The State of the Art of Underwater Wet Welding Practice: Part 2

This paper chronicles advancements in steel wet welding from the past ten years

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ABSTRACT

Developments in underwater wet welding (UWW) over the past four decades are reviewed, with an emphasis on the research that has been conducted in the last ten years. Shielded metal arc welding with rutile-based coated electrodes was established as the most applied process in the practice of wet welding of structural steels in shallow water. The advancements achieved in previous decades had already led to control of the chemical composition and microstructure of weld metals. Research and development in consumables formulation have led to control of the amount of hydrogen content and the level of weld porosity in the weld metal. The main focus of research and development in the last decade was on weldability of naval and offshore structural steels and acceptance of welding procedures for Class A weld classification according to American Welding Society D3.6, *Underwater Welding Code*. Applications of strictly controlled welding techniques, including new postweld heat treatment procedures, allowed for the welding of steels with carbon equivalent values greater than 0.40. Classification societies are meticulously scrutinizing wet welding procedures and wet weld properties in structural steels at depths smaller than 30 m prior to qualifying them as Class A capable. Alternate wet welding processes that have been tested in previous decades — such as friction stir welding, dry local habitat, and gas metal arc welding — have not achieved great success as originally claimed. Almost all of the new UWW process developments in the last decade have focused on the flux cored arc welding (FCAW) process. Part 1 of this paper covered developments in microstructural optimization and weld metal porosity control for UWW. Part 2 discusses the hydrogen pickup mechanism, weld cooling rate control, design, and qualification of consumables. It ends with a description of the advancements in FCAW applications for UWW.

KEYWORDS

- Underwater Wet Welding (UWW) • Welding Metallurgy
- Welding Procedure Development • Porosity Mitigation
- Hydrogen Control • Consumables Development

Introduction

This paper focuses on the advancements in wet welding of steels that were accomplished in the last ten years. This process is performed with no mechanical barrier between the water and the welding arc. The principal advantage of the process is its intrinsic simplicity, which allows it to be applied even in the most geometrically complex structures (Refs. 1–6).

The first comprehensive paper on underwater welding was published in 1976 (Ref. 7), and other important studies were published between 1990 and 2000 (Refs. 1, 2, 8–10). In 2001, Rowe and Liu (Ref. 11) conducted an extensive research containing experimental underwater wet welding (UWW), and they provided the results in detail. In the 2000s, there was some minor research conducted on UWW, but it did not include in depth reporting of experimental work data (Refs. 5, 12, 13). Additionally, UWW was discussed at the 3rd International Workshop on UWW held on November 2010 in Houston, Tex., during which some research was reported and future trends were discussed (Ref. 14). The last important research in this field was performed in 2012 by Liu et al. (Ref. 15) and is included in the American Welding Society (AWS) *Welding Handbook*.

This research highlights current developments in UWW processes. It shows that the progress made in previous decades has allowed researchers in the past ten years to develop state-of-the-art UWW processes. Part 1 of this paper focused on consumable composition optimization. Part 2 discusses weldability, consumables and procedure qualification, and alternate wet welding processes. The authors of this research aim to share this knowledge regarding recent developments in the art of wet welding with practicing welding engineers and researchers.

Hydrogen Pickup Mechanism

In 1977, Ozaki et al. (Ref. 16) studied hydrogen cracking in underwater steel welds and reported diffusible hydrogen (H_{dif}) amounts between 24 to 49 mL/100 g using the glycerin method for different types of electrodes. The authors

Fig. 1 — Weld metal diffusible hydrogen content as a function of the oxygen content of UWW (Ref. 21).

concluded underwater welds in high-strength steels cracked, and 50-ksi (yield strength) class steel was the borderline case as far as hydrogen cracking was concerned.

In 1983, Gooch (Refs. 17, 18) tested several types of shielded metal arc welding (SMAW) electrodes at surface pressure as well as 4-bar absolute pressure. For rutile-based electrodes, he reported diffusible hydrogen levels of approximately 90 mL/100 g of weld metal in UWW conditions. Ferritic steel, austenitic stainless steel, and nickel-based consumables with an oxidizing coating presented low-diffusible hydrogen levels of approximately 20 mL/100 g. Gooch related these results to the high inclusion density observed in the welds deposited with the oxidizing electrodes as well as to the low-hydrogen mobility in the face-centered cubic lattice structure of the austenitic stainless steel and the nickel-based weld metal matrix. He also reported that, in general, the hydrogen levels recorded were considerably greater than those for air welding and appeared to increase with increasing pressure (water depth).

In the same year, Ando and Asahina (Ref. 19) studied the relationship between the hydrostatic pressure and diffusible hydrogen content of welded joints. They measured diffusion hydrogen levels in welds deposited with six different types of SMAW electrodes in surface conditions with water depths of 0.03, 20, 60, and 100 m. They stated that the welds produced in water environments had a significantly higher amount of hydrogen than the welds produced in air. They also reported that the diffusible hydrogen decreased with the increase of hydrostatic pressure. These results demonstrated that Gooch's (Ref. 17) impression or expectation about diffusion hydrogen behavior with water depth was not confirmed for the electrodes tested by Ando and Asahina (Ref. 19). In 1985, Suga (Ref. 20) also confirmed the high amounts of hydrogen in underwater welds and stated that diffusible hydrogen negatively impacted the mechanical properties of weld metal.

In the 1990s, Pope and Liu (Ref. 21) as well as Medeiros and Liu (Ref. 22) conducted studies that revealed the role of fluxes in hydrogen mitigation aside from the weld metal

Fig. 2 — Diffusible hydrogen in the weld metal vs. hematite additions to the covering of steel electrodes (Ref. 22).

composition. Pope and Liu (Ref. 21) tested two flux systems in shallow-water wet welding. As expected, the rutile-based electrodes produced high amounts of hydrogen, and the oxidizing electrodes produced less hydrogen. The two systems showed different hydrogen contents even when the weld metal oxygen contents were similar — Fig. 1. They suggested that slag coverage on the metal droplet further controlled hydrogen pickup, and ionic transport appeared to be intimately related to hydrogen in wet welds.

To observe and understand the influence of the electrochemical nature in the electrical arc, Medeiros and Liu (Ref. 22) studied slags in contact with the weld pool. They reported that, for different flux compositions, the slag hydrogen decreased with increasing Fe₂O₃ contents until 54 wt-% and then increased — Fig. 2. After developing thermodynamic analysis of potential reactions involved in the system and conducting weld and slag characterization using the Mössbauer spectroscopy and x-ray diffraction data, the nature of OH⁻ ionic transport in hydrogen migration across a slag layer was recognized. Welding slag layers, depending on whether they are crystalline or amorphous, offer different resistance to the charged hydroxyl particles moving through them. The authors found that 2FeO·SiO₂ (fayalite) was crystalline and responsible for minimizing hydrogen pickup (via OH⁻ transport) in the weld metal. Their finding demonstrates that particular slag systems can be devised to minimize hydrogen pickup. In the same study, the authors also reported that oxidizing electrodes in the direct current electrode negative (DCEN) polarity produced smaller amounts of diffusible hydrogen than in the direct current electrode positive (DCEP) polarity.

Recent works produced by Fydrych and Rogalski (Ref. 23) on welding in shallow water depths (0.15 m) with different types of covered electrodes showed that the most relevant variables on weld metal diffusible hydrogen are the following: 1) salinity of water, 2) contamination of electrode, 3) electrode polarity, and 4) welding current (in this order). The order of relevance was determined by sta-

Fig. 3 — Low- (A) and high-resolution (B) 3D renderings of cracks. The cracks are mostly orthogonal to the welding direction. (Courtesy of Dr. Valter dos Santos and Prof. Sidnei Paciornik.)

tistical analysis. The amount of hydrogen was determined by the glycerin method and ranged from 45.9 to 87.4 mL/100 g of weld metal. Fydrych et al. (Ref. 24) also measured H_{dif} in welds deposited by rutile electrodes using a mercury-displacement method and found diffusible hydrogen contents ranging from 39 to 62 mL/100 g. They concluded in this work that using a higher welding current, increasing the salinity of the water, and changing the welding polarity from negative to positive would result in an increased diffusible hydrogen content in the deposited wet weld metal.

High-hardness microstructures in the weld metal in the presence of high amounts of hydrogen picked up in the molten state may lead to the formation of microcracks (hydrogen cracks). Paciornik et al. (Ref. 25), Padilla et al. (Ref. 26), and Silva et al. (Ref. 27) used a laboratory-scale x-ray microCT to analyze cracks. These modern techniques of measurement determined crack volumes of 0.35 vol-% in weld samples produced by rutile-based electrodes deposited at a water depth of 0.5 m. These researchers reported that the cracks in the weld metal were mostly transverse to the welding axis (as shown in Fig. 3) because the highest tensile residual stresses were oriented parallel to the welding axis. Due to its platelet shape, elongation reduced significantly in the all-weld metal tensile test.

Using modern measurement methods, such as gas chromatography, UWW research from the last decade has confirmed that rutile-based ferritic electrodes deposit welds with H_{dif} amounts in the range of 80 to 90 mL/100 g, and oxidizing electrodes deposit amounts in the range of 13 and 20 mL/100 g. Dos Santos et al. (Refs. 6, 28) studied the influence of $TiO_2/Fe_2O_3/SiO_2$ in an oxy-rutile flux formulation and confirmed this flux system can minimize diffusible hydrogen in weld metals made with UWW. Bead-on-plate welds deposited on carbon steels with carbon equivalent (CE) values between 0.33 and 0.4, and weld metal diffusible hydrogen contents of approximately 20 mL/100 g presented almost no transverse cold cracks. This is an im-

portant practical conclusion because hydrogen cracking can be controlled by matching the CE of the base metal to the amount of hydrogen deposited by the electrode type in that specific depth.

Quantitative crack evaluation by a manual method also showed the relationship between cracks and water depth. Longitudinal sections of groove butt welds produced at three different water depths showed a reduction in the number of cracks for rutile-based electrodes as the depth increased — Fig. 4. These results are exactly opposed to the porosity behavior with water depth. For the same type of flux in the same condition, dos Santos et al. (Refs. 6, 28) found that the number of cracks decreased with water depth while porosity increased. Because hydrogen is the main gas found in pores made with UWW and is the main cause of cold cracking, they theorized that for a high-hydrogen slag system (like in rutile-based electrodes), the amount of atomic hydrogen that combines and forms porosity increases with water depth and thus reduces the allowable diffusible hydrogen to generate cold cracks.

Silva et al. (Ref. 29) and dos Santos et al. (Ref. 30) studied the influence of water depth on diffusible hydrogen in UWW for rutile-based and oxy-rutile-based coated electrodes. The results obtained are shown in Fig. 5. The results showed the same trend reported by Ando and Asahina (Ref. 19) for rutile electrodes; as the water depth increased, the amount of H_{dif} decreased. Oxy-rutile electrodes presented the opposite trend; H_{dif} increased with the water depth. They related the H_{dif} reduction with the depth presented by rutile electrodes to the increase in weld metal porosity with the increasing water depth.

Using a fully automated UWW system with SMAW electrodes, Hecht-Linowitzki et al. (Ref. 31) reported the weld metal H_{dif} content deposited with rutile electrodes increased with increasing water depth from 80.9 mL/100 g weld material at 0.5 m to 102.6 mL/100 g weld material at 60 m. These results are contrary to those reported by Ando and Asahina (Ref. 19), Silva et al. (Ref. 29), and dos Santos et al.

Fig. 4 — Quantitative weld metal crack evaluation by a manual method in longitudinal sections of groove welds as a function of pressure (Refs. 6, 28).

(Ref. 30). These differences can be attributed to variations in the flux chemical composition of rutile-based electrodes.

Weld Cooling Rate Control — Martensite Avoidance

It is necessary to avoid martensite formation in the heat-affected zone (HAZ) of underwater wet welds because a hard microstructure with greater cracking susceptibility is one of the four necessary factors for hydrogen-induced cracking to occur (Ref. 11). The factors are as follows: 1) diffusible hydrogen content in the material, 2) tensile residual stress distribution in the welded component, 3) temperature of the welded component, and 4) a microstructure that is crack prone.

The smallest amount of diffusible hydrogen deposited for UWW reported in literature is 4 to 9 mL/100 g by nickel-based coated electrodes (Ref. 17). Ferritic steel electrodes with an oxidizing coating produced a minimum of 13 mL/100 g. These values assure that, in UWW, the first factor for cracking will be present. Due to the weld thermal experience, the HAZ of a weld is generally subjected to residual tensile stresses that can be detrimental to weld integrity. Tensile stresses tend to open up cracks or propagate existing cracks. Under proper conditions, cracks may propagate. For example, in weld locations where low temperatures are experienced, factors leading to cracking can be achieved. It is well established that cracking may occur at temperature ranges between approximately +100 and -100°C for ferritic steels. Additionally, temperature control is extremely difficult in UWW.

Of the four factors, susceptible microstructure and diffusible hydrogen content are more controllable, and most of the development work in avoiding UWW hydrogen embrittlement has focused on the control of these two factors. Martensite is the most common susceptible microstructure found in the HAZ and weld metal of carbon steels in UWW.

Fig. 5 — Diffusible hydrogen content in the weld bead depending on the water depth (Refs. 19, 29–31).

The HAZ of carbon steels in UWW conditions is exposed to high-convective heat transfer promoted by arc bubbles that periodically detach from the weld pool and arc region. High cooling rates presented in UWW make the ability of the HAZ or weld metal to form martensite dependent directly on the carbon content, which is interstitially dissolved in austenite and the amount of substitutional alloying elements dissolved in the austenite during austenitization.

In the 1970s, early UWW research determined the maximum CE for carbon steels that could be welded with mild steel electrodes without encountering hydrogen underbead cracking. Most of the works (Refs. 32, 33) suggested that CE values of steels should be limited to 0.4 to avoid hydrogen cracking during welding with common diffusible hydrogen levels found in UWW. However, some research reported extensive hydrogen cracking even when normal carbon steels with 0.3 to 0.42 CE were welded underwater (Ref. 34). A maximum hardness of about 600 HV was reported for the HAZ of underwater welds in mild steel with 0.33 CE due to the martensitic structure. Both hardness measurements and microscopic observation indicated, even in mild steels, hydrogen cracking can occur (Ref. 35).

In subsequent decades, studies confirmed the 0.4 CE traditional limit under which weld hydrogen cracking would not be commonly expected. For steels with CE values greater than 0.4, however, a pre- and/or postweld heat treatment would be recommended (Ref. 36). West et al. (Ref. 37) evaluated UWW electrodes and reported that HAZ cracking occurred in steel plates with a CE of 0.449.

In 2012, dos Santos et al. (Ref. 30) mapped the crack incidence in the HAZ of several studies performed over a period of more than 20 years that applied different SMAW electrodes as well as different base metal carbon and CE values. Crack/no crack region boundaries were plotted as a function of carbon content and CE values as well as diffusible hydrogen levels — Fig. 6. High carbon or CE values and high diffusible hydrogen contents were likely to result in weld HAZ

Fig. 6 — Crack incidence in the HAZ for commercial atmospheric and underwater electrodes: Base metal carbon maximum — 0.28 wt-%; CE maximum — 0.48 (Ref. 30).

cracking. Low carbon or CE values and low diffusible hydrogen contents were conditions for no cracking. The authors found that the safe limits for hydrogen cracking on the HAZ were 0.28 maximum wt-% carbon base metal and 0.28 maximum CE for diffusible hydrogen content around 20 mL/100 g of material (typical amount deposited by oxidizing or oxy-rutile-type electrodes).

AWS D3.6M:2017, *Underwater Welding Code* (Ref. 38), limits the HAZ maximum hardness as a function of steel grades. For example, the maximum hardness accepted in a welded joint is 325 HV for “higher strength ship steel” base metals with yield strengths greater than 350 MPa.

Several solutions to mitigate hydrogen cracking were proposed and tested throughout the years. These include the use of nickel electrodes (Refs. 17, 18) — which were limited to a very small water depth and hot cracking occurrence — or postweld heat treatment (Ref. 39). Several papers on local underwater weld softening heat treatment can be found in the literature (Refs. 39–41). For example, the application of a postheat oxy-hydrogen flame moving along the weld bead has already been successfully tested. Laser processing has also been attempted (Ref. 42). Nevertheless, successful application of industrial or in-situ treatments for UWW are not known.

The most common technique studied and applied to reduce the hardness of the HAZ and improve the weldability of high-strength steels is the temper-bead (TB) technique (Refs. 39, 43, 44). Recent studies (Ref. 44) simulate the TB technique in steel plates with 0.37 CE. The welds were produced at a 0.5-m water depth using rutile-based SMAW electrodes. Hardness measurements showed a reduction in the hardness values from 450 to 300 HV10 with values of the pitch (overlap) between subsequent beads in the range of 55 to 100%. Łabanowski et al. (Ref. 5) stated this method requires proper technique to ensure repeatability of the process, which is particularly difficult in the case of welding in the water environment. Due to the number of factors that need to be controlled to assure the effectiveness of this technique, it is practically unfeasible for UWW despite the successes claimed in other surface-welding applications.

Fig. 7 — Thermal cycles calculation for 1018 steel using the SOAR software by Sandia National Laboratories (Ref. 54).

Fydrzych et al. (Ref. 45) studied the weldability of high-strength steel in wet welding conditions. They used steel plates with CE values of 0.3 and 0.44 wt-%. They found hardness readings of approximately 280 HV10. They also found more than 400 HV10 in the HAZ of the 0.3 CE steel and the 0.44 CE steel, respectively. The authors conducted underwater Tekken tests and observed cracks in both steels.

Rogalski et al. (Ref. 46) studied UWW repair of API 5L X65M pipeline steel with 0.43 CE and welded at a depth of 0.5 m. Pipes were welded in two conditions — insulated and noninsulated from water. Even though hardness measurements were not performed in the critical point of the HAZ (i.e., close to the surface exposed to the water), the results measured ranged from 300 to 318 HV10 in the insulated pipe specimens and reached the values of 386 and 385 HV10 for the noninsulated specimens.

Olsen et al. (Ref. 43) and Pessoa et al. (Ref. 47) found that the TB technique was effective but required precise positioning of the TB pass on the previous edge bead. As a result, accurate placement of the in-situ TB is difficult in underwater conditions. Welders/divers must be exceptionally well trained to execute this technique in real conditions.

Another tested technique for weld-cooling rate control and martensite avoidance is the increase of heat input during welding. The increase in heat input leads to a reduced cooling rate and, consequently, a reduction in martensite formation in the HAZ (Refs. 48, 49).

The cooling rates during steel welding are usually expressed by the cooling time between 800° and 500°C (t_{8-5}). Typical values for t_{8-5} in wet welding vary from 0.8 to 6.0 s, with welding heat inputs varying from 1 to 3.5 kJ/mm (Ref. 50). Stalker (Ref. 51), Nóbrega (Ref. 52), and Pan et al. (Ref. 53) also reported values of t_{8-5} between 2 and 3 s.

Figure 7 (Ref. 54) shows the calculation of thermal cycles using the SOAR software by Sandia National Laboratories (Ref. 55) for AISI 1018 steel. In Fig. 7, the arc power was incrementally increased to determine the various temperature-time profiles of the different welding conditions. By marking the range of 800° and 500°C, the times between 800° and 500°C for each of the welding conditions can be determined.

Fig. 8 — Envelopes of Class A approved results concerning tensile strength and elongation (Ref. 61).

As the arc power increased, the $\Delta t_{8/5}$ (or t_{8-5}) increased. However, a very sizeable increase in arc power was needed (e.g., increasing from 6 to 12 kW) to increase the $\Delta t_{8/5}$ from 2.3 to 4 s. This increase in arc power can be accomplished, in part, by using larger electrodes and a high arc current. These changes will have other consequences in terms of practical welding, which must be carefully evaluated before adoption. A second option for the increasing temperature and $\Delta t_{8/5}$ is the use of supplemental chemical heat. The use of exothermic chemical reactions with commensurate enthalpy change should be considered for control of the weld cooling rate and microstructure (Ref. 54).

Recent work performed by Fydrych et al. (Ref. 56) studied the effect of heat input on the weldability of a high-strength steel with 0.38 CE. They produced controlled thermal severity joints at a 0.2-m water depth using 4.0-mm-diameter rutile electrodes. The heat input varied between 1.3 and 1.9 kJ/mm. All of the welds that exhibited cold cracks had hardness measurements in the range of 370 to 460 HV10. The authors did not find any correlation between the heat input and the maximum hardness in the HAZ.

Li et al. (Ref. 57) explored the effects of heat input on the arc stability and weld quality during underwater flux cored arc welding (FCAW) on steels of 0.41 CE. Weld beads and joints were produced at a water depth of 0.5 m with the heat input varying from 16 to 39 kJ/cm. The authors concluded that heat input had a limited effect on the reduction of hardness of the coarse-grained HAZ (CGHAZ) even though the cooling rate slowed down from 3.2 to 7.9 s from 800° to 500°C. The measured hardness of the CGHAZ was about 400 HV for all conditions tested.

The studies performed at a 0.5-m water depth using S355 steel (0.39 CE) using heat input in the range of 0.8 to 2.5 kJ/mm concluded that increasing the heat input resulted in an increase in $\Delta t_{8/5}$ from 1.5 to 4.9 s (Ref. 58). Increasing the cooling time was observed in the different CGHAZ microstructures. Lower heat inputs produced only lath martensite in the CGHAZ while higher heat inputs produced small amounts of upper bainite aside from the predominant lath martensite. The maximum hardness measured in the CG-

HAZ with 0.8 kJ/mm was 417 HV5, which decreased to 396 and 376 HV5 at 1.5 and 2.5 kJ/mm, respectively. Gao et al. (Ref. 58) concluded the welds in that study did not meet the requirements for Class A and B welds according to AWS D3.6 (Ref. 38), and “the prevention of rapid cooling by increasing welding heat input is not effective.”

Another way to increase the heat input in UWW conditions is by using chemical heat to supplement arc heat, e.g., the use of exothermic electrodes. Oxidation of Al is strongly exothermic, and CaC_2 burning releases heat that can be used to reduce the required current value or increase the $\Delta t_{8/5}$ time. In a study performed with tubular covered electrodes, Pessoa et al. (Ref. 59) found exothermic additions promoted increases in heat input but did not evaluate hardness in the HAZ.

In 2017, Li et al. (Ref. 60) applied the same principle of exothermicity in an underwater wet FCAW study. It was reported that an Al addition of 30 wt-% in the flux increased the average welding current from 205 to 215 A, leading to improvements in arc stability and weld penetration. They did not measure the HAZ hardness to check the effect of higher heat inputs on the microstructure of the HAZ (Ref. 60). Gao et al. (Ref. 58) also suggested that it is almost impossible to perform preheat treatment and postweld heat treatment in an underwater environment.

Underwater induction heating-assisted postweld treatment was successfully developed and tested (Ref. 61). Pessoa et al. (Ref. 62) showed that underwater wet induction heating is suitable and safe to be applied to temper the HAZ of the capping passes in multilayer underwater wet welded joints. A variable-power-type induction source coupled with an oval coil inductor with a field concentrator induced temperatures above the critical temperature (austenitization temperature) in a tempered AISI 1045 steel plate. The underwater procedure reduced the maximum hardness values from 636 to 361 HV, and the depth of the heat-treated layer reached about 10 mm. The procedure was applied in a V-groove butt joint on steel with a 0.32 CE value and welded at a 10-m water depth. The maximum hardness in the cap passes was reduced from 350 to 211 HV10.

In 2015, Zhang et al. (Ref. 63) applied real-time induction to heat underwater wet joints during welding. This extra heat was used to increase the temperature in the weld joint, simulating a preheating process and reducing the cooling rate of the HAZ. It was reported that, with an application of 350-V induction heating, the HAZ hardness values decreased from 425 to 300 HV. However, its in-situ application depended on the development of automated systems, with the geometric shapes of the joints being the major variable of concern.

Between all the techniques and procedures described in this paper, induction-assisted postweld heat treatment appeared to be most promising and reliable for microstructure control, maximum HAZ hardness reduction, and elongation improvement because it allows for fine control and repeatability of the thermal cycle.

Designing UWW-Specific Electrodes

With all the developments in the control of the HAZ, weld metal microstructure, cooling rate, minimization of porosity, and hydrogen level, much progress in UWW has been achieved. The remaining major challenges to accom-

Fig. 9 — Welding torch for underwater wet FCAW: A — With the sealing system that prevents water from entering the contact tip surroundings; B — with no sealing system assembled (Ref. 100).

plish AWS D3.6 (Ref. 38) requirements for Class A classification are adequate elongation in all-weld tensile testing for rutile-based electrodes and bend angle in bend testing for oxidizing coated electrodes.

West et al. (Ref. 37) reported that for rutile-based electrodes, the weld metal tensile and yield strength exceeded the base metal values, but the elongation of 4.8 to 9.3% was substantially lower than that observed in welds produced in air. However, reasonable ductility was obtained because welds consistently passed a 4T radius side bend test.

Using oxy-rutile-based electrodes, dos Santos et al. (Ref. 6) reported all-weld elongation results consistently above 16% for a group of more than 35 all-weld tests. Welds deposited using rutile-based electrodes tested in similar conditions because the welds produced using oxy-rutile-based welds presented a maximum elongation below 12%. These low results were related to a higher incidence of weld defects in the tensile specimens, mostly transverse hydrogen cracks in weld metal. In a recent presentation, dos Santos et al. (Ref. 61) reported 20 and 17.8% of all-weld maximum elongation accomplished in butt welds was produced at a 10-m water depth in laboratory conditions using two different oxy-rutile formulations.

Figure 8 summarizes all the tensile test results obtained by this research group. It shows the results relating the ultimate tensile strength to elongation (Ref. 61). According to AWS D3.6 (Ref. 38), for lower-strength welds, the minimum elongation required is 18%. The red box in Fig. 8 shows that the vast majority of the results (in the range of 18 to 17%) met this requirement. The blue box in Fig. 8 highlights a large number of the results in the 14 to 23% range, which met the minimum requirement (14%) for higher-strength welds. It is important to also point out the range of strengths up to 550 MPa (almost 80 ksi) that, together with the elongation values, strongly indicates that Class A welds are possible.

In comparison, Rowe and Liu (Ref. 11) summarized all UWW mechanical properties reported in literature and reported no single result with more than 14% all-weld elongation. A decade later, dos Santos et al. (Ref. 6) summarized all mechanical properties reported in the UWW literature with elongations as high as 27%.

In recent literature, researchers reported all-weld elongations of 18.6 (Ref. 64), 14 (Ref. 65), and 16.2% (Ref. 66) for SMAW electrodes of their own formulations. The welds were deposited at a 3-m water depth in laboratory conditions. At water depths less than 5 m, it was possible to minimize porosity formation in the weld metal and accomplish higher elongation results. In water depths greater than 10 m,

porosity and other defects became more intense, deteriorating weld mechanical properties (Ref. 67).

Consumables Qualification

It is important to note that most of the reported data on UWW elongation and other mechanical properties were obtained in laboratory conditions (water tanks or hyperbaric chambers) using gravity-feeding systems. Qualification work, however, must be performed for specific conditions and procedures, including testing in pools and on-site welding.

With all the developments of the last five decades, most of the main issues in UWW in shallow waters (up to a 30-m water depth) were solved. To qualify an UWW procedure is more a matter of training the welders/divers than consumables qualification. It was reported that two AWS D3.6 (Ref. 38) code requirements are still difficult to meet (Ref. 47). Specifically, the hardness limit on the HAZ depends greatly on the hardenability of the base metal. The required elongation values for rutile-based electrode welds of 14 to 16% maximum can be difficult to achieve consistently because any discontinuities in the all-weld tensile samples can be the determinant factor for the success or failure in classification.

Most contractors are investing in hard training to perform UWW at optimum consumable conditions. A recent work studied the effects of different techniques that can be executed by trained welders for in-situ conditions. Pessoa et al. (Ref. 68) reported that controlled grinding after each pass reduces the amount of porosity, number of weld metal cracks, size of the columnar region, and maximum and average hardness in the weld metal and HAZ. This procedure also improved the amount of recrystallized regions in the weld metal of multipass underwater welds.

In the last decade, some UWW studies in repair techniques (maintenance) and fracture mechanics were performed (Refs. 69–72). These researchers focused on understanding the effects of specific techniques on mechanical, fatigue, and fracture properties. Techniques such as controlled grinding or ultrasonic impact treatment affect weld metal porosity and joint residual stress. By applying new techniques and developing new procedures, it is possible to expand the application of UWW to the maintenance of offshore structures.

In 1999, a consumables company reported achieving Class A procedure. This was attended and witnessed by six classification societies (Ref. 73). The welding procedure coupons were completed in three positions — 2F horizontal,

3F vertical, and 4F overhead. A 20-mm groove butt joint weld (for the Charpy impact test and all-weld metal tensile test), a longitudinal fillet weld, and shear strength test specimens were produced in accordance with the specification. The company reported a 17% maximum all-weld elongation. No details were provided about water depth or results repeatability. Since that time, another consumables company (Ref. 74) reported reaching elongation values of 16% in welding trials conducted at a 3-m water depth in a freshwater training tank. In general, it can be stated that there has been a lack of qualification procedures published in open welding literature that presents enough data from a statistical analysis point to check for verification and validation. Companies are still holding details of qualification as confidential and proprietary information.

In summary of this section, all developments witnessed in the last 50 years have strengthened UWW as a viable technology, producing welds with higher quality, greater acceptance, and increased application in offshore structural repair at shallow water depths (Refs. 75, 76).

FCAW

As the most promising alternative to SMAW, FCAW led research and development in the last decade. The process presents a higher deposition rate and is less dependent on the welder/diver than SMAW. These advantages increase the possibility of automation, but — on the other hand — they mean a more complex process and parametrization. The various design possibilities of fluxes for self-shielded electrodes allow for controlling the metallurgical aspects of weld metal as is possible with coated electrodes.

In the early 1980s, commercial FCAW consumables were evaluated in underwater welding conditions by van den Brinck and Sipkes (Ref. 77). In 1995, Brydon and Nixon (Ref. 78) performed an underwater wet FCAW investigation using commercially available consumables. In both cases, large numbers of defects and difficulties in producing sound wet welds were reported. In 1996 and 1999, Kononenko (Refs. 79, 80) reported the development of a rutile-type flux-cored wire to repair pipelines that had satisfactory weld quality. Rowe and Liu (Ref. 11) suggested the techniques that had been used to develop wet rutile SMAW electrodes could guide the research and development of wet FCAW consumables. The underwater wet FCAW development strategy should focus on the identification and understanding of the dominant controlling factors through process stability (arc plasma and metal transfer studies) followed by performance optimization in flux formulation. Pessoa et al. (Ref. 59) developed a flux-cored SMAW process with tubular-covered electrodes and studied the effect of flux composition (aluminum and calcium carbide powder) on porosity and microstructure formation of wet welds.

In the last decade, some attempts have been made to acquire quality wet welds by adjusting the chemical composition of the flux core. Calcium fluoride (Ref. 81) and boric acid (Ref. 82) are examples of additions tested. Additionally, some researchers investigated the effects of the water environment, such as flow speed, salinity, and depth (Refs. 83–85), on the underwater wet FCAW process to simulate practical welding conditions. Li et al. (Refs. 86, 87) designed a self-shielded, nickel-based FCAW wire that could be used

for UWW of austenite stainless steel and low-alloy steel.

Jia et al. (Refs. 88, 89) performed a spectroscopic analysis of the arc plasma of underwater wet FCAW and confirmed the expected presence of atomic hydrogen in the underwater arc plasma. They also confirmed what was reported by SMAW researchers in previous decades, that the underwater welding arc is constricted by the water environment like plasma arc welding with mechanical constriction. The metal transfer process of underwater wet FCAW was observed by Guo et al. using an x-ray transmission method (Ref. 90), and the effects of welding parameters on molten droplet transfer mode were analyzed (Ref. 91). Wang et al. (Ref. 92) also studied the dynamic behavior of the bubble evolution in underwater wet FCAW. Additionally, metal transfer, electrode extension, heat input, and other factors have been studied to understand this more complex process in UWW applications (Refs. 57, 90, 93).

Łabanowski et al. (Ref. 5) and Fydrych et al. (Ref. 45) have studied the susceptibility of high-strength low-alloy steels to hydrogen cracking using underwater wet FCAW. The results were similar to those obtained in the SMAW process because the H_{diff} content of the deposited E71T11 tubular electrodes was in the range of 25 to 44 mL/100 g (Ref. 94), and the microstructure of the HAZ depended more on the chemical composition of the base metal.

These same researchers studied the effects of heat input, water depth, and shielded gases on weld metal toughness (Ref. 5). These studies showed that greater complexity of the process implies a need to control a larger number of parameters. Assisting techniques were tested to improve the welding quality of the underwater wet FCAW process. An induction-heating-assisted underwater wet FCAW process was explored by Zhang et al. (Ref. 63) to reduce the hardness of the HAZ and weld metal by controlling the cooling rate. An ultrasonic-assisted underwater wet FCAW process was proposed by Sun et al. (Ref. 95) and Wang et al. (Ref. 96) to improve the arc stability and performance of welded joints. The effects of an external mechanical constraint on the underwater wet FCAW process stability were studied by Wang et al. (Ref. 97). A double-jacket filler wire was developed by Lizunkova et al. (Ref. 98) to protect the metal droplets and wire seam from the surrounding water. Pulsed wire feed technology was adopted by Guo et al. (Ref. 99) to control metal transfer and improve the quality of underwater wet FCAW.

All the tests performed with FCAW in wet conditions were characterized by very low depths (0.2 to 0.4 m) (Ref. 90) due to the difficulty of insulating the contact nozzle against the water flowing back into the conduit. Recent work has studied the effect of contact-tip insulation on FCAW (Ref. 100). Wet welds using self-shielded electrodes were carried out using a special torch that kept the contact tip dry under the water. Welds performed with the insulated contact-tip torch, shown in Fig. 9, have better shaped beads and a more stable arc in comparison to beads deposited with no mechanical barrier between the water and the contact tip. The results highlight the increased stability of the underwater wet FCAW process when the electric sliding contact is kept isolated from the water during welding.

Due to its higher complexity compared to SMAW, FCAW will require much more development for in-situ conditions and higher water depths.

Summary

After organizing all the results obtained from the literature on UWW and reviewing the published developments on UWW from the past four decades, with special emphasis on the advancements achieved in the most recent decade, it is possible to summarize the main conclusions as follows:

1) Discontinuities in underwater wet welds were studied and quantified. Through application of modern measurement and detection techniques, as well as new understandings of the mechanism that controls the formation of diffusible hydrogen, underwater wet welds now present mechanical properties and performance that meet all requirements of AWS D3.6.

2) The hydrogen-cracking mechanism in UWW was found to be controlled by the amount of hydrogen in the weld metal and the type of microstructure present in the weld metal and HAZ. The slag/metal interface was identified as being responsible for controlling the weld metal hydrogen pickup. Oxidizing fluxes proved to be effective in reducing diffusible hydrogen levels in underwater wet weld metal. This type of flux promotes the formation of fayalite ($2\text{FeO} \cdot \text{SiO}_2$) that is associated with lower diffusible hydrogen values. DCEN polarity and austenitic consumables were reported to mitigate cold cracking.

3) In UWW, high-hardness microstructures depend only on the hardenability of the steel present in the HAZ and weld metal. Once wet welding promotes higher cooling rates, tensile stress and relatively low temperatures are present. The established techniques used to soften and avoid martensite formation in dry welds — such as pre- and post-weld heat treatment with flames and electric resistance systems, TB, and heat input control — proved to be not effective in underwater wet in-situ conditions. In the last decades, induction heating proved to be effective as a tempering technique to soften high-hardness regions in underwater wet welded joints and allowed for the use of weld steels with a CE higher than 0.4.

4) The research in the last decade has reported a large amount of consistent all-weld elongation results above 14 and 16% in the tensile specimens produced with a commercial oxy-rutile-developed electrode. This performance was the result of a lower incidence of weld defects, which was achieved by applying all the progress obtained in controlling the HAZ and weld metal microstructure and properties, and in minimization of nonmetallic inclusions, porosity, and hydrogen levels. Nowadays, commercial electrodes specifically designed for UWW applications are available, presenting mechanical properties that meet all specific code requirements.

5) With all the developments from the last five decades, most of the main issues in UWW in shallow water (up to a 30-m water depth) were resolved. Training welders/divers who are able to properly execute a welding procedure that minimizes discontinuities in the weld metal is the determinant factor for success or failure in classification. Consumables/welding companies reported achieving Class A welding procedure classification by developing techniques that can be executed by the welders for in-situ conditions with high repeatability. These are basic techniques applied in dry conditions and include controlled weld travel speed, electrode angle, pass sequence, and grinding, which can be controlled by

a well-trained and skillful welder/diver.

6) Due to the possibility of increasing productivity and automation, FCAW emerged in the last decade as the most promising alternative to SMAW. It presents a higher deposition rate and is less dependent on the welder/diver than SMAW. On the other hand, it presents the disadvantage of a more complex process and difficulties in parametrization. To minimize these disadvantages, researchers are focusing on studying arc physics and metal transfer phenomena, trying to apply the knowledge developed in underwater wet SMAW processes, and developing innovative assisted techniques.

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