Investigation of Diffusible Hydrogen Content and Microstructure Examination of Underwater Welding

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Abstract

Underwater welding is developed for underwater repair applications. This process can be done by two principles, wet welding and dry welding. Wet welding process is designed for welding repair of ship and offshore structure where dry welding process is not possible. However, wet welding process gives low weld quality since it is done in worst welding environment. Hydrogen in water can cause many problems in welds such as severe porosity and hydrogen induced cracking. The objective of this study is to investigate diffusible hydrogen and microstructure in weld metal. Three types of filler metal, E6013, E309-16 and E312-16, are modified in order to be used for underwater welding. Diffusible hydrogen is measured. Microstructure and hardness of weldment are investigated.

Keywords*: Diffusible Hydrogen, Underwater Welding*

1 Introduction

Underwater welding can be subdivided into two major categories: welding in a wet environment and welding in a dry environment. For wet welding, the relatively poor quality of welds made in a wet environment is due primarily to the problem of heat transfer, welder visibility, and the presence of hydrogen in the arc atmosphere during the welding operation. It is normally necessary for temporary weld repair of ship, offshore, dock and other harbor facilities [1].

In underwater wet welding, the weld will have much higher cooling rate than that of conventional atmospheric weld since it is exposed to the water at all time as shown in figure 1. This results in rapid heat convection loss and hydrogen diffusion from water vapor decomposing to the weld pool at high temperature as shown in equation below [2].

$$H_2O_{(v)} = H_{2(g)} + (1/2)O_{2(g)}$$

Since large quantities of hydrogen are present, hydrogen cracking is one of the major problems in this process as shown in figure 2. High cooling rate of weld metal and heat affected zone can result in susceptible microstructure and high contraction stress. Many researchers [3-5] have studied and reported these problems. The mean of successful underwater welding is to properly select welding technique and welding electrode that can control or suppress diffusible hydrogen in the weld pool. However the comparison effect of rutile and austenitic stainless steel filler metal on diffusible hydrogen and weldability are not completely studied. The objective of this study is to investigate diffusible hydrogen content obtained from coated rutile filler metal (E6013) and austenitic stainless steel filler metal (E309-16 and E312-16). Therefore his study examines how the use of these electrodes affects the welding of SS400 mild steel.

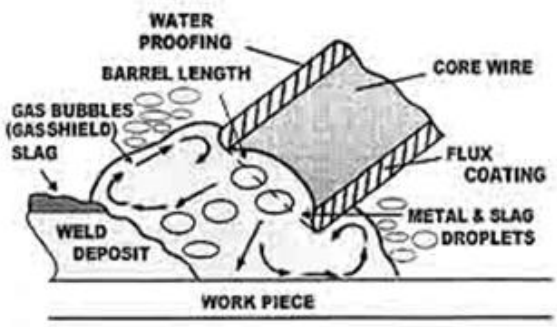

Figure 1: Illustrate of shield metal arc wet welding process

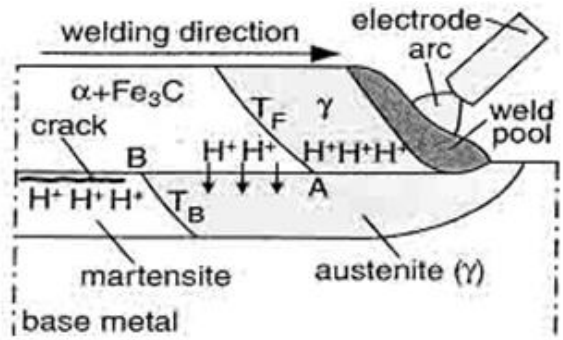

Figure 2: Illustrate of hydrogen ion diffusion into the heat affected zone where T_F is Austenite/ (Ferrite+Pearlite) transformation temperature and T_B is Austenite/ Martensite transformation temperature [6]

2 Experimental procedure

2.1 *Welding procedure*

Low carbon steel with the carbon equivalent of 0.2181 was used in this study. The samples with the thickness of 12 mm were cut into 25 mm * 130 mm in size. They were dried at 650^{o}C for 1 hour to remove any remain hydrogen as much as possible and weighed before welding (initial weight). AWS A5.1 E6013 and AWS A5.4 E309-16 with 4 mm diameter were selected for this study. This size of diameter was recommended by JIS Z3113. The electrodes were coated with the waterproof medium made of silicone. Figure 3 showed welding setup for underwater welding. The prepared sample was immerged into the water tank and contacted with work clamp. Then test sample was welded by SMAW wet welding process. One weld bead was deposited with drag and weaving technique.

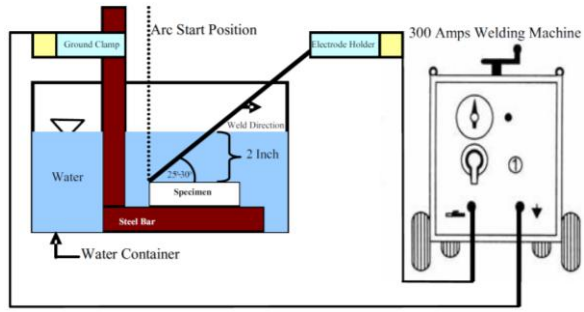

Figure 3: Illustrate of underwater wet welding experimental setup

Table 1 indicates welding parameters used for determining diffusible hydrogen content. Both atmospheric and underwater welding was used to compare the amount of diffusible hydrogen in weld metal. Welding current was set at 15 A lower than the highest value of welding current recommended by manufacturer. Welding parameters were controlled in order to keep almost the same heat input since heat input can affect the amount of diffusible hydrogen.

Table 1: Indicate of welding parameters in two conditions

Type of Electrode	Welding Conditions	Volt (avg.) (V)	Amp (avg.) (A)	Welding Speed, (avg.) (mm/s)	Heat Input, (avg.) (KJ/mm)
E6013	Atmospheric	22.22	114.71	2.15	1.19
E6013	Underwater	27.51	171.85	4.56	1.04
E309-16	Atmospheric	31.95	124.62	3.41	1.17
E309-16	Underwater	31.48	172.19	5.19	1.04
E312-16	Underwater	31.54	173.73	5.29	1.04

2.2 *Measurement of hydrogen content [7]*

JIS Z3113 standard (Method for Measurement of Hydrogen Evolved from Deposited Metal) was used as a reference for measurement of diffusible hydrogen. After the completion of the weld, the sample was rapidly cooled by immersion in iced water for 10 seconds. Then weld slag was immediately removed. The sample was then dried and cleaned by lint free cloth. Then the sample was inserted into the hydrogen collector by means of glycerin replacement method as shown in figure 4. All steps mentioned above shall be completed as fast as possible (within 60 seconds after the completion

of weld). Collection of gas shall be performed by immersing the sample in glycerin maintained at 45 ± 3°C for 48 hours. The volume of diffusible hydrogen collected at the top of the glassware was read and recorded. Then the sample that was removed from glassware was rinsed in water, dried and weighed (final weight). The weight of the deposited weld metal was determined by the difference between initial and final weight. For each sample, the volume of diffusible hydrogen collected per 100 g of deposited weld metal was calculated.

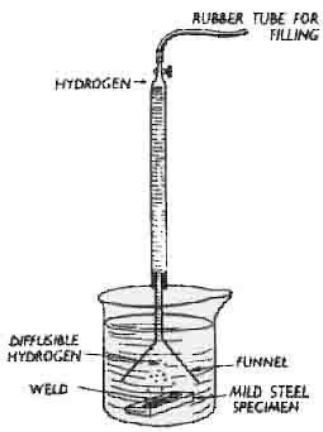

Figure 4: Illustrate of hydrogen collector equipment setup

2.3 *Y- groove restrain cracking test [8]*

The Y-slit specimen was cut from the plate and prepared according to figure 5. Test piece were cut into 12 mm * 75 mm * 200 mm and from the plates in such a way that their longitudinal dimension was parallel to the rolling direction of the plates. The test specimens were beveled by milling machine. The restraining welds were made by conventional SMAW. Then specimens were welded in atmospheric and underwater welding. The test welds were carried out in a flat position and started when the temperature of the whole test piece reaching surrounding temperature for atmospheric welding and water temperature for underwater welding. Welding parameters for each electrode were similar to table 1. The welded specimens were submerged in a container for 48 hours and then sectioned to determine cracking. Metallographic examination and hardness test were also investigated.

2.4 *Measurement of hardness [9]*

In the metallographic examination, the specimens were polished and etched. Macrostructure and microstructure examination was observed. The hardness was also measured by using Vicker hardness (HV10). The hardness measurements were taken at 2 mm below the weld surface and across weld metal, heat affected zone and base metal with 0.5 mm increment. Hardness distributions for each welding condition were plotted and studied.

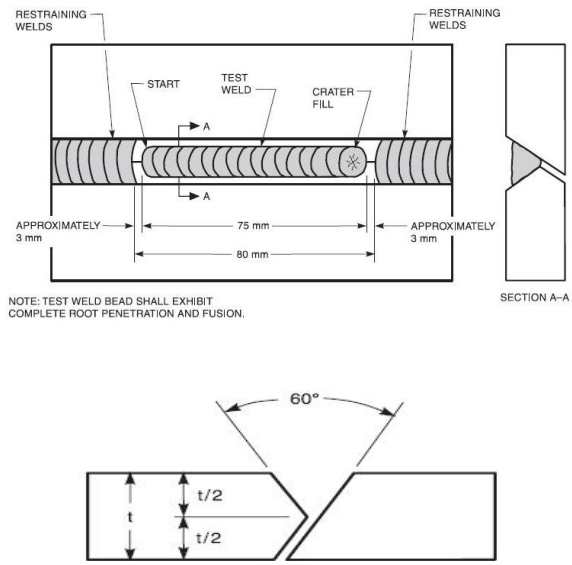

Figure 5: Illustrate of butt joint preparation for Y- Groove Restrain Cracking Test [8]

3 Experimental results and discussions

3.1 *Hydrogen content in the weld*

Figure 6 showed the example of the diffusible hydrogen measurement. The volume (ml) of diffusible hydrogen was read and recorded after 48 hours. Then the sample was removed, cleaned and dried. The sample was weighted to determine the weight of weld deposit. The amount of diffusible hydrogen was calculated per 100 g of weld deposit and plotted in figure 7.

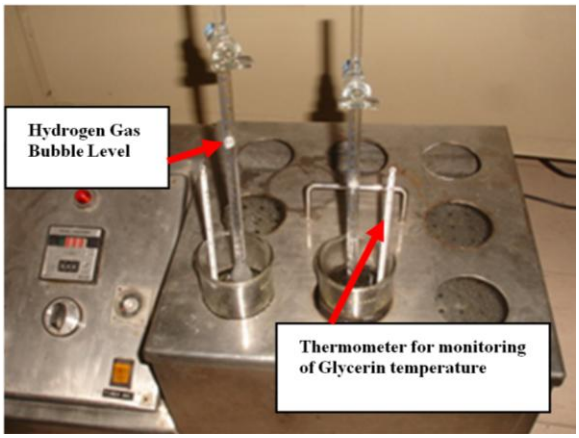

Figure 6: Illustrate of hydrogen gas bubble level diffusing from the weld into hydrogen collector equipment setup

Figure 7 showed that E6013 used in atmospheric welding gave diffusible hydrogen with averaging of 10.57 ml/100g. For underwater environment, silicone coated E6013 gave diffusible hydrogen as high as 65.11ml/100g. Austenitic filler metal, E309-16, appeared to give lower diffusible hydrogen content of 30.06ml/100g and 4.28ml/100g for underwater and atmospheric weld, respectively. This was because of high hydrogen-solubility.

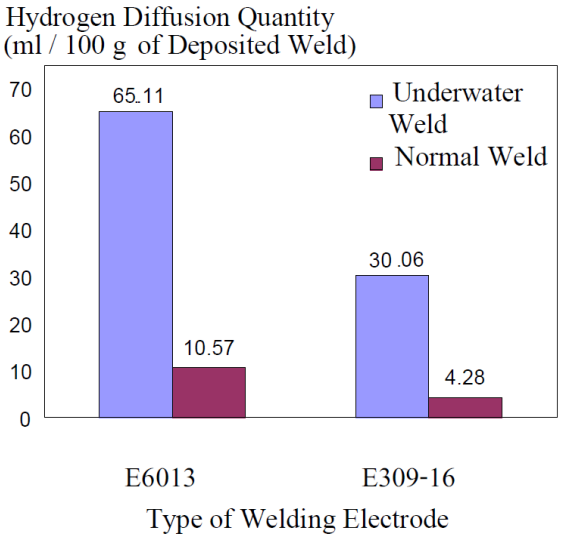

Figure 7: Illustrate comparison of average hydrogen diffusion quantity of the weld from two welding conditions and two welding electrodes

3.2 *Analysis of y-groove restrained cracking test*

The Y-groove test specimens were visually inspected and section to expose possible crack. It can be seen that no crack were found in the mild steel used in this study. Even though Silicone coated E6013 gave diffusible hydrogen content as high as 65 ml/100g, no crack was observed both in weld metal and heat affected zone. Atmospheric weld also gave no crack in the Y-groove test specimen. However Silicone coated E309-16 gave cracking at weld centerline. This crack was observed immediately after the completion of weld. It can be stated that high contraction stress could be the reason for this hot cracking as shown in figure 8. Austenitic filler metal can prevent hydrogen cracking but it was susceptible to hot cracking if the welding procedure was not properly controlled.

This study showed that all Y-groove test specimens welded with silicone coated E309-16 were centerline cracking.

Figure 8: Illustrate of weld hot cracking when used E309-16 electrode, (Nital 2% Etching)

Another austenitic filler metal, silicone coated E312-16, was used to solve this problem. This filler metal contained higher ferrite content as high as almost 40% ferrite and gave higher tensile strength. The result showed that no crack was found in all tested samples when welded with E312-16 as shown in figure 9.

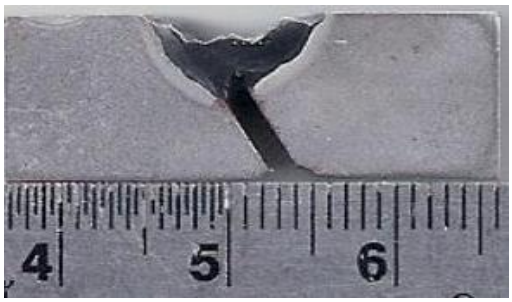

Figure 9: Illustrate of underwater weld in Y-Groove Section by using E312-16 electrode, (Nital 2% Etching)

Figure 10 and 11 showed weld metal microstructure of E309-16 and E312-16, respectively. It can be seen from figure 10 that ferrite percentage of E309-16 weld metal analyzed by using image analyzer was about 26.61%. E312-16 weld deposit showed higher ferrite percentage at 37.62 % as shown in figure 11.

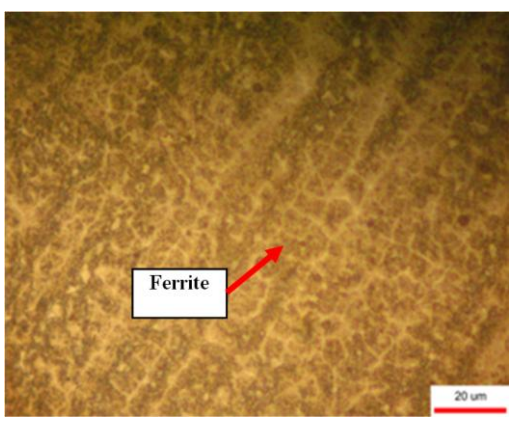

Figure 10: Illustrate of ferrite in weld metal microstructure of E309-16 weld deposit in underwater weld condition, X100 (Vilella's Reagent Etching)

According to filler metal manufacture's information, the tensile strength of E309-16 electrode was 87,500 PSI (600 MPA) and the tensile strength of E312-16 electrode was 109,000 PSI (750 MPA). This higher tensile strength of E312-16 and higher ferrite content in weld metal was able to resist high residual stress and shrinkage stress occurring in the Y-Groove restrain joint geometry. High contraction stress resulted from rapidly cooling of underwater weld metal. Austenitic stainless steel also had higher coefficient of thermal expansion (CTE) as well as higher residual stress. This could promote solidification cracking.

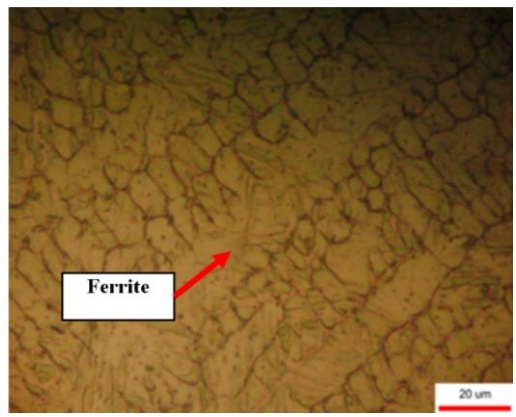

Figure 11: Illustrate of ferrite in weld metal microstructure of E312-16 weld deposit in underwater weld condition, X100 (Vilella's Reagent Etching)

3.3 *Hardness distribution within atmospheric and underwater weld*

Figure 12 illustrated location, number of test and spacing of hardness measurements transverse to Y-Groove test specimen. The average hardness values were determined by averaging of 4 points in weld metal location, 4 points in heat affected zone and 4 points in base metal. The hardness distributions within atmospheric and underwater welds of mild steel for each filler metal and welding condition were illustrated in figure 13.

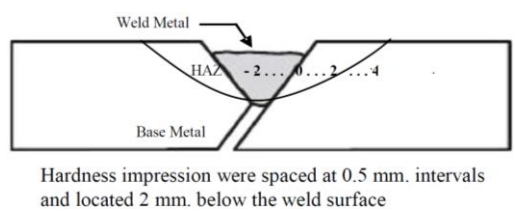

Figure 12: Illustrate location and spacing of hardness measurement on Y-Groove test specimen

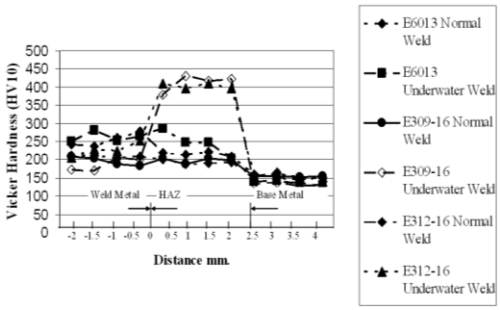

Figure 13: Illustrate of weld hardness value comparison from location and impression space in figure 12

For atmospheric weld, figure 13 showed that the hardness in weld metal and heat affected zone was about the same and slightly higher than that of the base metal. For underwater weld, the hardness in weld metal and heat affected zone obtained from E6013 weld metal was slightly increased comparing with those obtained in atmospheric weld. It can be stated that underwater environment gave higher cooling rate resulting in higher hardness however this cooling rate only slightly affected mild steel base metal and E6013 weld metal. For this reason, even though E6013 weld deposit gave as high as 65.11ml/100g of diffusible hydrogen, no cracking was observed. Lower strength filler metal (E6013) also provided acceptable hardness both in weld metal and heat affected zone. Microstructure of the heat affected zone area for E6013 underwater weld was shown in figure 14. Figure 14 illustrated Widmanstatten structure in heat affected zone which was corresponding well with the maximum hardness of 285.6 (HV10) obtained in figure 13. For underwater weld, stainless steel filler (E309-16 and E312-12) gave the hardness in weld metal and base metal was almost the same as that of the atmospheric weld. However the hardness in heat affected zone was as high as 429.20 (HV10) for these austenitic filler metals. Figure 15 illustrated microstructure showing plate martensite in heat affected zone of underwater weld made with E309-16 stainless steel electrode. The austenitic stainless steel filler metals were observed to produce underwater welds containing martensite structure along fusion boundaries; this was due to the high base metal dilution and the high quenching rate caused by the water environment. However no cracking in heat affected zone was observed in all test welds in this study. This could result from low diffusible hydrogen of 4.28ml/100g in weld deposit since austenitic filler metal had large hydrogen solubility and tended to keep hydrogen away from heat affected zone. As mentioned in 3.2, centerline cracking (hot cracking) was observed in E309-16 weld deposit but none of them was originated from heat affected zone.

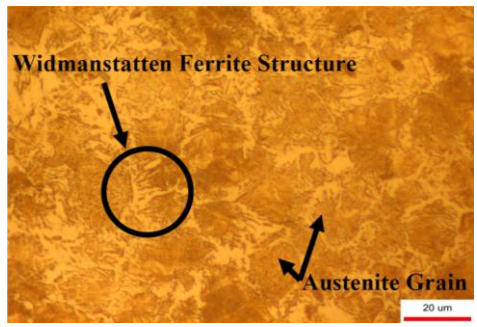

Figure 14: Illustrate of heat affected zone Widmanstatten ferrite structure of underwater weld made with E6013 carbon steel electrode in mild steel, X100 (Nital 2% Etching)

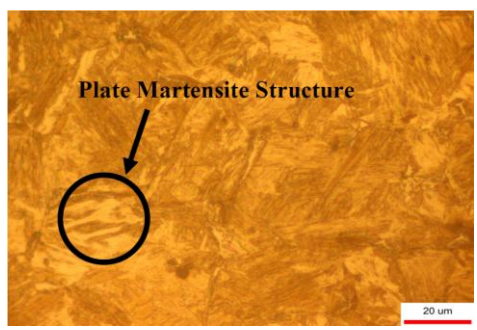

Figure 15: Illustrate of heat affected zone plate martensite of underwater weld made with E309-16 stainless steel electrode in mild steel, X100 (Nital 2% Etching)

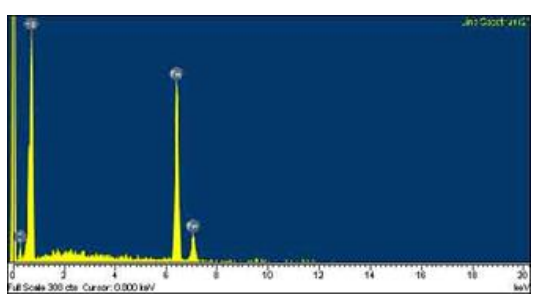

Figure 16: Illustrate of EDS spectra of qualitative element composition of heat affected zone plate martensite in underwater weld made with E309-16 stainless steel electrode in mild steel

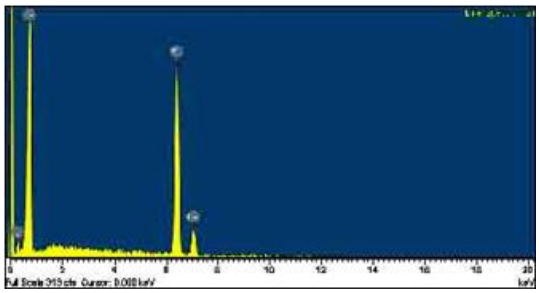

Figure 17: Illustrate of EDS spectra of qualitative element composition of heat affected zone plate martensite in underwater weld made with E312-16 stainless steel electrode in mild steel

Figure 16 and Figure 17 showed the qualitative element composition of heat affected zone showing plate martensite in underwater weld made with E309-16 and E312-16 respectively. These showed the peak of Fe and C resulted from Fe_3C in this HAZ where high hardness was observed.

4 Conclusions

1. For underwater environment, silicone coated E6013 gave diffusible hydrogen as high as 65.11ml/100g comparing with diffusible hydrogen of 10.57 ml/100g in atmospheric welds. Austenitic filler metal, E309-16, appeared to give lower diffusible hydrogen content of 30.06ml/100g and 4.28ml/100g for underwater and atmospheric weld, respectively. This was because of high hydrogen-solubility in austenitic welds.
2. For low carbon steel electrode, E6013, no crack in weld metal and heat affected zone was observed both atmospheric and underwater weld.
3. For underwater weld, the hardness in weld metal and heat affected zone obtained from E6013 weld metal was slightly increased comparing with those obtained in atmospheric weld because underwater environment gave higher cooling rate resulting in higher hardness however this cooling rate only slightly affected mild steel base metal and E6013 weld metal.
4. Austenitic filler metal can prevent hydrogen cracking but it was susceptible to hot cracking if the welding procedure was not properly controlled. This study showed that all Y-groove test specimens welded with silicone coated E309-16 contained centerline cracking. E312-16 can be used to solve this problem. This filler metal contained higher ferrite content as high as almost 40% ferrite and gave higher tensile strength.
5. The hardness in heat affected zone was as high as 429.20 (HV10) for both E309-16 and E312-16 filler metals. The austenitic stainless steel filler metals were observed to produce underwater welds containing martensite structure along fusion boundaries; this was due to the high base metal dilution and the high quenching rate caused by the water environment.

Reference

[1] ASM Handbook, Vol.6, "Underwater Welding", Welding Brazing and Soldering, ASM International, Ohio, USA, pp.2465 – 2478, (1993).

[2] Ibarra, S., Grubbs, C. E., and Liu, S., "State of the Art and Practice of Underwater Wet Welding of Steel", International Workshop on Underwater Welding of Marine Structures, New Orleans, Louisiana, USA, pp.71 – 86, (December 7 – 9, 1994).

[3] Grubbs, C. E., and Seth, O. H., "Multi pass All Position Wet Welding-A New Underwater Tool," Forth Annual Offshore Technology Conference, 1972, Houston, Texas, Paper/Communication OTC 1620.

[4] Masubuchi, K. and Meloney, M. B., "Underwater Welding of Low Carbon and high Strength (HY-80) Steel," Sixth Annual Offshore Technology Conference, 1974, Houston, Texas, Paper/Communication OTC 1951.

[5] Brown, R. T., and Masubuchi, K., "Fundamental Research on Underwater Welding," Welding Journal, 54 (6), June 1975, Res.Suppl., pp. 178-s to 188-s.

[6] S. Kou, Welding Metallurgy, Second Edition (New York: John Wiley & Sons, Inc., 2002).

[7] Japanese Industrial Standards, "Method for Measurement of Hydrogen Evolved from Deposited Metal," JIS Z 3113-1975.

[8] Japanese Industrial Standards, "Method of Y-Groove Weld Cracking Test," JIS Z 3158-1993.

[9] AWS B 4.0 – 2000 Standard Methods for Mechanical Testing of Welds. Miami, Fla.: American Welding Society, pp.90-93.