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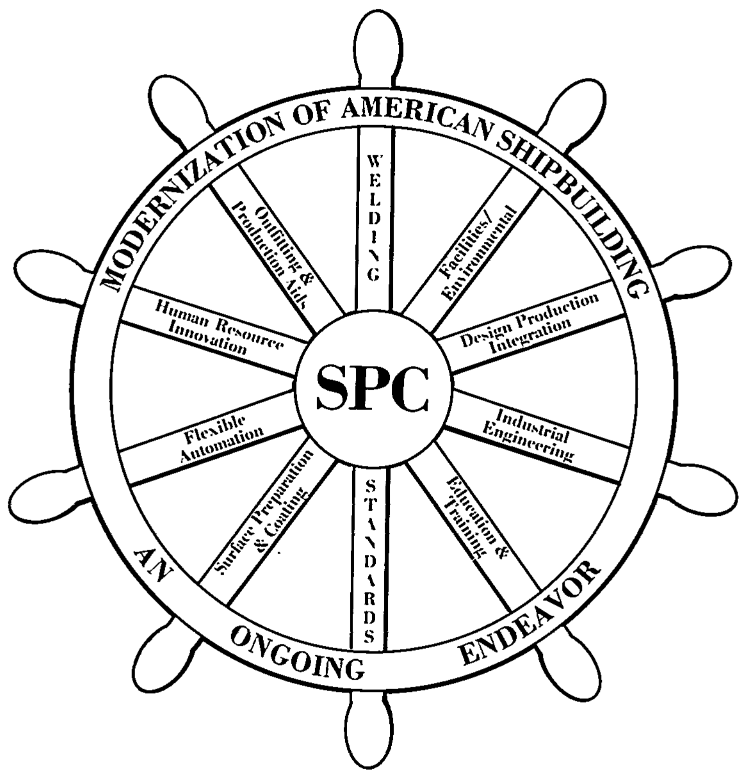

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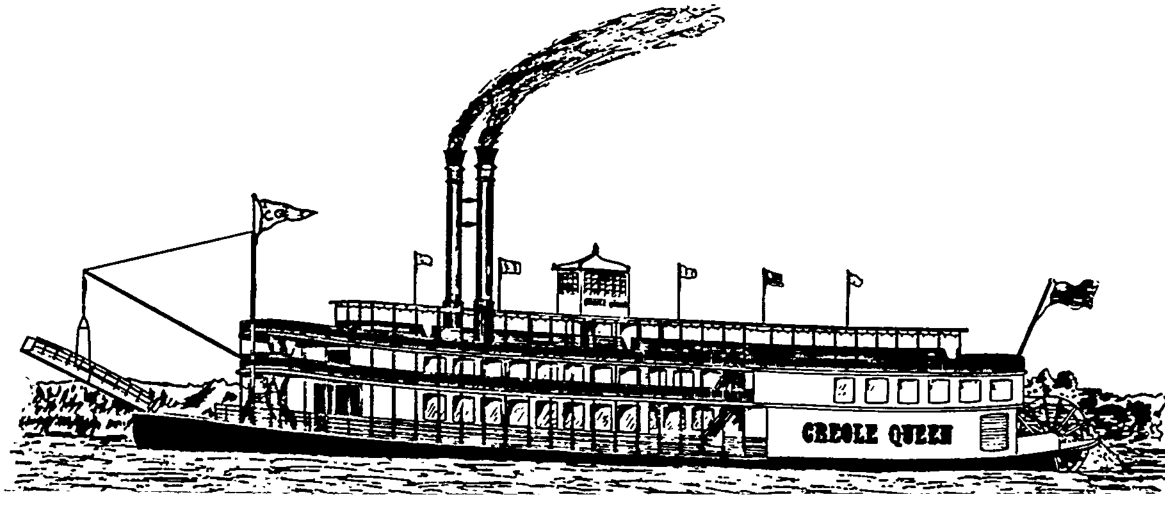

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
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Evaluation of Commercially Available Wet Welding No. 19 Electrodes for Potential Repair of U.S. Navy Ships

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ABSTRACT

As part of a program to determine the viability of underwater wet welding for repair of U. S. Navy surface ships, eight commercially available shielded metal arc wet welding electrodes were evaluated by a series of screening tests. Two E7014 "type" electrodes provided superior results and were used for welding procedure qualification testing on ASTM A-36 steel with a carbon equivalent of 0.35. Qualification testing included visual, liquid penetrant and radiographic inspection, as well as bend testing, reduced section tensile testing, all-weld-metal tensile testing, Charpy impact testing, macroscopic examination, hardness testing, and chemical analyses. The wet welding was performed in the vertical, overhead and horizontal positions. The welding took place at seven and thirty-three feet of sea water.

Nondestructive and destructive test results show that both electrodes exceed the requirements of American Welding Society specification for underwater welding, AWS D3.6 (Ref. 2) Type B. Weld quality and strength were found to be approximately on a par with welds made in an air environment. Weldment ductility and toughness were appreciably lower than would be expected of air welds.

1.0 INTRODUCTION

The term "wet welding" refers to wet hyperbaric welding (welding in the wet at ambient pressures greater than one atmosphere) as opposed to dry hyperbaric welding (sometimes referred to as dry chamber welding). In wet welding, there is no mechanical barrier separating the welding arc from the surrounding water; and the only physical barrier are the bubbles being generated by the heat of welding and decomposition of the electrode flux and waterproofing materials. The work covered by this paper, as well as all comments contained herein, are in reference to wet welding using the shielded metal arc (covered electrode) welding process.

Until the late nineteen sixties and early nineteen seventies, wet welding was considered appropriate only for non-critical applications, such as emergency temporary repairs and salvage work. Until the late nineteen seventies, some ship fabrication documents considered wet welds to be only sixty-percent efficient. Private industry began producing structural quality wet welds, for permanent repair to offshore structures, in the early nineteen seventies. These welds were produced by diving companies using their own in-house, proprietary wet welding electrodes; the welds developed the full strength of the mild steel base metal, and thus were considered one hundred percent efficient. However, weld metal toughness, ductility and internal quality were less than what would be expected of welds made in a normal air environment; and base metal heat-affected-zone hardness was higher than that normally associated with welds made in a dry environment. Today, internal quality of wet welds has improved somewhat; but weld metal ductility and toughness, and base metal heat-affected-zone hardness, are still not on a par with welds made in the dry. However, for commercial applications, wet welds have been shown to exhibit acceptable structural properties under a number of loading conditions.

Because of the success of wet welding in the various commercial applications, and the large costs associated with the drydocking of ships, the U. S. Navy has started a program to evaluate and, where appropriate, develop and implement underwater welding for repair of Navy ships. Both dry habitzt and wet welding are encompassed in the program. The work described herein represents a portion of the overall program. Wet welding has been successfully used in permanent and temporary repairs on ships and other commercial floating structures. The scope of this work was as follows:

- Evaluation and comparison of commercially available wet welding electrodes, to determine those exhibiting superior properties.

- Performance of wet welding procedure qualification testing using those electrodes found to be superior during the electrode evaluation or screening tests. The qualification testing used steel produced to the requirements of MIL-s-22698 (Ref. 5).

- Development of welding procedure specifications based on the qualification welding performed.

2.0 PROGRAM TESTING AND EVALUATION

2.1 Facilities

Diving and welding facilities were provided by Global Divers and Contractors of New Iberia, Louisiana; The Global test tank is shown in Figure 1. The wet welding tank was 36 feet high, 20 feet in diameter, and contained sea water. The filtering system maintained clear water throughout the welding operations. The air compressor and volume tank were adequate for the support of two welder/divers working at the same time. The welding machines were both 400 ampere Miller diesel driven generators.

FIGURE 1. Global Divers Test Tank

2.2 Materials and Examinations

The base metal consisted of both high carbon equivalent (CE) and low CE steel plate meeting the requirements of MIL-S-22698. Mill certificates were obtained for each steel, and independent chemical analyses were also made. The following represents the properties of these steels:

Steel	Thickness	*Carbon Equivalent	UTS KSI/MPa	YS KSI/MPa	Elongation
ASTM A36	3/8"	0.280	67.7/467	50.6/349	25%
"	1/2"	0.376	67.6/466	47.7/329	29%
"	3/4"	0.350	71.1/490	50.0/345	29%
DH 36	3/8"	0.449	80.0/552	60.0/414	25%
"	1/2"	0.443	78.3/540	55.3/381	21%
"	3/4"	0.435	77.7/536	60.3/416	25%

$$*CE = C + Mn/6 + (Cr + Mo + V)/5 + (CU + Ni)/15$$

Six mild steel and two austenitic steel electrodes were evaluated. The electrodes are identified by numbers 1 through 8. All electrodes, except Number 8, were 1/8″ in diameter; Electrode Number 8 was 5/32″ in diameter. Electrode Numbers 1, 2, 3 and 8 were E7014 “types”; Electrode Numbers 6 and 7 were E6013 “types”; Electrode Number 4 was E309-16; Electrode No. 5 was an E31O-16 “type”.

All nondestructive examination was accomplished in accordance with MIL-STD-271 (Ref. 4). Destructive examination specimens were prepared and tested in accordance with AWS B4.O (Ref. 1) and AWS D3.6.

2.3 Environmental Conditions

The temperature of the water in the tank ranged from 75F to 85F. Welding was accomplished at depths of 33 FSW and 7 FSW. Visibility was excellent at all times. The divers’ breathing medium was air. The pressure at depth was 14.7 PSI gage at 33 FSW, and 3.1 PSI gage at 7 FSW. Allowable times at 33 FSW were determined using the 40-foot criteria of the U.S. Navy dive tables.

2.4 Test Plate Design & Testing

2.4.1 The eight commercially available wet welding electrodes were initially tested during the screening tests. Based on these tests, two electrodes were chosen for qualification testing.

2.4.2 Screening tests. All screening tests were accomplished at a 33 foot water depth using two welder/divers. This allowed duplication of all tests, reducing the chances of accepting an electrode which would run successfully only when a unique style of welding was utilized. Test plates consisted of cruciform specimens and grooved plate specimens, the design of which is shown in Figure 2. DH 36 steel, 3/8″ thick, was used for the cruciform specimens following the welding sequence shown in Figure 3. The object of the welding sequence was to induce relatively high restraint to allow determination of any propensity for cracking in either the weld or base metal heat-affected-zone. The cruciform specimens were liquid penetrant inspected after welding. They were then sectioned to provide two MACRO sections, 1 1/2″ from each end; the MACROS were sanded to a 120 grit finish, etched, and examined at a magnification of 7x. The welding electrodes which were found acceptable were further evaluated using the grooved plates.

The grooved plates were prepared to allow both a vertical and an overhead weld to be made in each plate. Both high CE (DH 36) and low CE (A36) steel were used for the grooved plates. After welding and visual inspection, the plates were liquid penetrant inspected, radiographed, and sectioned to provide two MACROS and 12 face bend specimens for each weld. The MACROs were prepared and evaluated as specified above for the cruciform MACROS. Four face bends were performed over radii of 6T, 4T and 2T, T being the bend specimen thickness (3/8″). When four bends passed the 6T bend test, four more specimens were. then tested over the 4T bend radius; success over the 4T bend radius warranted four additional bends over the 2T bend radius. The 6T bend radius is specified by the American Welding Society specification for underwater welding AWS D3.6 for Type B welds, whereas the 2T radius is typical of that specified for in-air surface welding and dry hyperbaric underwater welding.

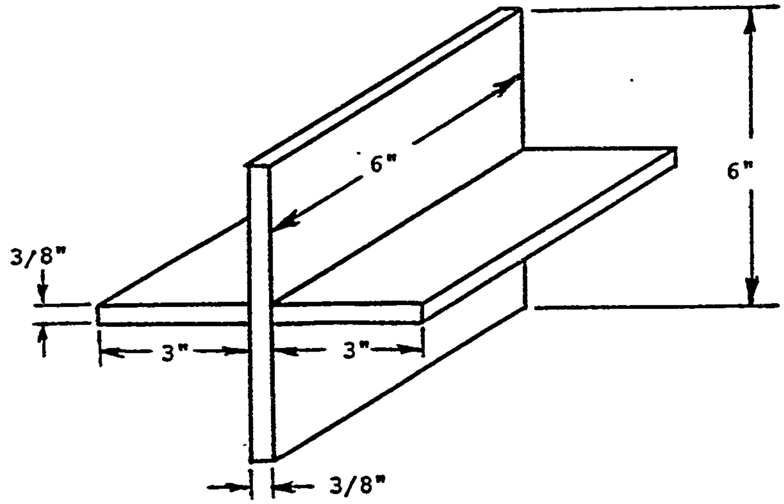
The cruciform and grooved plate weldments were evaluated using the form shown in Figure 4; one of these forms was completed, for the vertical and overhead positions, for each wet welding electrode being evaluated. Those electrodes with the highest total scores were selected for qualification testing at 33 and 7 FSW respectively. As can be seen from the form shown in Figure 4, the “GRADING CRITERIA” specifies three grades for each type of test -- the lowest grade being one, and the highest grade being three. The grade is multiplied by the weight factor (indicates the relative importance of the specific evaluation criterion) to obtain the score for each test performed.

2.4.3 Qualification tests. Test plates consisted of 3/4″ ASTM A36 steel. Test plate X, which was 20″ long, was used to obtain two reduced section tensiles, four side bends, one VICRO section with Vickers hardness readings, five weld metal Charpy impact specimens, and five base metal heat-affected-zone Charpy impact specimens. Charpy impact test temperature was 28F. Test plate Y, which was 16″ long, was used to obtain two all-weld-metal tensile specimens and weld metal chemistries. Test plate X and Y designs are shown in Figure 5.

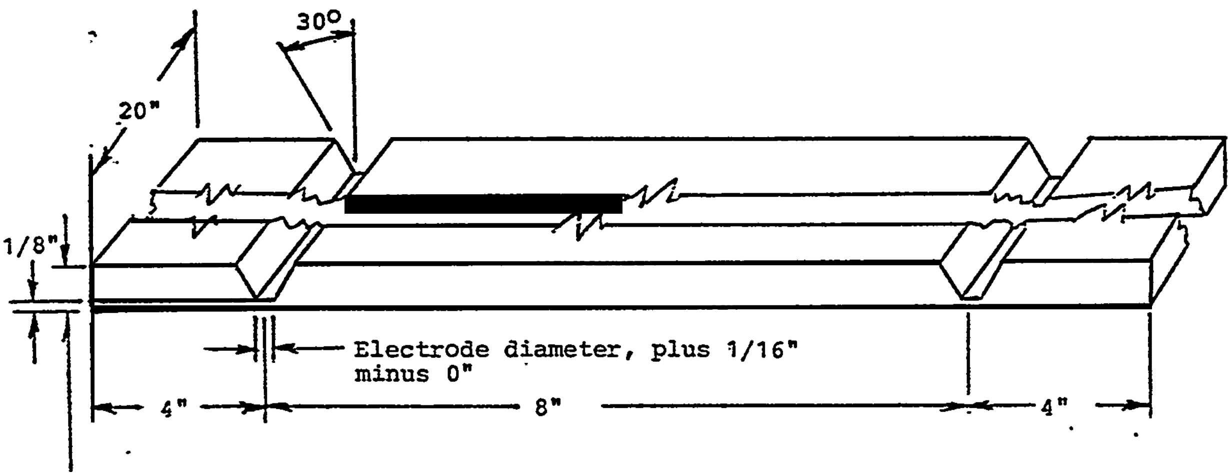
Each wet welding electrode, selected for qualification testing, was qualification tested in accordance with the following:

Position	Test Plate Type	Depth, FS?W
V	X & Y	33 & 7
H	X	33
OH	X & Y	33 & 7

Accordingly, a total of nine butt welds (five for Test Plate X and four for



CRUCIFORM SPECIMEN



GROOVED PLATE SPECIMEN

FIGURE 2. Screening Test Plates

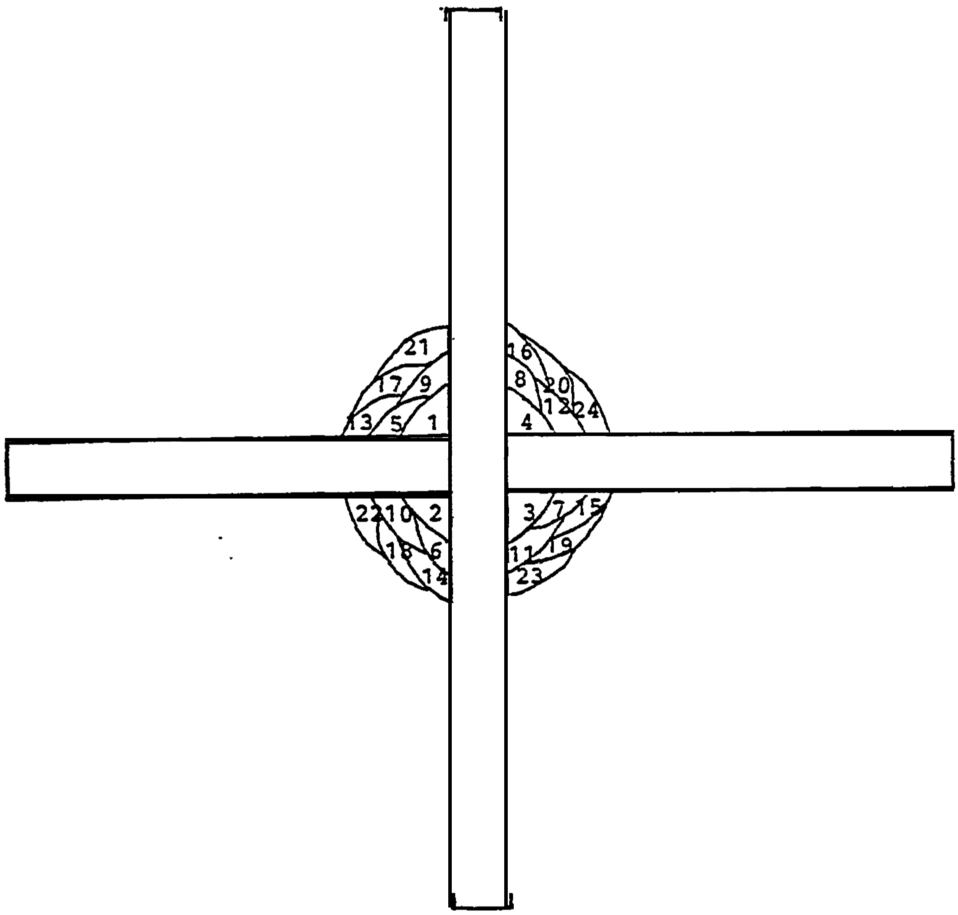


FIGURE 3. Typical Welding Sequence for Cruciform Specimen

Test Plate Y) were attempted for each wet welding electrode chosen for qualification testing. Qualification tests were summarized using the form shown in Figure 6.

2.5 Test Results

2.5.1 Screening tests

2.5.1.1 Cruciform. All cruciform were made using the high CE DH 36 steel. Cruciform bead appearance ranged from good (Figures 7 and 8) to poor (Figures 9 and 10). The cruciform were welded in the vertical and overhead positions at a water depth of 33 feet. Three layers of weld metal were deposited in each corner (see Figure 3).

Weldability, visual and liquid penetrant inspection, and MACRO sections were evaluated and graded using the form shown in Figure 4. Representative photographs of the MACRO sections are shown in Figures 11 through 18. Mild steel electrode Numbers 2, 6, 7 and 8 were rejected based on weldability and surface appearance; each of the electrodes suffered arc outages during welding -- resulting in rough weld beads. Electrode Numbers 2, 6 and 7 MACROS are shown in Figures 13, 17 and 18. MACRO sections were not taken from the electrode No. 8 cruciform, since the irregularity of the weld beads were obviously unacceptable. The electrode would hardly sustain an arc (see Figure 9) with the electrode negative -- which is the polarity normally used with the mild steel electrodes; when the polarity was changed to electrode positive (see Figure 10) , better, but unacceptable, results were obtained. The waterproof coating integrity of the electrode was poor, allowing some of the electrode flux coating to dissolve in the water, which probably caused most of the problems.

The austenitic stainless steel electrodes, Numbers 4 ad 5, were rejected based on longitudinal, center

WET WELDING SCREENING EVALUATION FORM

EVALUATION CRITERIA	weight FACTOR	CRUCIFORM FILLET GRADE	CRUCIFORM FILLET SCORE	GROOVED PLATE GRADE	GROOVED PLATE SCORE	TOTAL SCORE
Arc stability 1/	1					
Arc start/restart 1/	1					
Puddle control 1/	1					
Puddle visibility 1/	1					
Slag removal 1/	1					
Gen. visual weld appearance 1/	1					
Interpass grinding 2/	2	N/A	N/A			
Visual Inspection 3/	3					
MT/PT inspection 3/	4					
MACRO examination 4/	4					
RT inspection 5/	4	N/A	N/A			
Bend testing 6/	5	N/A	N/A			

*CF-
Weld I.D. Number

*GP-
Weld I.D. Number

Welder/diver

Position

- *CF (cruciform fillet)*
- GP (grooved plate)

SCORE: weight factor x grade

GRADING CRITERIA

1/Poor---1
Fair---2
Good---3

2/Complete weld pass(es)---l
Starts/stops, occas. pinhole---2
None---3

3/Meets AWS D3.6, Type B---1
Meets N/S 0900-003-8000, Cl. 2---2
Neets N/S 0900-003-80001 Cl, 1---3

4/Meets AWS D3.6, Type B---1
Meets AWS D3.6, Type A---2
Meets MIL-STD-248---3

5/Meets AWS D3.6, Type B---1
Meets AWS D3.6, Type A---2
Meets N/S 0900-003-9000, Cl. 1---3

6/6T meets MIL-STD-248---1
4T meets MIL-STD-248---2
2T meets MIL-STD-248---3

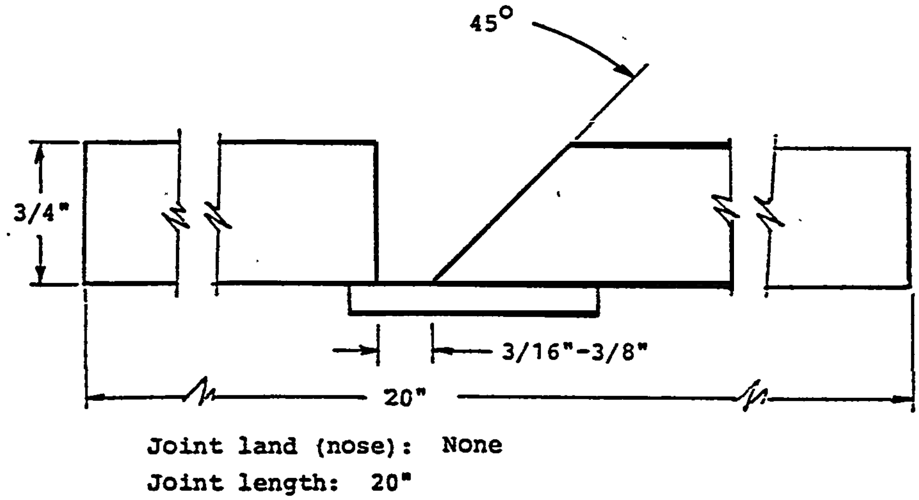
Electrode Diameter, Brand & Type ______________________

Start Time (cruciform): __________ Finish Time: __________ Date : __________

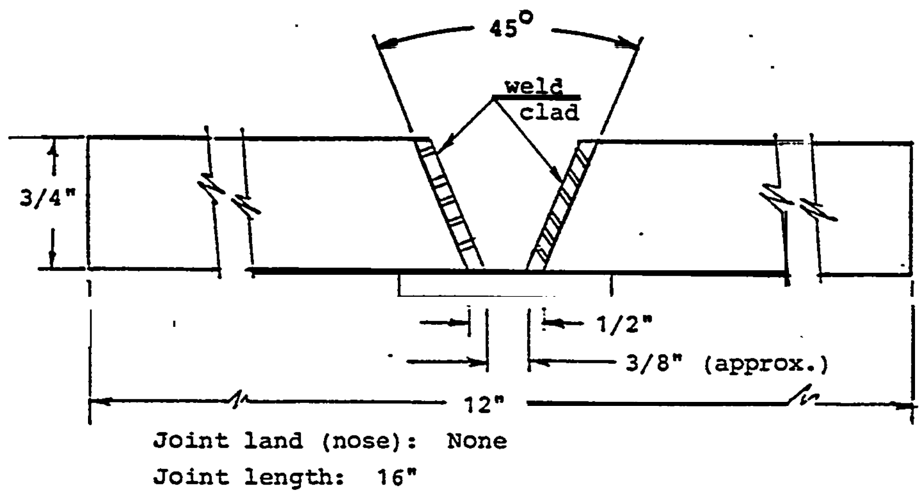
Start Time (grooved plate) : __________ Finish Time: __________ Date : __________

Name of Evaluator 6 Firm: ______________________

FIGURE 4. Grading Form



X PLATE



Y PLATE

FIGURE 5. Qualification Test Plates

bead, cracking. This cracking tendency was most pronounced in the root pass of the welds. It is not known whether this cracking tendency is a result of the dilution by the carbon steel base metal, or due to the small weld cross section of the initial (root) pass coupled with high restraint and a known tendency for hot cracking of the austenitic stainless steels. The No. 5 electrode did not show the cracking tendency during cruciform welding; however, the cracking manifested itself through the entire thickness of the root pass of the first grooved plate weld. As a result, the grooved plate weld was not completed, and no further welding was attempted using this electrode. Electrode No. 4 and No. 5 NACROS are shown in Figures 15 and 16.

No base metal or heat-affected-zone cracking was detected in any weldment by visual or liquid penetrant inspection.

PROCEDURE QUALIFICATION TEST RESULTS

TYPE OF TEST	TEST RESULTS OR ACCEPTANCE STANDARDS MET								
Visual Inspection 1/	Test Plate X:				Test Plate Y:				
Magnetic Particle Inspection 1/	Test Plate X:				Test Plate Y:				
Liquid Penetrant Inspection 1/	Test Plate X:				Test Plate Y:				
Radiographic Inspection 1/	Test Plate X:				Test Plate Y:				
Side Bends 2/									
Reduced Section Tensiles 2/	Fail. Locat.:		UTS :		Ys		Elong.		
MACRO Evaluation 1/ 2/									
wardness Values 2/	Avg. BM:		Avg. IIAZ:		Avg. WM:				
Charpy-V-Notch 2/	Avg./Min. IIAZ: /				Avg./Min. WM: ; /				
AWM Tensile 3/	UTS :		Ys :		Elongation:				
WM Chemistry 3/	C:	Mn:	Si:	P:	S:	Cut	Ni:	MO :	
	V:	Cr:	oxygen:						

1/ The test plan specifies a range of acceptance standards for these inspections. The most stringent acceptance standard passed shall be recorded.

2/ Test Plate X only

3/ Test Plate Y only

Electrode Brand, Diameter & Type: ____________________

Base Metal; ____________________ Welding Position: ____________________

Name of Evaluator: ____________________ Firm; ____________________

Weld I.D. Number: TEST PLATE X: ____________________ Water Depth: ____________

TEST PLATE Y: ____________________

FIGURE 6. Qualification Test Summary Form

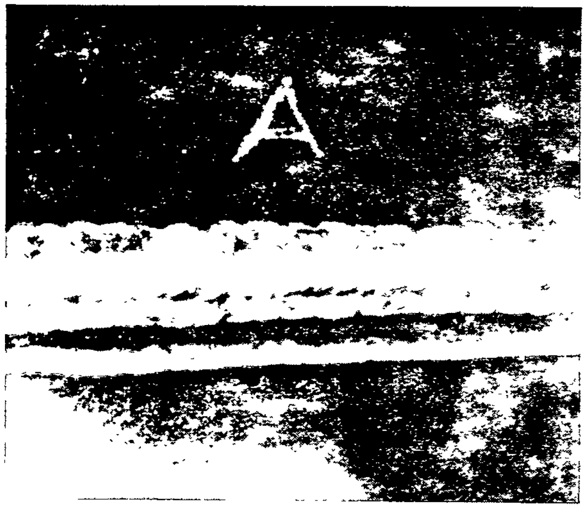
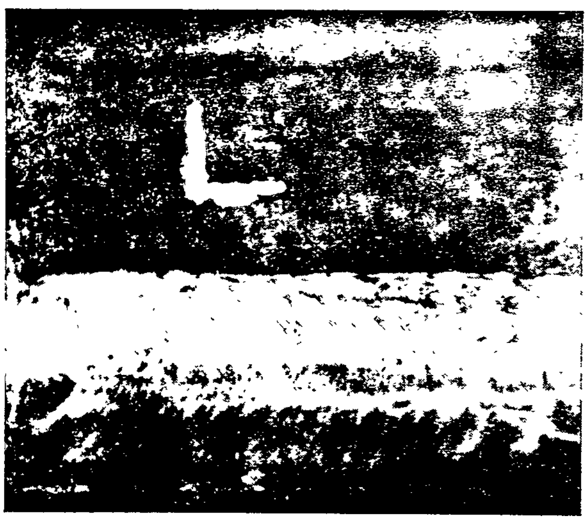


FIGURE 7. Electrode No. 1
Vertical Fillet, 33 FSW



FIGUPW 8. Electrode No. 3
Overhead Fillet, 33 FSW

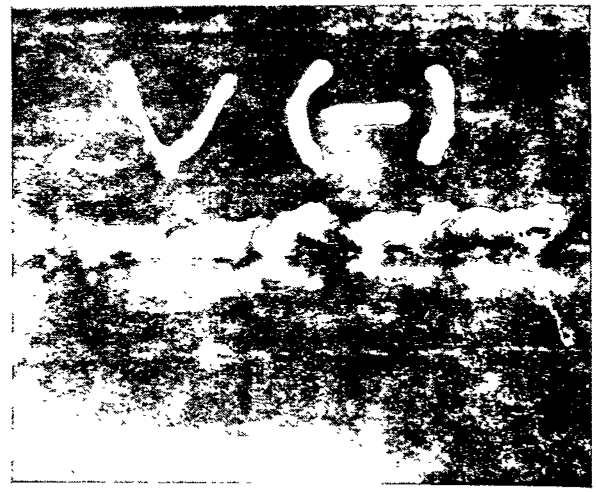


FIGURE 9. Electrode No. 8
Vertical Fillet, 33 FSW

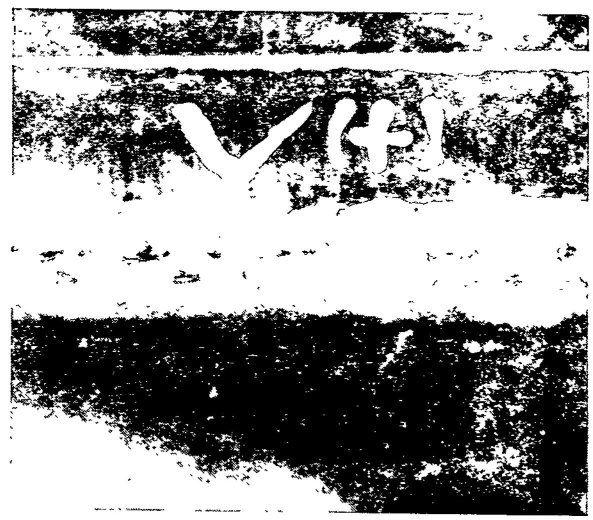


FIGURE 10. Electrode No. 8
Vertical Fillet, 33 FSW
Electrode Positive

This is particularly significant for the DH 36 steel, which had a carbon equivalent of 0.449. Neither was underbead cracking observed on the MACRO surfaces when prepared to a 120 grit finish and examined at a 7x magnification. However, upon closer examination, all the mild steel weldments in the DH 36 steel showed underbead cracking. This will be discussed in Section 2.5.1.2 below.

Based on the cruciform scoring us- *ing* the form of Figure **4**, Electrode Nos. 1, **3** and 5 were chosen for further testing using grooved plates.

2.5.1.2 Grooved plates. The austenitic stainless steel electrode, No. 5, was eliminated as described in **2.5.1.1** above based on root pass cracking.

The two mild steel electrodes, Nos. 1 and 3, were further evaluaked ***using*** **3/8"** high CE DH 36 steel grooved plates. With respect to visual inspection, liquid Penetrant inspection, bend testing, and MACRO evaluation, both Electrode Nos. 1 and 3 produced similar results. With respect to radiographic inspection, Electrode No. 3 generslly produced a cleaner weld due to a significantly lower porosity level. Representative MACROS of these welds are shown in Figure 19.

Bend testing of the high CE (DH 36 steel) grooved plate welds produced some interesting results. Of the 16 6T bend

FIGURE 11. Electrode No. 1
Vertical Fillet, 33 FSW

FIGURE 13. Electrode No. 2
Vertical Fillet, ,33 FSW

FIGURE 12. Electrode No. 1
Overhead Fillet, 33 FSW

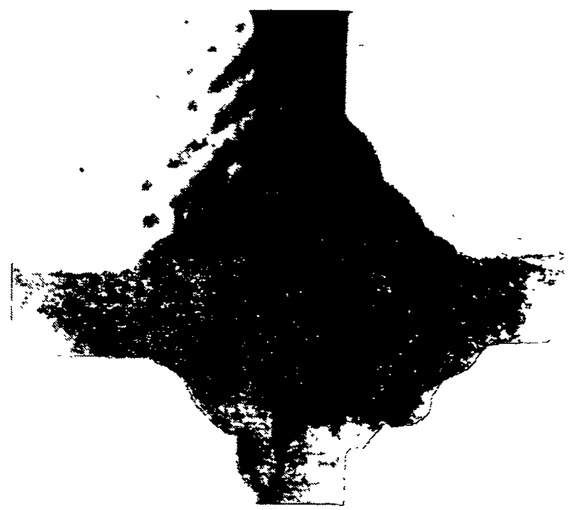


FIGURE 14. Electrode No. 3
Overhead Fillet, 33 FSW

specimens tested for each electrode, only one specimen per electrode failed to pass the test; and these failures were a result of a single linear indication, slightly longer than 1/8″, which was clearly visible but did not "open up" (crack-like indication, as opposed to a tear). Of the 16 4T bend specimens tested for each electrode, nine specimens failed for each electrode; although most of these failures were fractures, a few had only small -- but rejectable -- linear indications. The significance of these results is that all failures were in the heat-affected-zone of the base metal, which attests somewhat to the integrity of the wet welds. However, the failures caused some concern as to whether or not underbead cracking was present, but had not been detected in the MACRO evaluations. Underbead cracking is usually predicted when wet welding high CE steels (CE greater than 0.40) using ferritic electrodes. Accordingly, a cruciform MACRO and a grooved plate MACRO were prepared to a 400 grit finish (the earlier finish was 120 grit, which is normal for MACRO examination), etched and re-examined. Underbead cracking, in the heat-affected-zone, was found in both samples. Figure 20 shows two of the underbead cracks in a cruciform MACRO.

As a result of the underbead cracking problem with the DH 36 steel/ferritic electrode combination, the grooved plate welds were repeated using

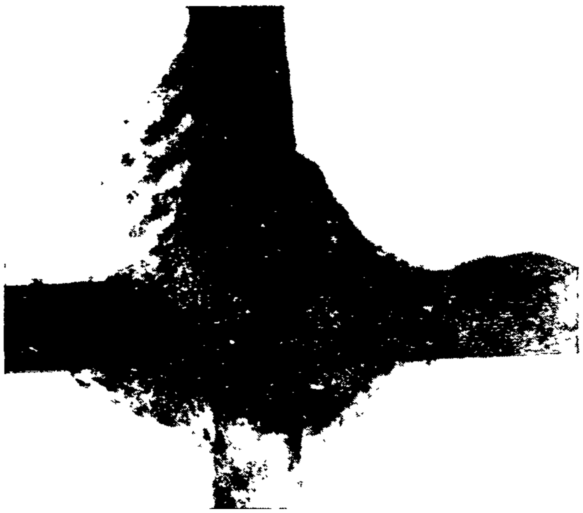


FIGURE 15. Electrode No. 4
Vertical Fillet, 33 FSW

FIGURE 17. Electrode No. 6
Vertical Fillet, 33 FSW

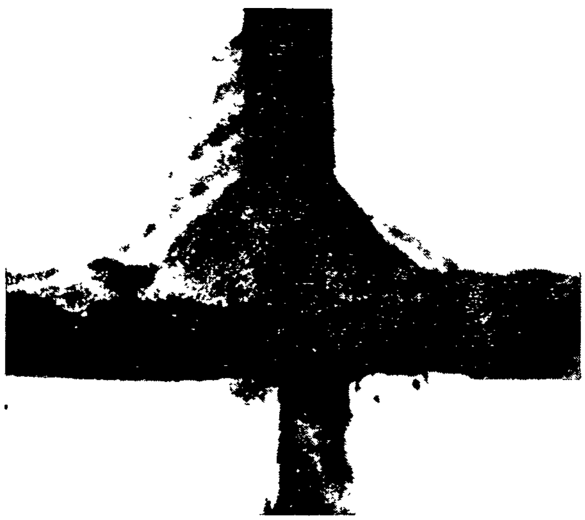


FIGURE 16. Electrode No. 5
Overhead Fillet, 33 FSW

FIGURE 18. Electrode No. 7
Overhead Fillet, 33 FSW

the low CE A36 steel plate. These tests show results similar to those obtained with the DH 36 steel grooved plates, except for the bend tests. All the 6T and 4T bends passed for Electrode Numbers 1 and 3. Eowever, none of the 2T bends passed; these failures occurred in the weld metal -- as opposed to the heat-affected-zone -- when bent to an angle of approximately 30 to 45 degrees.

2.5.1.3 Screening tests summary and conclusions. Using the grading sheet of Fiqure 4. the total score was 109.67 for Electrode Number 1 and 115.29 for Electrode Number 3. The higher score for Electrcde Number 3 is a result of cleaner welds as shown by radiographic inspection; the Number 3 electrode tended to produce less weld metal porosity in all positions of welding. This was also confirmed in the MACRO evaluations. Otherwise, the two electrodes tended to be fairly equal in terms of weldability and overall weld quality.

Both Electrode Numbers 1 and 3 caused underbead cracking in the high CE DH 36 steel; this underbead cracking was found in both the cruciforms and the grooved plates. Physical evidence of the underbead cracking was manifested in the heat-affected-zone failures of the bend tests. However, when used on the low CE ASTM A36 steel plate, there was no evidence of the underbead cracking, and all the bends for the low CE metal successfully passed the 6T and 4T tests.

Both Electrode Numbers 1 and 3 exceeded the bend test requirements of AWS D3.6 fcr Type B welds, in that they successfully passed testing over a 4T bend radius (one-third smaller than the 6T radius required by AWS D3.6). Also, each electrode occasionally met the Class 1 radiographic acceptance standards of NAVSHIPS 0900-LP-003-9000 (Ref. 7), which are more stringent standards than those of AWS D3.6 for Type B or A Welds. Based on these test results,and the fact that the MACRO specimens met the requirements of MIL-STD-248 (Ref. 3), both these electrodes were considered suitable for welding procedure qualification testing.

FIGURE 19. Grooved Plate MACROS

A - Elect. No. 1, Vertical 33 FSW
B - Elect. No. 1, Overhead 33 FSW
c - Elect. No. 3, Vertical 33 FSW
D - Elect. No. 3, Overhead 33 FSW

2.5.2 Qualification tests

2.5.2.1 Electrode Number 1. Qualification testing was performed for Electrode Number 1 as shown in Table I. The electrode number is the first digit of the specimen identification number. Maximum and minimum mechanical properties are shown in Table II. Typical completed welds are shown in Figures 21 through 24 (weld nomenclatures are shown in Table I) . Electrode Number 1 was found to consistently meet the following conditions at *7 FSW and 33 FSW:

a. Radiographic acceptance standards of AWS D3.6 for Type B welds.

FIGURE 20. HAZ Underbead Cracking
DH 36 Steel, 17.5 X

b. Class 2 visual inspection standards of NAVSHIPS 0900-LP-003-8000, Ref. 6, (except as indicated below).

c. Class 1 liquid penetrant inspection standards of NAVSHIPS 0900-LP-003-8000.

d. More stringent bend test requirement- (4T vs 6T) than those specified by AWS D3.6 for Type B welds.

e. Tensile strengths exceeding that of the ASTM A36 base metal.

* Overhead position qualification could not be accomplished at 7 FSW.

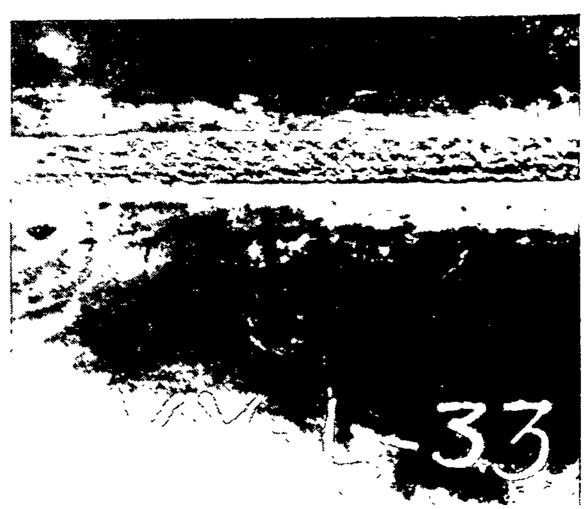


FIGURE 21. Electrode No. 1
Vertical Qualification
33 FSW

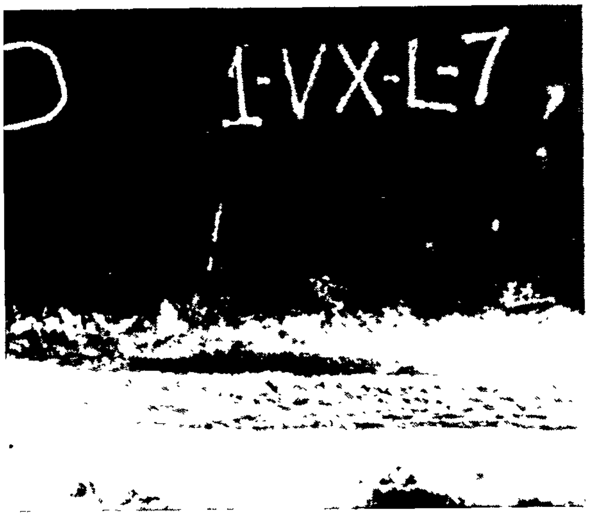


FIGURE 22. Electrode No. 1
Vertical Qualification
7 FSW

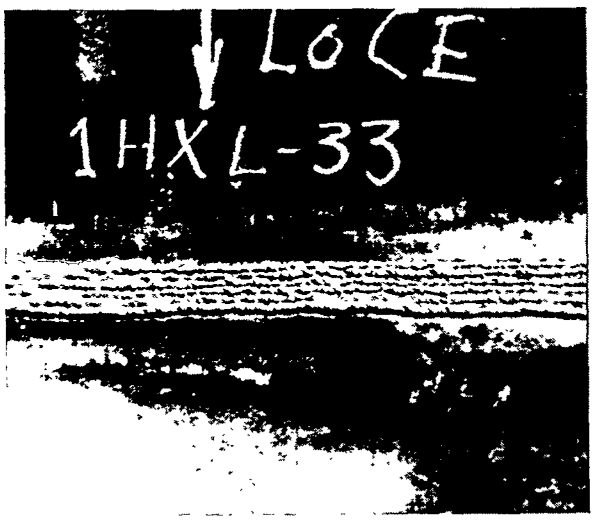


FIGURE 23. Electrode No. 1
Horizontal Qualification
33 FSW

Electrode Number 1 did not demonstrate the same degree of weldability at 7 FSW as at 33 FSW. The electrode could not be qualified in the overhead position at 7 FSW due to the high crowned, narrow beads. The Y plate could not be completed; the X plate was completed at 7 FSW in the overhead position, and the rough capping beads were ground off prior to radiographic inspection; however, the weld failed the AWS D3.6 Type B acceptance standards due to extensive slag and lack of fusion.

Electrode Number 1 also demonstrated significant undercutting tendencies in the overhead position at both water depths, such that one test plate (10Y-H-33 , Figure 24) failed to meet any surface inspection acceptance standards. The electrode also tended to undercut in the horizontal welding position, but to a lesser extent than in the overhead position.

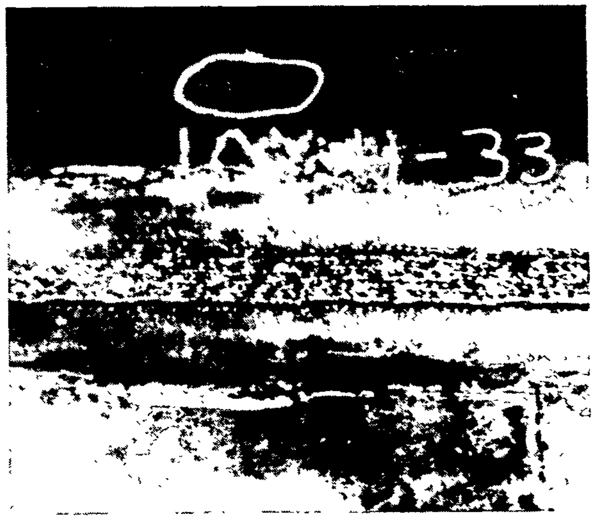


FIGURE 24. Electrode No. 1
Overhead Qualification
33 FSW

The waterproof coating of Electrode Number 1 is soft and must be protected from the water until the electrode is ready for use. Accordingly, each electrode comes in an individual plastic bag, taped around the electrode stub end. This allows the stub to be inserted into the electrode holder prior to removing the bag. The bag can be removed completely, or the electrode tip can be punched through the bag, allowing the bag to be pushed up around the electrode toward the electrode holder. The welder/divers found the bags to present visibility problems unless completely removed. Since water sometimes leaked into the taped end of the bags, the in-water life of the electrodes can be somewhat limited. The maximum water exposure time for the electrodes was not determined; however, it was found that exposure (in the bag) overnight resulted in poor electrode performance.

Electrode Number 1 can be used with either the drag or the oscillation welding technique; however, the oscillation technique (type of swirling motion) seemed to produce better results and was essential in the overhead welding position. The electrode deposited a fairly tenacious “sooty” substance at the weld toes in the horizontal and overhead positions; this had to be removed prior to making the next weld pass. Slag removal was easy for the electrode.

Electrode Number 1 can be described as a high deposition, moderately easy to use wet welding electrode. Weld quality is good except for moderate porosity which easily meets the requirements of AWS D3.6 for Type B welds; this porosity is more pronounced in the vertical position. The porosity does not appear to be detrimental in terms of the mechanical testing which was accomplished for the electrode. Overhead welding, at the seven foot depth, produced unacceptable weld bead profiles.

2.5.2.2 <u>Electrode Number 3.</u> Qualification testing was performed for Electrode Number 3 as shown in Table I; maximum and minimum mechanical properties are shown in Table II. The completed welds are shown in Figures 25 through 29 (weld nomenclatures are shown in Table I). Electrode Number 3 was found to consistently meet the following conditions at 7 FSW and 33 FSW:

a. Type B radiographic acceptance standards of AWS D3.6.

b. Class 2 visual inspection standards of NAVSHIPS 0900-LP-003-8000.

c. Class 1 liquid penetrant inspection standards of NAVSHIPS 0900-LP-003-8000.

d. More stringent bend test requirements (4T vs 6T) than those required by AWS D3.6 for Type B welds.

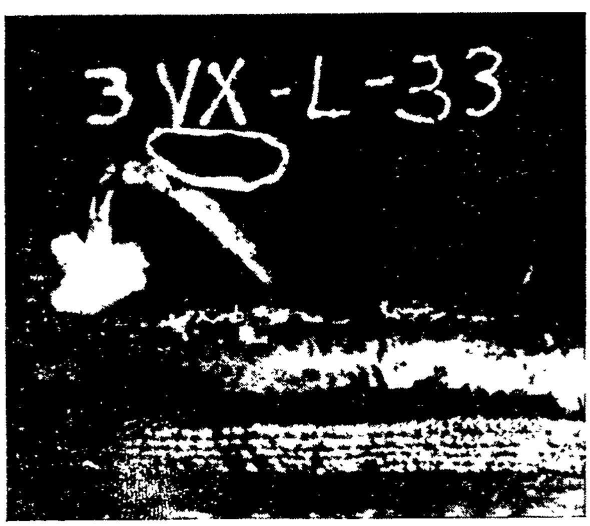


FIGURE 25. Electrode No. 3 Vertical Qualification 33, FSW

FIGURE 26. Electrode No. 3 Vertical Qualification 7 FSW

e. Tensile strength exceeding that of the ASTM A36 base metal.

Electrode Number 3 showed a decreased weldability in the overhead position at 7 FSW; as with Electrode Number 1, the weld beads tended to be narrower and higher crowned than at 33 FSW. However, both the X and Y plates were successfully qualified in the overhead position at 7 FSW. Radiographs of the X plate showed linear indications at the weld toes in the root. Removal of backing strap showed "wagon track" type slag, sometimes associated with root undercut. The weld was then background and rewelded; radiographic inspection was again performed and showed the weld to meet the acceptance standards of AWS D3.6 for Type B welds. Therefore, at 7 FSW, Electrode Number 3 may be considered qualified for plate butt welds in the overhead position only where the weld can be cleaned and welded from the back side.

Electrode Number 3 had a paraffin coating over the primary waterproof coating. The paraffin tended to "bloom out" at the arc, reducing visibility. The welder/divers sometimes removed the paraffin by short circuiting the electrode for three or four seconds (causing the electrode to heat up slightly) and sliding the entire layer of paraffin off the electrode. (The paraffin was added by the electrode manufacturer after the screening tests were completed; it was added due to the reported oxidation of the primary waterproof coating, although the primary waterproof coating never failed to adequately protect the electrode from the water.)

Electrode Number 3 can be described as a high deposition, easy to use wet welding electrode. The overall weldability and puddle control were slightly better than Electrode Number 1, and weld porosity was significantly lower than that of Electrode Number 1. However, the mechanical properties of the two electrodes were equivalent. Electrode Number 3 can be used with either the drag or the oscillation technique. Electrode Number 3 had easy slag removal.

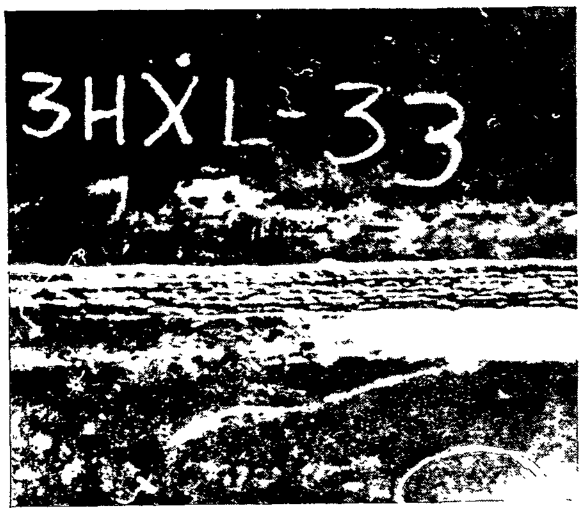


FIGURE 27. Electrode No. 3
Horizontal Qualification
33 FSW

FIGURE 28. Electrode No. 3
Overhead Qualification
33 FSW

2.5.2.3 <u>Qualification testing summary and conclusions</u>. Both Electrode Numbers 1 and 3 were found to be suitable for making all-position welds in mild steel, with the exception of Electrode No. 1 in the overhead position at 7 FSW. Both electrodes can be used by a welder/diver with average welding ability; weldability and ease of slag removal make the electrodes usable with minimal training. Overhead welding is more difficult than the other positions due to decreased visibility of the welding arc; this is a result of the bubbles being hindered, by the plate, in their movement toward the water surface. This results in capping beads which are a little more irregular than those of other welding positions (see Figures 24, 28 and 29). Figure 28 shows 50 percent of the length of the cap removed by grinding; this was done to determine whether or not the irregular ("ropy") bead profile would interfere with radiographic film interpretation. It was found that the cap did not interfere with film interpretation. The undercut shown in Figure 28 is less than 1/16 inch in depth.

FIGURE 29. Electrode No. 3
Overhead Qualification
7 FSW

Weld quality for both Electrode Number 1 and 3 is considered good and represents state-of-the-art technology. The weld quality for both electrodes can be further described as follows, where the visability is good and properly trained welder/divers are used for the welding:

a. Visual weld appearance should consistently meet the Class 2 requirements of NAVSHIPS 0900-LP-003-8000 and the Type B weld requirements of AWS D3.6. Figures 30 and 31 show close-up views of Electrode Number 3 welds made in the vertical position at 33 FSW.

b. Magnetic particle and liquid penetrant inspections should consistently meet the Class 1 requirements of NAVSHIPS 0900-LP-003-8000.

c. Radiographic inspection should consistently meet the Type B weld requirements of AWS D3.6. Where porosity less than 1/16 inch is ignored, both electrodes are capable of meeting Class 1 requirements of NAVSHIPS 0900-LP-9000 in certain instances, and they should meet the Class 3 requirements in most cases. Based on mechanical test results, the varying degrees of porosity (from none, to that allowed by AWS D3.6 Type B) showed no effect on either strength or toughness. A comparison of porosity levels between Electrode Number 1 and 3 for identical 33 FSW vertical welds, as shown by radiographic film comparison, can be seen in Figures 32 and 33; Electrode No. 3 is shown to produce significantly less porosity.

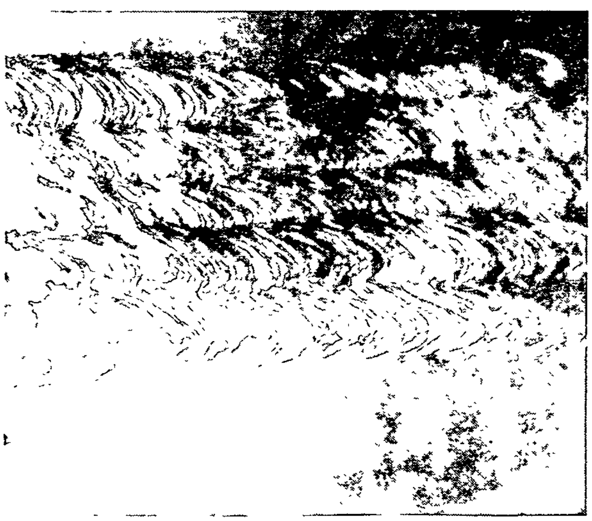


FIGURE 30. Electrode No. 3 Vertical Qualification 33 FSW

The strength, in terms of yield and tensile, of both Electrode Numbers 1 and 3 is satisfactory. In comparing base metal properties of 2.2 with weld metal properties of Table II, and as summarized in Table III, the following can be concluded:

a. Based on average values, the weld metal ultimate strength exceeds that of the A36 steel by approximately 13 percent; the weld metal yield strength exceeds that of the A36 steel by approximately 45 percent.

b. Based on average values, the weld metal ultimate strength is less than that of the DH 36 steel by approximately one percent. However, the weld metal yield strength exceeds that of the DH 36 steel by approximately 22 percent.

FIGURE 31. In-Air Butt Weld (E7018, Single Pass Cap) Intersecting a Wet Butt Weld (Electrode No. 3) Vertical, 33 FSW

FIGURE 32. Electrode No. 1 Radiograph of 33 FSW Vertical Butt Weld

Weld ductility for both Electrode Numbers 1 and 3 is obviously less than that of the base metals. It can be seen from Table III that the weld metal elongation is less than one-third that of the base metals and well below the 17 percent minimum required for air welds. However, successful bend testing using 6T (4½ inch diameter) and 4T (3 inch diameter) radius plungers showed reasonable ductility (air welds are usually bent using a 1½ inch diameter plunger). Since the tensile and yield strengths of the weld metal were considerably higher than that of the A36 steel base metal, the base metal sustained more of the bend elongation than did the weld; however, since the radius of the bend specimens was fairly constant around the circumference of the bend (no flat spots in the higher strength weld area), the weld metal apparently had reasonable elongation and thus ductility. It should also be kept in mind that 30 of 32 face bend specimens passed the 6T radius bend during the screening tests, and that the base metal was DH 36 steel. In addition, 14 of 32 specimens passed the 4T tests; those that failed did so in the heat-affected-zone, as opposed to the weld metal.

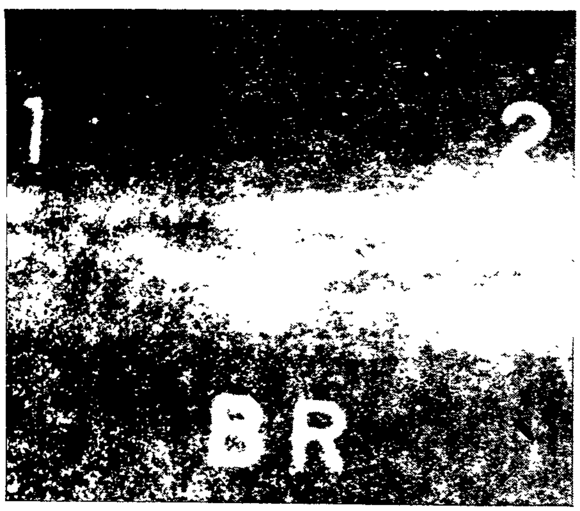


FIGURE 33. Electrode No. 3
Radiograph of 33 FSW
Vertical Butt Weld

The weld metal toughness of Electrode Number 1 and 3, as shown by the Charpy impact test, is less than 1/2 that of the A36 base metal (see Table III). However, the Charpy breaks exhibited a ductile fracture mode (80 to 100 percent shear). The work of Ref. 8, which will be further discussed in Section 3, showed that wet welds, displaying similar results, were at or near upper shelf at 28 F. Porosity shown in some heat-affected-zone specimen fracture surfaces, along with erratic heat-affected-zone energy values, indicate that the heat-affected-zone Charpys were not always failing in only the heat-affected-zone. The failures were sometimes veering off toward the weld metal. Heat-affected-zone Charpy impact average values ranged from 28 to 61 foot-pounds.

With respect to macroscopic examination, all the wet welds met the Type A (dry weld) requirements of AWS D3.6 -- except that some specimens had minor root cracking associated with slag inclusions or gaps between the plate and backing bar; AWS D3.6 allows no cracking in the MACRO specimens. Most of the MACRO specimen root cracking was not in excess of 1/32 inch. However, some of the specimens had slag inclusions which exceeded 1/32 inch, which is rejectable to the requirements of MIL-STD-248C. Representative MACROs are shown in Figures 34 through 40. MIL-STD-248C recognizes that backing bar butt welds have an occasional tendency for minor cracking in the root, and will accept these indications if not longer than 1/32 inch. This cracking tendency was demonstrated in the wet welds, <u>but only</u> associated with minor root slag or, on one occasion, a gap between the plate surface and the backing bar.

FIGURE 34. Electrode No. 1
Overhead Qualification
33 FSW (3X)

There was no case where the weld metal hardness exceeded the 325 H_v10 maximum allowed by AWS D3.6 for Type A welds. In fact, the weld metal hardness never reached 250 H_v10, and the majority of the readings were below 200 H_v10. The only areas exceeding 325 H_v10 were in the base metal heat-affected-zone just beneath the weld cap. In other work, excessive HAZ hardness, just under a wet weld cap, have been reduced to acceptable values by using the "temper bead technique". However, this requires a well trained welder/diver and good in-water visibility.

FIGURE 35. Electrode No. 1
Vertical Qualification
7 FSW (3X)

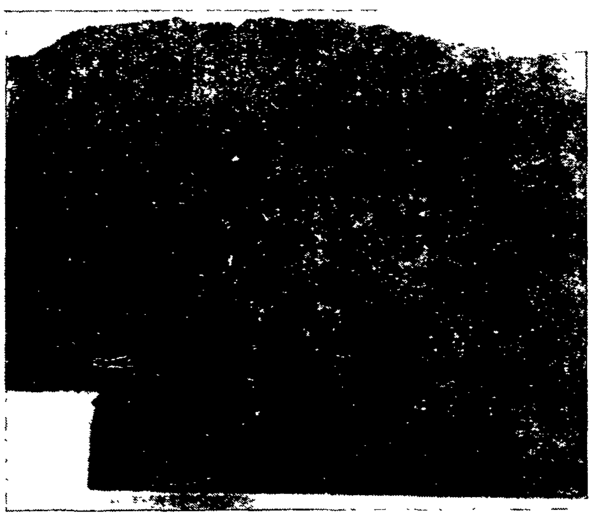


FIGURE 36. Electrode No. 1
Vertical Qualification
33 FSW (3X)

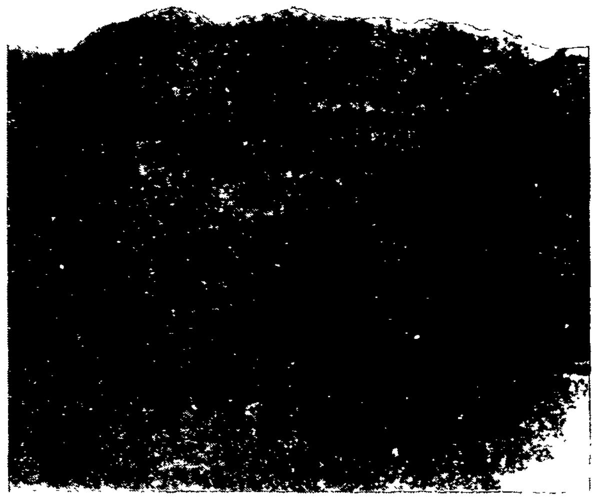


FIGURE 37. Electrode No. 3
Vertical Qualification
33 FSW (3X)

FIGURE 38. Electrode No. 3
Overhead Qualification
33 FSW (3X)

3.0 DISCUSSION

Two commercially available mild steel wet welding electrodes have been qualified to the requirements of AWS D3.6 for wet welding ordinary strength structural carbon steel; as allowed by AWS D3.6, this qualification extends to a water depth of 66 feet. Based on the requirements of AWS D3.6, this qualification is limited to steels with a maximum carbon equivalent of 0.350 and a maximum carbon content of 0.17 percent by weight. Additional testing would be required to qualify the electrodes to weld steels with a higher carbon content and/or carbon equivalent. (A very promising stainless steel electrode, for use in welding the higher carbon equivalent steels, underwent initial screening tests; however, the screening tests could not be completed, because most of the electrodes were damaged in shipment. Refer to Figures 41 and 42.)

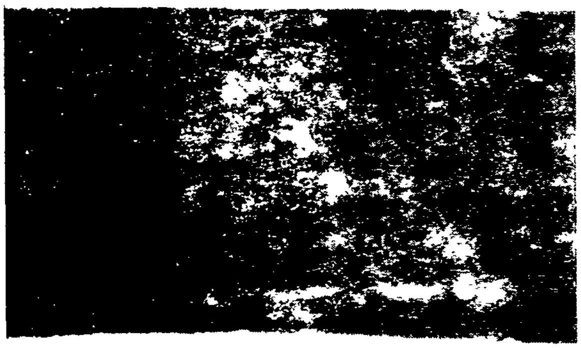


FIGURE 39. Electrode No. 3
Overheat Qualification
7 FSW (3X)

FIGURE 40. Electrode No. 3
Vertical Qualification
7 FSW (3X)

The qualification testing has established that the mild steel electrodes meet a weld quality standard somewhere between that considered acceptable for wet welds by the American Welding Society, and that considered

FIGURE 41. Experimental Stainless
Steel Electrode
Vertical Fillet, 33 FSW

acceptable for dry welds by the U. S. Navy. The primary weld discontinuity was porosity -- the degree of which had no observable impact on any of the mechanical test results. Neither did the minor cracking, associated with root discontinuities, have any impact on the mechanical test results. Of the initial 36 side bend specimens, two failed due to slag/incomplete root penetration; two additional bend specimens, for each failed specimen, passed the bend test for a total of 40 bends.

Bend tests exceeded AWS D3.6 requirements for Type B welds, and tensile and yield strengths far exceeded minimum base metal requirements and the requirements of applicable filler metal specifications. Weldment toughness and ductility are reduced compared to air welds, but may be considered adequate for certain applications. Weldment hardness exceeded AWS D3.6 requirements for Type A welds only in the heat-affected-zone just under the weld cap.

Ref. 8, which is an underwater welding study performed by the Southwest Research Institute for the Ship Structures Committee through the U. S. Coast Guard, makes the following observation in the opening statement of the "ABSTRACT": "Data reported herein indicate that the wet......welding (SMAW) process can produce welds suitable for structural applications provided certain limitations of the welds are considered in design." The SWRI Report includes the same mechanical testing as covered in this report, and in addition, fracture toughness (J_{Ic}) testing. However, the SWRI work covered welds made only in the flat position, and the welding took place in fresh water. All test results in this report pretty much paralleled these corresponding tests of the SWRI Report. The mechanical properties of electrode Numbers 1 and 3 (E7014 "type" electrodes) appear to be equivalent to those of the E6013 "type" electrodes tested in the SWRI work. It would be considered worthwhile to make a detailed comparison between the results of this study and the results of the SWRI work. The applicability of the fracture toughness calculations and weld design recommendations, established in the SWRI work, could then be assessed for the two wet welding electrodes of this study.

Another previous study, Ref. 9, addresses crack growth rate of wet welds made with E6013 electrodes. The welds were made in fresh water at a depth of approximately 33 feet. Two meaningful conclusions of the Ref. 8 study are as follows:

a. Crack growth rates increased with porosity level.

b. At stress intensity factors of approximately 30 KSI $\sqrt{in}$ and below, depending on porosity level, crack growth rates for the wet welds were less than for surface or dry habitat welds.

FIGURE 42. Experimental Stainless Steel Electrode Overhead Bead-on-Plate 33 FSW

In regard to depth, the following was found:

a. There was no significant difference in mechanical properties at 7 FSW, as compared to 33 FSW, except a slight increase in ultimate and yield strengths.

b. Weld metal carbon and manganese decreased somewhat at the deeper depth, which may account for the lower strength levels. Weld metal oxygen levels at 7 FSW were only on the average about 1.4 percent of that at 33 FSW.

c. Overhead welding became more difficult at 7 FSW, such that Electrode Number 1 could not be qualified.

The results achieved in this project have shown that wet welding can have a degree of integrity such that its use may be justified for limited applications in Naval surface ship repair. Such applications would include:

- Permanent nonstructural repair in low carbon equivalent steels.
- Temporary structural repairs, performed on an emergency basis, where replacement or rewelding of the repaired area might be deferred until the next scheduled drydocking.

4.0 ACKNOWLEDGEMENTS

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5.0 REFERENCES

(1) ANSI/AWS B4.0-85 Standard Methods for Mechanical Testing of Welds.

(2) ANSI/AWS D3.6-83 Specification for Underwater Welding.

(3) MIL-STD-248C Welding and Brazing Procedure and Performance Qualification.

(4) MIL-STD-271E (SHIPS) Nondestructive Testing Requirements for Metals.

(5) MIL-S-22698B (SH) Steel Plate; Carbon, Structural for Ships.

(6) NAVSHIPS 0900-LP-003-8000 Surface Inspection Acceptance Standards for Metals.

(7) NAVSHIPS 0900-LP-003-9000 Radiographic Acceptance Standards for Production and Repair Welds.

(8) Norris, E. B., Dexter, R. J., Schick, W. R., and Watson, P. D., "Underwater Wet And Wet-Backed Welds: Toughness, Mechanical Properties and Design Guidelines", Southwest Research Institute (Draft) Report 7168, 31 March 1986.

(9) Matlock, D. K., Edwards, G. R., Olson, D. L., and Iberra, S., "An Evaluation of the Fatigue Behavior in Surface, Habitat and Underwater Wet Welds", Submitted to the Second International Conference on Offshore Welded Structures, London, England, 16-18 November 1982.

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TABLE I. QUALIFICATION TESTING PERFORMED

WELD I.D. NO.	POSITION/ DEPTH	TESTING/INSPECTION PT	RT	BENDS	RST	CHARPY W/M	B/M	HAZ	MACRO/ HARD	AWM	W/M CHEM.
1VX-L-33	VERT/33	X	X	X	X	X		X	X		
3VX-L-33	VERT/33	X	X	X	X	X		X	X		
1HX-L-33	HORZ/33	X	X	X	X						
3HX-L-33	HORZ/33	X	X	X	X						
1OX-L-33	OVERHD/33	X	X	X	X	X		X	X		
3OX-L-33	OVERHD/33	X	X	X	X	X		X	X		
1VY-L-33	VERT/33	X	X							X	X
3VY-L-33	VERT/33	X	X							X	X
1OY-L-33	OVERHD/33	X	X							X	X
3OY-L-33	OVERHD/33	X	X							X	X
1VX-L-7	VERT/7	X	X	X	X	X		X	X		
3VX-L-7	VERT/7	X	X	X	X	X	X		X		
1OX-L-7	OVERHD/7	X	X								
3OX-L-7	OVERHD/7	X	X	X	X	X		X	X		
1VY-L-7	VERT/7	X	X							X	X
3VY-L-7	VERT/7	X	X							X	X
1OY-L-7	OVERHD/7										
3OY-L-7	OVERHD/7	X	X							X	X
3OX-ST-7-5/32	OVERHD/7	X	X								
3OX-ST-7-3/8	OVERHD/7	X	X								

1/ First digit: Electrode Number
Second digit: Position of welding
Third digit: Type of test plate
Fourth digit: Carbon equivalent, high vs low
Remaining digits: Water depth

TABLE II. TENSILE AND IMPACT QUALIFICATION TEST RESULTS

ELECTRODE AND WATER DEPTH	TENSILE STRENGTH, PSI		YIELD STRENGTH, PSI		ELONGATION, %		IMPACT ENERGY AT 28° F, FT.LBS.	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	*Minimum	*Maximum
Electrode No. 1 33 FSW	73,400	74,500	65,300	68,100	6.6	9.3	29.8	31.8
Electrode No. 1 7 FSW	74,700	75,900	65,800	68,350	8.0	8.8	33.5	33.5
Electrode No. 3 33 FSW	77,050	83,050	70,900	76,550	6.0	8.3	25.1	32.0
Electrode No. 3 7 FSW	78,350	84,050	74,500	82,400	4.8**	8.8	28.2	24.5

* Based on average values for each weldment tested.

** Questionable value.

TABLE III. COMPARATIVE WELD METAL/BASE METAL PROPERTIES

Properties	Average Weld Metal	Average Base Metal A36	Average Base Metal DH 36	Base Metal Spec. A36	Base Metal Spec. DH 36
Tensile Strength** KSI	77.6	68.8	78.7	50-80	71-90
Yield Strength** KSI	71.5	49.4	58.5	36 Min.	51 Min.
Elongation, %**	7.6	27.7	23.7	23 Min.	22 Min.
Impact Energy at 28° F, Ft.Lbs.	29.8	75.5	No Tests Run	Not Req'd.	N/A*

* Different temperature requirements.

** From all-weld-metal testing.