part of Phase 4 of the above program, a thesis study was conducted during the 1972/73 academic year by Lt. M. B. Meloney, U.S. Navy, who was then a graduate student at M.I.T. This paper briefly summarizes results obtained in this thesis study (4).

Part 1 of this study evaluated some of the properties of multipass shielded metal-arc underwater welds. Multipass welds are very often recommended or required during underwater repair welding due to poor joint fit-up, thick plating, etc., and are therefore commonly employed in underwater repair and salvaging operations (5). However, the physics, and even the basic properties of multipass welds are not well-known. Grubbs (6) in 1972 reported success by the Chicago Bridge and Iron Company in producing sound multipass underwater SMA welds, but this was the only reference found which investigated any aspect of multipass welding.

Part 2 of this study was an initial investigation into the feasibility of welding HY-80 steel joints underwater. The U.S. Navy has almost two decades of experience in the air welding of HY-80 plate for submarine hulls (7,8). Its large strength-to-weight ratio, plus good weldability under controlled conditions makes HY-80 steel an obvious choice as a surface ship hull material as well. There is presently a substantial number of naval vessels afloat with all or part of their hull structure fabricated with HY-80 steel.

A literature survey revealed no published record of any experimental or theoretical work done on underwater welding of any high-strength steel. Verbal conversations with some engineers at the Department of the Navy indicated that no study has been made on underwater welding of HY-80 steel. In fact, the consensus of opinion was that a high-strength quenched-and-tempered steel such as HY-80 could not be satisfactorily welded underwater. The major

reason appears to be sensitivity of HY-80 steel to hydrogen embrittlement. Even in air welding, delayed cracking due to hydrogen often occurs, especially when a weld is made with electrodes which have absorbed moisture. When a weld is made underwater, hydrogen which exists in water would cause delayed cracking.

However, no one, to the best of our knowledge, has ever tried to weld HY-80 steel underwater. We are fully aware that high-quality welds in HY-80 steel would not be obtained in underwater wet welding. We felt that it is worth a while to find out whether it is possible to perform emergency underwater repair or temporary welding for salvaging operations. The major objective of this study was to determine the practical limits of joint strength and ductility, as well as the overall quality which is achievable in the underwater welding of HY-80 steel.

PART 1 - UNDERWATER WELDING OF LOW-CARBON STEEL

Objective

The objective of Part 1 investigation was two-fold. First, to gain practical experience in the "art" of underwater welding under controlled laboratory conditions in order to fabricate actual fillet-weld lap and tee joints underwater from HY-80 steel plates. Second, to determine the tensile strength and notch toughness of multipass underwater welded butt joints and compare these values to bead-on-plate specimens and base plate properties. All welds were made by one of the authors, Lt. M. B. Meloney, who is not a qualified welder.

Procedures

Water Tank. The welding experiments were conducted in a steel tank measuring 4 feet long, 3 feet high, and 2 feet wide. The tank was filled with ordinary tap water (Boston, Mass.).

Power Source. A Lincoln Ideal-arc Model R3M 400 amp D.C. welding machine was used as the power source. DCRP was used in all experiments because of the ease in all experiments in initiating and maintaining an arc, and the less dense flux cloud produced during welding, with no apparent loss in weld penetration.

Welding Criteria. MIL-STD-00418B

(SHIPS) - Mechanical Tests for Welded Joints (9) was used as a standard in the preparation, welding, cutting, and testing of tensile and Charpy impact specimens.

Welding Materials. Cold rolled mild steel (ASTM 242) plates in 3/16" and 3/4" thick were used. These plates were welded with E6013 electrodes 5/32" in diameter. Electrodes were coated with paraffin prior to welding.

Welding of 1/4" Specimens for Tensile Tests. Plates 10 inches long and 6 inches wide were received in a cleaned and surface-primed condition. For transverse bead-on-plate welds, the weld was made across the width of the plate. For longitudinal bead-on-plate welds, three 10" x 2" strips were machine cut from each 10" x 6" plate prior to welding. For transverse butt joints, each 10" x 6" plate was cut in half across the width so that two 5" x 6" plates could be butt welded to the original 10" x 6" size, and then cut to proper specimen sizes.

The regions to be welded on each plate was sanded and wire-brushed to remove primer paint and expose clean metal along the desired weld line. The plates were clamped to a tray placed in the water tank and manually welded in fresh water 8 inches deep.

Bead-on-plate welds were made in single pass. Ungrooved butt joints were multipass, with two full passes made on both sides of the plates. Due to the excessive turbidity which evolves during underwater welding, it was necessary to use a wooden straight edge as an electrode guide in order to lay down a straight weld bead along the desired weld line.

After completing the transverse welds, one inch was cut off each long side of the plate and discarded in order to eliminate any edge effects in the test specimens. The remaining 10" x 4" welded plate was cut into two 10" x 2" pieces and machined as shown in Figure 1.

The longitudinal welded plates also were machined to the same size as the transverse tensile specimen. The weld reinforcement was ground off, but care was taken not to eliminate weld undercut.

Welding of 3/4" Specimens for Charpy Tests. Two 4" x 4" x 3/4" plates were butt welded in the same manner as the 1/4" transverse butt joints. Many multipass welds were made in the ungrooved joint in order

to completely fill the joint. All passes were made on one side with hand clamps preventing angular distortion of the plates. The joint gap was approximately two electrode diameters wide, so two full passes could be made side-by-side without resulting in slag entrapment. Five Charpy specimens (10mm x 10mm and 55mm long) were prepared from the welded butt joint. The specimens were cut perpendicular to the weld bead with the center of the metal coinciding the center of the Charpy specimen.

Welding Parameters. The Navy Underwater Cutting and Welding Manual (5) gives a recommended current range for welding underwater with E6013 electrodes. This was used as a guideline in initial bead-on-plate test runs. Then the range of current settings for given travel speeds was optimized as follows:

1/4" mild steel plate

Current	190-205 Amps (DCRP)
Voltage	28-33 Volts
Travel speed	11.7-14.5 in/min.
Ambient temp.	39.6°F

3/4" mild steel plate

Current	210-230 Amps (DCRP)
Voltage	21-27 Volts
Travel speed	9.5-11.4 in/min.
Ambient temp.	41°F

Experimental Results. Results of tensile tests are shown in Table 1. Charpy impact tests were conducted at three temperatures, 68°F, 32°F, and -60°F. Test results are shown in Table 2.

Discussion of Results

Bead-on-Plate Tensile Tests. Weld penetration in the longitudinal and transverse bead-on-plate specimens extended down to about two-thirds the plate thickness. However, even with this deep penetration, specimen behavior during the testing approached that of unwelded base plate rather than that of welded butt joints.

Transverse bead-on-plate specimens showed the best strength and ductility of the three specimens tested. This is rather surprising in view of the fact that these specimens were loaded in a direction perpendicular to weld undercut. Instead these specimens performed significantly better than the longitudinal bead-on-plate welds which were loaded in parallel to weld undercut notches,

and thus failed by a means other than root crack initiation and propagation.

In the longitudinal weld specimens, all zones of the weld strain equally and simultaneously. The region with the poorest ductility will therefore initiate fracture below the ultimate tensile strength of the surrounding base metal. All fractures in these specimens initiated in the weld metal bead. The conclusion then is that for underwater welded mild steel, weld metal embrittlement rather than weld undercut will initiate premature failure.

Butt Joint Tensile Tests. Comparison of butt weld test results to bead-on-plate test results indicates that bead-on-plate specimens do not simulate actual butt joint behavior very well. No matter how deep the bead-on-plate weld penetration may be, there will still be some base metal below the weld bead which will significantly alter test results.

Transverse multipass butt joints had 68% the tensile strength and only 42% the ductility of the transverse bead-on-plate specimens, whereas the bead-on-plate specimens had 93.2% the tensile strength and 74% the ductility of ASTM 242 base plate. In addition, the butt joints all failed through the weld metal, as predicted by the longitudinal specimen test results, while the transverse bead-on-plate specimens failed in all three regions without preference.

Series 3 results correlate very well with the work of Grubbs (6) who also tested the tensile and impact properties of multipass underwater welded mild steel. This leads to the conclusion that the extensive bead-on-plate underwater welding investigation carried out by Silva (10) does not give a good indication of actual underwater welded joint performance.

Charpy Impact Tests. Results of impact tests show that the multipass underwater welds met the minimum impact values for marine steels (i.e., 10 to 15 ft-lb. minimum at 32°F) (7). The brittle fracture transition temperature is just about at 32°F which makes the welds barely satisfactory for use in the coldest ocean water regions.

Again, Charpy impact test results correlate well with the work of Grubbs*

* Multipass underwater weld Charpy impact values were: 24 ft-lb. at 70°F; 22 ft-lb. at 30°F; 10 ft-lb. at -30°F.

except for the higher value at 30°F which indicates a significantly lower transition temperature (about 0°F) for his welds (6).

Conclusions

- a. Satisfactory multipass underwater welded butt joints can be fabricated. However, joint strength could be significantly improved by increasing weld metal and heat affected zone ductility, and decreasing weld undercut. Weld zone ductility can be increased by reducing the severe quenching effect of the aqueous environment and thereby improving weld zone microstructure. Undercut can be reduced through improved welding technique and optimization of welding parameters.
Improving weld zone grain structure will also increase joint notch toughness.
- b. Porosity was not a significant problem either in single pass bead-on-plate welds or in multipass butt joints.
- c. Bead-on-plate tensile specimens indicated the weakest regions in the underwater weld zone (i.e., weld metal, and undercut notch root) where premature fracture is most likely to occur. However, bead-on-plate specimens did not give a valid indication of actual butt joint performance.
- d. Excessive turbidity created in the water during welding made proper placing of the bead extremely difficult, especially in the welding of thin plate butt joints where a close fit up leaves no groove to guide the electrode along the desired weld line. In multipass welding, a wider joint gap may be used which provides better guidance for the welder.

PART 2 - UNDERWATER WELDING OF HY-80 STEEL

Objective

The objective of Part 2 investigation was to determine the feasibility of welding HY-80 steel plate underwater in order to fabricate joints of reasonable quality and strength for temporary repairs such as interim (voyage) repairs or for use during

salvage operations. The general approach taken was to compare specific properties of simple underwater welded joints with the same joint configuration welded in air. Joints were fabricated and specimens prepared and tested in accordance with Department of Defense MIL-STD-00418B Mechanical Tests for Welded Joints

(9) and with MIL-S-16216H Fabrication, Welding and Inspection of HY-80 Submarine Hulls (8).

Fillet-weld lap joints, tee-bend joints and tee-tensile joints were fabricated with 1/4" HY-80 plate in air and underwater, and the specimens tested and compared. Also, 3/4" tee-bend joints and tee-tensile joints were fabricated underwater, with specimens cut and tested. Fillet-weld lap joints and tee joints were selected, because these joints are more suitable for repair work than butt joints which require accurate joint fit-up. Most welds were made by Lt. Meloney, while some air welds were made by a qualified Navy welder for HY-80 construction.

Since the major objective of this study was to obtain practical evidence, only limited investigations were made of metallurgical structures of welds. Detailed metallurgical studies of underwater HY-80 weldments are being made at M.I.T.

Procedures

The same welding equipment and set-up used for the underwater welding of low-carbon steel was used for the underwater welding of HY-80 steel plates, 1/4" and 3/4" thick. E11018 and E310-16 electrodes 1/8" in diameter, heated in holding ovens for a minimum of four hours, were used. Both electrodes were hand-coated with paraffin after cooling and prior to welding.

Welding of 1/4" HY-80 Fillet-Weld Shear Specimens. Transverse fillet shear specimens were cut from welded plates as shown in Figure 2. Specimens were welded with E11018 electrodes 1/8-inch in diameter.

Specimens also were welded with E310-16 electrodes. This was based on results obtained by Grubbs (6) who reported success in reducing hydrogen trapping and cracking problems through the use of austenitic stainless steel electrodes in the underwater multipass welding of structural grade steels with high carbon equivalent.

The range of welding parameters used in the underwater welding of

fillet weld shear specimens were as follows:

E11018 electrode

current	180-210 Amps (DCRP)
voltage	28-36 Volts
travel speed	9.8-12.1 in/min.
heat input	32,132-36,030 Joules/in.
ambient temp.	43.6°F

E310-16 electrode

current	160-180 Amps (DCRP)
voltage	35-39 Volts
travel speed	10.6-13.7 in/min.
heat input	27,328-35,660 Joules/sec
ambient temp.	44.1°F

Immediately after welding, the plates were carefully visually examined for surface cracking (i.e., longitudinal, transverse, crater cracking) under a 5X viewing glass. The welded plate was then stored on a laboratory shelf for a minimum of 7 days, then visually examined again and cut into 1-1/4" specimens on a heavy-duty hydraulic band saw. No case of surface cracking (immediate or delayed) was found through visual observation. In addition, a dye penetrant test was conducted on a randomly selected plate prior to cutting into specimens. All four E11018 beads showed no case of surface cracking. Substructure characteristics will be discussed later.

Air-Welded Specimens. For comparison with the underwater welded specimens, identical shear fillet weld specimens were air welded using the following parameters:

E11018 electrode

current	120-135 Amps (DCRP)
voltage	43-48 Volts
travel speed	8.0-13.3 in/min.
heat input	25,985-43,537 Joules/in.
ambient temp.	72.5°F

Some specimens were welded by Lt. Meloney, while other specimens were welded by a qualified Navy welder for HY-80 construction.

Welding of 1/4" HY-80 Tee Joints. Tee joint specimens used for tee-bend tests and tee-tensile tests were cut from welded plates as shown in Figure 3. Six specimens were cut from each plate, with three being used as tee-bend specimens and three as tee-tensile specimens. The plate assembly was placed in the water tank tray, with the base plate positioned at a 45 degree angle to the horizontal plane. Both single

and multipass welds were made, using 1/8" E11018 electrodes.

Single and multipass welds also were made in air, using 1/8" E11018 electrodes.

Experimental Results

Fillet-weld shear tests and tee-bend tests were conducted in accordance with the procedures and specifications of MIL-STD 00418B (9). Results are listed in Tables 3 through 7. Figure 4 shows a cross-section of a single pass underwater welded tee joint using E11018 electrodes.

Discussion of Test Results

1/4" HY-80 Fillet-Weld Shear Tests.

It is first apparent that the single pass underwater fillet weld (Series 5) had extremely poor shear strength. There were a number of reasons for this, including inadequate penetration, off-center weld bead positioning, and excessive undercut.

More encouraging was the performance of the multipass shear specimens in which penetration was adequate, the wider bead positioned correctly, and the effects of undercut lessened. The average shear strength of these specimens was 69,056 psi, which is 79.7% of comparable single pass air-weld specimens also welded by Meloney (Series 7).

Air-welded specimens made by an qualified Navy welder (Series 8) showed the highest average shear strength of 104,614 psi, while that of Series 7 was 86,632 psi. The reason multipass underwater welds are compared to single pass air welds in this case is that with the air-welded specimens an adequate and acceptable joint was made with a single pass. The use of the drag technique, which is required in low visibility underwater welding, inhibits the welder from weaving the electrode along an ungrooved joint fit-up, as is frequently done in air welding.

Shear strengths of multipass underwater welds using E310-16 electrodes (Series 9) were lower than those of multipass underwater welds using E11018 electrodes (Series 6) but higher than those of single pass welds (Series 5).

1/4" HY-80 Tee-Bend Tests. The significant characteristic of the tee-bend test is that it measures primarily weld surface quality. Table 4 shows that the base metal

bend strength is greater than that of any welded specimen. Thus, in no case was 100% joint efficiency attained, and welded tee joints will degrade bend strength to a degree proportional to weld surface quality. MIL-STD-00418B does not take into account weld bead size in bend strength calculations. However, it can be seen from Table 4 that weld bead size is not significant since, for air welds (no undercut) single pass bend strength (13,230 psi) is 96.3% of multipass bend strength (13,733 psi), even though the average multipass throat dimension was 21% larger than that of the single pass series. The overall loss in bend strength for single pass and multipass underwater welds was 32.1% and 29.9% respectively compared to air welds. Therefore, weld degradation due to surface defects is significant, i.e., an average of 31% for single and multipass welds. The multipass underwater welds had somewhat higher bend strength than single pass underwater welds due partly to the larger fillet size and partly to the less significant, further removed undercut notch.

1/4" HY-80 Tee Tensile Tests.

Tee-tensile tests were conducted in order to determine relative tee joint strength in the absence of bending. As shown in Figure 4, a tee joint has two undercut notches, one at each fillet toe. However, it was found that fracture did not initiate from these notches and fracture occurred in a shear mode in the weld metal. In other words, even though the weld had undercuts, the "weakest link" in the joint was the weld metal. Results are shown in Table 5.

Since specimens in Series 14 showed poor results, an additional weld was prepared underwater (Series 15). Shear strength of Series 15 (67,185 psi) was 88% of that of Series 17. By comparing results of Series 16 and 17, one finds that the maximum loads increases approximately proportionally to the throat dimension because the shear strength remains about the same.

3/4" HY-80 Tee Joints. The minimum preheat temperature for 3/4" HY-80 plate is 125°F versus 75°F for 1/4" plate (8), therefore, the adverse effect of ambient water temperature on the underwater weldability of 3/4" HY-80 was expected to be considerable. Experimental results and metallographic examination

of 3/4" welded joints confirmed this expectation.

Bend tests of 3/4" underwater welded multipass tee joints were conducted for the purpose of comparing tee-bend performance to base plate performance. However, the bend strength of the unwelded 3/4" plate greatly exceeded the rated capacity of the bend testing machine resulting in an incomplete set of data. Even so, some tentative conclusions on the relative bend strength of 3/4" tee joints can be drawn. Firstly, as shown in Table 6, the bend strength of these joints is well below 58% of base plate bend strength compared to 68.4% for 1/4" tee joints. Secondly, the ratio of total bend angle at failure for 3/4" tee joints is 24.5% the total bend angle of 1/4" tee joints (Table 4). Assuming 3/4" base plate has the ductility of 1/4" base plate (i.e., 180° total bend angle without failure), the percentage of 3/4" tee joint to base plate ductility is only about 5%.

Tee-tensile test results were equally disappointing (as shown in Table 7). The shear strength of 3/4" underwater welded multipass tee joints was only 31.4% the shear strength of 1/4" underwater welded multipass tee joints. The loss in weldability of thick HY-80 plate (>1/2") is extraordinary.

Tee Joints Welded in Salt Water.

At a last step in this investigation, 1/4" and 3/4" tee joints were welded in salt water, to see if there was any difference in joint weldability between fresh and salt water. "Dayno Synthetic Sea Salt" was used to make the artificial sea water used in this test. Since time did not permit the cutting and testing of test specimens, it was decided to weld the two sets of tee joints under the identical conditions used in making the fresh water welds and then make a qualitative comparison of weld quality obtained in the two aqueous media. No reference was found which investigated the difference in the hydrogen cracking potential of a salt water media compared to fresh water; however, since no case of hydrogen-induced macrocracking was observed in any fresh water weld, none was anticipated in salt water welding. The rationale here was that fresh water welding produced an ample supply of dissociated hydrogen in the arc, and quenched

the weld bead just as fast as salt water would. Thus, the conditions for hydrogen cracking were present, and the fact that none occurred in fresh water was quite surprising. Salt water welding would be expected to cause some changes in the rate of hydrogen dissociation, and possibly in the amount entrapped in the weld zone, but these would be minor perturbations from fresh water welding conditions, and therefore, no major changes from fresh water results would be expected.

Metallurgical Studies

Limited studies also were made of metallurgical structures of underwater welds of HY-80 steel plates. However, results are not discussed here because of the limited length of this paper.

The most interesting results was that no extensive crack was observed in any of the HY-80 welds made underwater. Masubuchi and Martin (11) reported the occurrence of microcracks in the heat-affected zone close to the fusion line even in HY-80 welds made in air. Similar microcracks also were found in HY-80 underwater welds made in this study. However, none of these microcracks extended to a macrocrack which indicates that HY-80 steel is rather insensitive to hydrogen cracking. A further study is being conducted on this subject.

CONCLUSIONS

- a. Experimental results showed that fairly efficient joints, comparable to underwater welded mild steel joint efficiency, could be fabricated underwater with thin HY-80 steel plate. (Thin plate here means <1/2", i.e., where minimum preheat temperature increases above 75°F). For thicknesses greater than 1/2" underwater weldability decreases dramatically. These findings may appear restrictive however, due to the higher strength to weight ratio of HY-80 steel compared to mild steel, most unarmored naval ship hulls will require relatively thin plate when fabricated from HY-80 steel. Therefore, the 1/2" maximum thickness restriction may in fact encompass the large majority of future naval ships.

- b. Loss in underwater welded joint strength and ductility, when compared to similar air welded joints, resulted from two main causes: weld undercut, and weld zone microstructural changes and defects caused by severe quenching. It was found that for 1/4" HY-80 steel plate undercut accounts for almost 75% of the total underwater weld degradation, and weld zone structural changes and effects for the other 25%.
- c. In 3/4" HY-80 underwater welded joints, internal weld defects, especially heavy slag inclusion, prevented adequate fusion of weld metal and base metal. This accounts for the major portion of total weld degradation when compared to 3/4" HY-80 base plate.
- d. In general, multipass underwater welding of HY-80 steel is preferred to single pass welding. Multipass welds were much more porous than single pass welds, but the effect of porosity was secondary compared to single pass weld undercut caused by the severe quenching of the aqueous environment. Porosity will reduce effective weld crosssectional area, but undercut will cause severe stress intensities at the notch roots which, in turn, cause premature, catastrophic fracture, especially in the presence of bend stresses. Multipass welds not only decrease the degree of undercut, but increase fillet size and in so doing, "push" the undercut further away from the joint intersection. Therefore, a crack which initiates at an undercut notch root must propagate through a greater portion of the fracture tough HY-80 base plate rather than through the more notch sensitive weld metal and heat affected zone.
- e. It was demonstrated in the underwater welding of thin HY-80 plate that weld undercut could be greatly reduced (but not eliminated) through the optimization of welding parameters and proper welding technique. This is where the largest payoff per dollar invested will result.
- f. Underwater weld quality and overall joint strength could be significantly increased through the use of post-weld surface treatment. After both single and

multipass welding, weld beads should mechanically be peened or ground down in order to eliminate surface cavities, and reduce or eliminate undercut.

Unlike weld undercut, surface cavities will not significantly reduce joint strength per se; however, it will allow the water environment access deep into the weld metal. This will result in accelerated corrosion through the formation of differential aeration cells which would eventually cause extensive local corrosion through the heat affected zone and into the base metal.

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TABLE 1 - RESULTS OF LOW-CARBON STEEL TENSILE TESTS

SERIES 1: SINGLE PASS LONGITUDINAL BEAD-ON-PLATE

SPECIMEN	TENSILE STRENGTH (PSI)	% ELONG. IN 2 IN.	% REDUCTION IN AREA	FRACTURE LOCATION*
1A	65,610	9.4	12.0	W.M.
1B	60,370	7.8	11.1	W.M.
1C	64,000	9.3	12.0	W.M.
1D	66,200	9.3	11.9	W.M.
1E	54,825	12.5	11.0	W.M.
AVERAGE SERIES 1	62,200	9.7	11.6	---

SERIES 2: SINGLE PASS TRANSVERSE BEAD-ON-PLATE

2A	72,210	26.9	19.3	B.M.
2B	68,925	24.2	23.4	B.M.
2C	64,710	15.9	24.5	HAZ
2D	52,840	11.9	16.3	W.M.
2E	55,140	13.0	14.6	W.M.
AVERAGE SERIES 2	62,765	18.4	19.6	---

SERIES 3: MULTIPASS TRANSVERSE BUTT WELD

3A	49,333	6.3	9.7	W.M.
3B	51,200	9.7	11.3	W.M.
3C	27,570	3.6	6.1	W.M.
3D	43,285	7.4	9.2	W.M.
AVERAGE SERIES 3	42,847	6.8	9.1	---

*NOTES ON FRACTURE LOCATION:

W.M. = WELD METAL
HAZ = HEAT AFFECTED ZONE
B.M. = BASE METAL

TABLE 2 - RESULTS OF MULTIPASS LOW-CARBON STEEL
CHARPY IMPACT TESTS (SERIES 4)

SPECIMEN	TEST TEMPERATURE (°F)	IMPACT ENERGY (FT-LBS.)
4A	68°F	28.0
4B	68°F	28.2
4C	68°F	26.1
AVERAGE	68°F	27.4
4D	32°F	20.0
4E	32°F	13.5
4F	32°F	11.7
AVERAGE	32°F	15.1
4G	-60°F	7.6
4H	-60°F	6.4
4I	-60°F	8.0
AVERAGE	-60°F	7.3

TABLE 3 - RESULTS OF FILLET WELD SHEAR TESTS

SERIES 5: SINGLE PASS UNDERWATER WELDS USING E11018 ELECTRODES

SPECIMEN	MAX. LOAD TO FAILURE (LBS.)	SHEAR STRENGTH (LBS.) LINEAR INCH (IN.)	AVE. THROAT DIMENSION (IN.)	SHEAR STRENGTH (PSI)
5A	17,500	7,000	0.1435	48,800
5B	11,800	4,720	0.1172	40,280
5C	20,300	8,120	0.1570	51,720
AVERAGE SERIES 5	16,533	6,613	0.1392	46,933

SERIES 6: MULTIPASS UNDERWATER WELDS USING E11018 ELECTRODES

6A	33,600	13,440	0.1758	76,472
6B	36,100	14,444	0.2120	68,132
6C	25,175	10,069	0.1609	62,562
AVERAGE SERIES 6	31,625	12,651	0.1829	69,055

SERIES 7: SINGLE PASS AIR WELDS BY MELONEY USING E11018 ELECTRODES

7A	32,100	12,840	0.1461	87,916
7B	31,600	12,640	0.1589	79,522
7C	37,945	15,179	0.1642	92,470
AVERAGE SERIES 7	33,881	13,553	0.1564	86,637

SERIES 8: SINGLE PASS AIR WELDS BY QUALIFIED HY-80 WELDER USING E11018 ELECTRODES

8A	41,460	16,584	0.1561	106,204
8B	39,280	15,713	0.1523	102,156
8C	38,770	15,508	0.1484	104,484
AVERAGE SERIES 8	39,837	15,935	0.1523	104,281

SERIES 9: MULTIPASS UNDERWATER WELDS USING E310-16 ELECTRODES

9A	22,565	9,026	0.1856	48,644
9B	26,842	10,736	0.1894	56,674
AVERAGE SERIES 9	24,703	9,881	0.1875	52,660

* Note: All welds except those in Series 8 were welded by Lt. Meloney

TABLE 4 - RESULTS OF TEE-BEND TESTS*

SERIES 10: SINGLE PASS UNDERWATER WELDS USING E11018 ELECTRODES

SPECIMEN	FRACTURE LOAD (LBS)	TOTAL BEND ANGLE AT FAILURE	TYPE FRACTURE**
10A	9,894	43°	2
10B	8,590	29.5°	2
10C	8,934	32°	2
10D	8,514	30°	2
AVERAGE SERIES 10	8,983	33.6°	---

SERIES 11: MULTIPASS UNDERWATER WELDS USING E11018 ELECTRODES

11A	9,254	31°	2
11B	9,365	33°	2
11C	9,548	33.5°	2
11D	10,341	46°	2
AVERAGE SERIES 11	9,627	35.9°	---

SERIES 12: SINGLE PASS AIR WELDS USING E11018 ELECTRODES

12A	13,418	71.5°	2
12B	12,897	69°	2
12C	13,376	72°	2
AVERAGE SERIES 12	13,230	70.8°	---

SERIES 13: MULTIPASS AIR WELDS USING E11018 ELECTRODES

13A	13,952	76.5°	2
13B	13,362	72°	2
13C	13,957	81°	2
13D	13,662	71°	2
AVERAGE SERIES 13	13,733	75°	---

SERIES 14: 1/4" HY-80 BASE PLATE (UNWELDED)

B.P.A.	14,170	180°	No Fracture
B.P.B.	13,978	180°	No Fracture
AVERAGE SERIES B.P.	14,074	180°	---

* All welds were made by Lt. Meloney

**Refer to Figure 5 for fracture types

TABLE 5 - RESULTS OF TEE-TENSILE TESTS

SERIES 14 & 15: MULTIPASS UNDERWATER WELDS BY MELONEY USING E11018 ELECTRODES

SPECIMEN	MAX. LOAD TO FAILURE (LBS.)	SHEAR STRENGTH (LBS.) LINEAR INCH (IN.)	AVE. THROAT DIMENSION (IN)	SHEAR STRENGTH (PSI)
14A*	15,520	6,207	0.1579	39,300
14B**	12,542	5,017	0.1356	36,996
14C***	16,500	6,600	0.1445	45,658
AVERAGE SERIES 14	14,854	5,941	0.1460	40,651
15A	25,520	10,208	0.1563	65,310
15B	27,356	10,942	0.1602	68,326
15C	27,060	10,823	0.1594	67,920
AVERAGE SERIES 15	26,645	10,657	0.1586	67,185
SERIES 16: SINGLE PASS AIR WELDS BY QUALIFIED HY-80 WELDER USING E11018 ELECTRODES				
16A	24,620	9,848	0.1269	77,604
16B	23,925	9,570	0.1285	74,464
16C	21,775	8,711	0.1241	70,193
AVERAGE SERIES 16	23,440	9,376	0.1265	74,087
SERIES 17: MULTIPASS AIR WELDS BY QUALIFIED HY-80 WELDER USING E11018 ELECTRODES				
17A	30,670	12,266	0.1567	78,276
17B	28,200	11,280	0.1523	74,064
17C	29,120	11,774	0.1556	75,668
AVERAGE SERIES 17	29,330	11,773	0.1547	76,003

* 13.5° Total Bend

** 28° Total Bend

*** 9° Total Bend

TABLE 6 - RESULTS OF TEE-BEND TESTS IN 3/4" HY-80 PLATES

SERIES 18: MULTIPASS UNDERWATER WELD BY MELONEY USING E11018 ELECTRODES

SPECIMEN	FRACTURE LOAD (LBS)	TOTAL BEND ANGLE AT FAILURE	TYPE FRACTURE
18A	37,858	9°	3
18B	38,550	9.5°	3
18C	36,519	8°	3
AVERAGE SERIES 18	37,642	8.8°	---
SERIES B.P.: 3/4" HY-80 BASE PLATE (UNWELDED)			
B.P.A.	64,275*	42°	No Fracture
B.P.B.	64,275*	39°	No Fracture
AVERAGE BASE PLATE	64,275*	40.5°	---

* Rated capacity of bend testing machine

TABLE 7 - RESULTS OF TEE-TENSILE TESTS IN 3/4" HY-80 PLATES

SERIES 19: MULTIPASS UNDERWATER WELD BY MELONEY USING E11018 ELECTRODES

SPECIMEN	MAX. LOAD TO FAILURE (LBS)	SHEAR STRENGTH LINEAR INCH	($\frac{\text{LBS.}}{\text{IN.}}$)	AVE. THROAT DIMENSION (IN)	SHEAR STRENGTH (PSI)
19A	28,730	11,493		0.5078	22,632
19B	21,910	8,762		0.4296	20,395
19C	18,915	7,566		0.3711	20,388
AVERAGE SERIES 19	23,185	9,273		0.4361	21,138

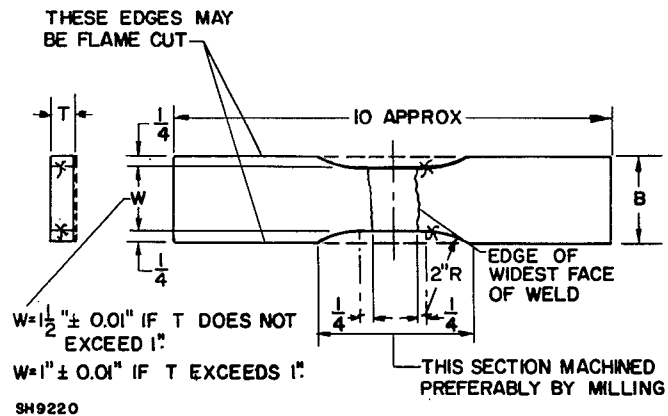


Fig. 1 - Transverse tensile specimen.

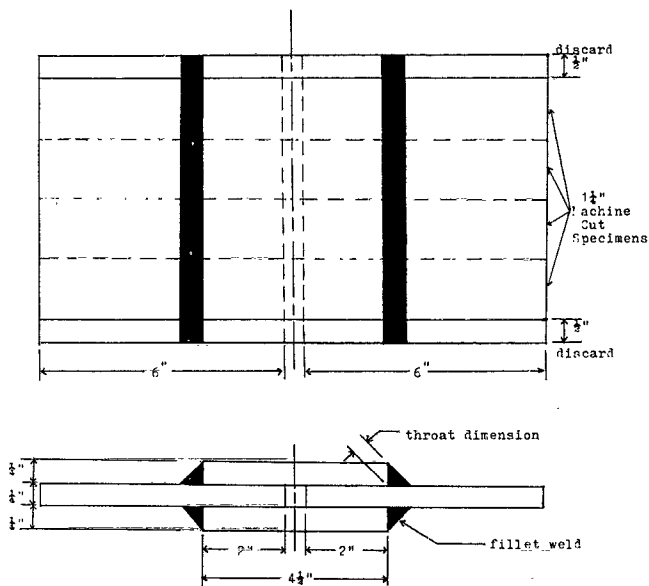


Fig. 2 - Transverse fillet-weld specimen.

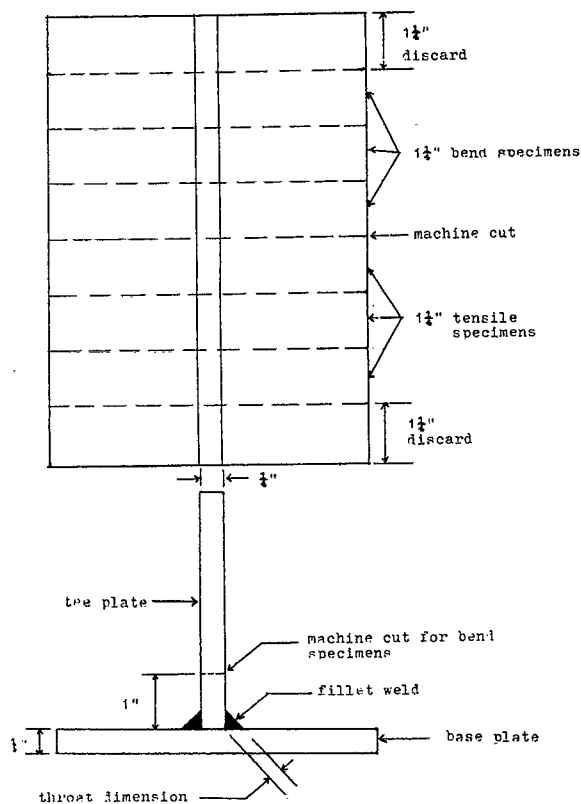


Fig. 3 - Tee-bend and tee-tensile specimens.



Fig. 4 - Single pass underwater welded tee joint using E11018 electrode. (3x, 3% NITAL ETCH)

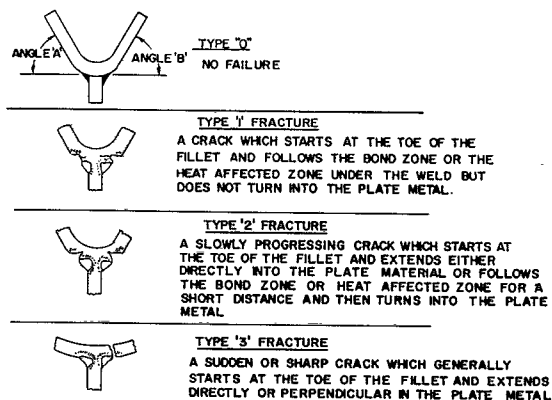


Fig. 5 - Types of fracture in tee-bend specimens.