Recent Trends And Devolopment Of Underwater Welding

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Abstract- Interest in underwater welding (UW) is increasing day by day with developments in marine transport, oil and natural gas. Today, many oil rigs are used in the sea. These structures are damaged by collision sand storms over time, and various types of underwater welding techniques are used to eliminate these damages. Under water welding presents serious difficulties compared to normal welding techniques. Therefore, researchers are conducting various experiments and applications to overcome these difficulties. The present paper describes the new trends and future welding techniques of underwater welding.

Keywords Underwater welding, Underwater wet welding, Underwater dry welding, Underwater Robot Welding, Recent development.

Özet - Sualtı kaynaklarına (UW) olan ilgi, deniz taşımacılığı, petrol ve doğal gazdaki gelişmelerle gün geçtikçe artmaktadır. Bugün denizde birçok petrol kulesi kullanılıyor. Bu yapılar zamanla çarpışma kum fırtınaları nedeniyle hasar görür ve bu hasarları ortadan kaldırmak için çeşitli sualtı kaynak teknikleri kullanılır. Su altı kaynağı, normal kaynak tekniklerine kıyasla ciddi zorluklar gösterir. Bu nedenle, araştırmacılar bu zorlukların üstesinden gelmek için çeşitli deneyler ve uygulamalar yapmaktadır. Bu makalede, su altı kaynağının yeni eğilimleri ve gelecekteki kaynak teknikleri açıklanmaktadır.

Anahtar Kelimeler Sualtı kaynağı, sualtı ıslak kaynağı, sualtı kuru kaynağı, sualtı robotu kaynağı, sualtı kaynağı alanındaki son teknolojik gelişmeler

1. Introduction

Last developments in UW have increased use of wet and dry hyperbaric welding within the naval construction and building. The American National Standards Institute (ANSI) has established procedures for underwater welding specifications and underwater welding specifications [1]. Nowadays welding process has become significant in all manufacturing application. Although many welding techniques are applied on land, but it is not possible to apply these techniques underwater. Generally underwater welding is made in shallow water, but the difficult part of UW is made in the deep water. With the discovery of oil deposits in the seas in recent years, the importance of UW has increased. because if there is any problem in oil pipelines or drilling vessels, it should be repaired with UW. Many researchers are working on new underwater techniques and development. In this article include development and new trends application of UW techniques.

2. Background of Development Underwater Welding (UW)

The UW was found by several repairers who needed it through testing and error. These test techniques have come from the beginning of 1940 to the today and they are continuing. The development of the Underwater Welding (UW) was realized by the development of electrodes. In 1946 ‘Van der Willingen’ produced special waterproof electrodes. With these developments, several technicians in Russia have done some work on UW. And they are developed shielded metal-arc and gas metal arc welding on underwater. After that this testing and development, Professor K. Masubuchi built the Department of Marine Engineering at the Massachusetts Institute and he is studied " Basic Research of UW ". This study is the first and most significant worked on Underwater Welding [1, 2, 3, 4].

Today, there are several types of welds methods to repair the pipelines of ships. The difference of these applications from other types of welding is that they are made underwater in the deep water.

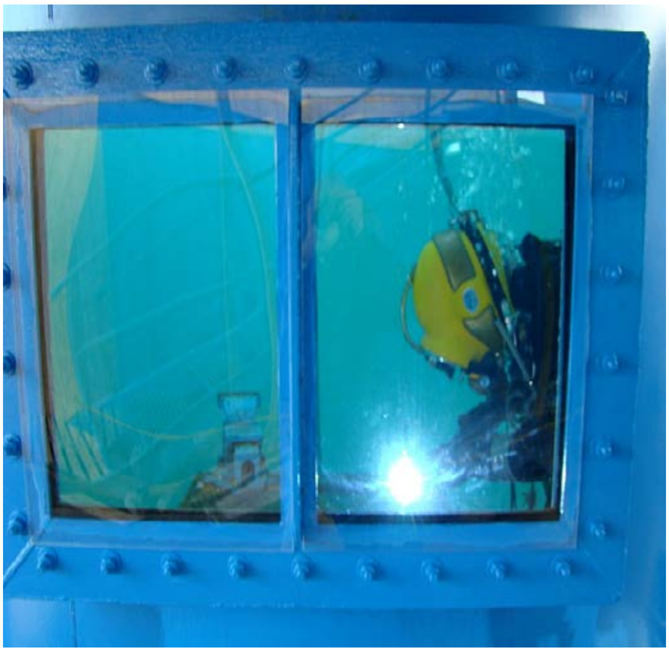

Fig. 1. Student diver practices welding underwater. Adapted from [5].

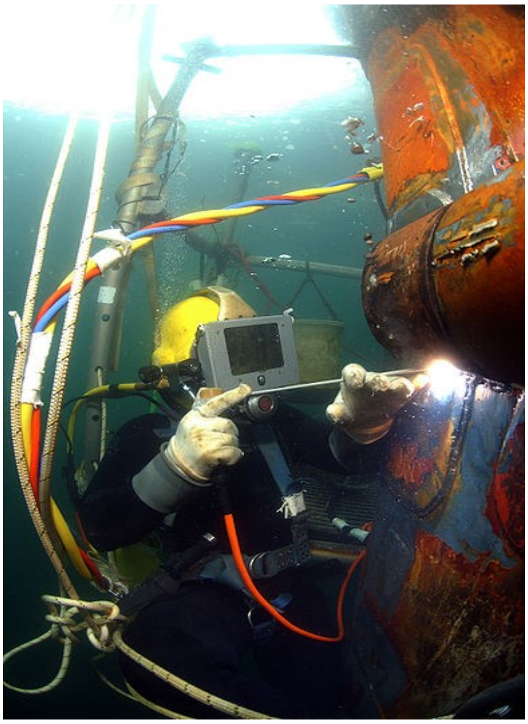

Fig. 2. Navy Diver 1st Class Josh Moore welds a repair patch on the submerged bow of amphibious transport dock USS Ogden (LPD 5) while the ship was in port at Naval Base San Diego (Jan. 4, 2007). Murray is a member of the Southwest Region Maintenance Center (SWRMC) Dive Locker's UW team. U.S. Navy photo by Mass Communication Specialist Senior Chief Andrew McKaskle.

3. Classification of Underwater Welding Techniques

Underwater welding (UW) consists mainly of three forms: dry underwater welding, underwater wet welding and local dry underwater welding.

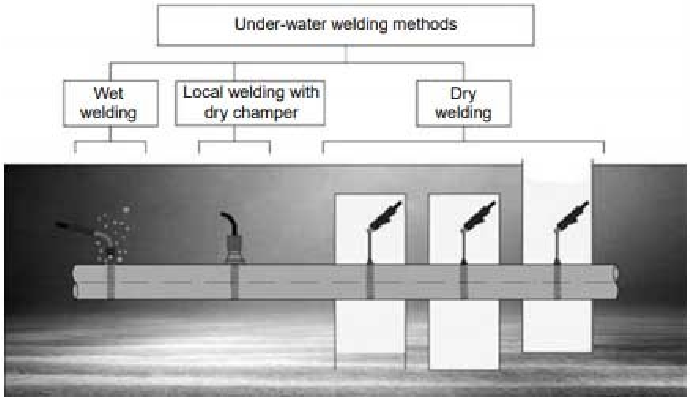

Fig. 3. Classification of (UW) processes [19].

3.1. Underwater Wet Welding(UWW)

In the Wet welding technique, welding area directly interacts with water. Operators are used waterproof electrodes in this technique.

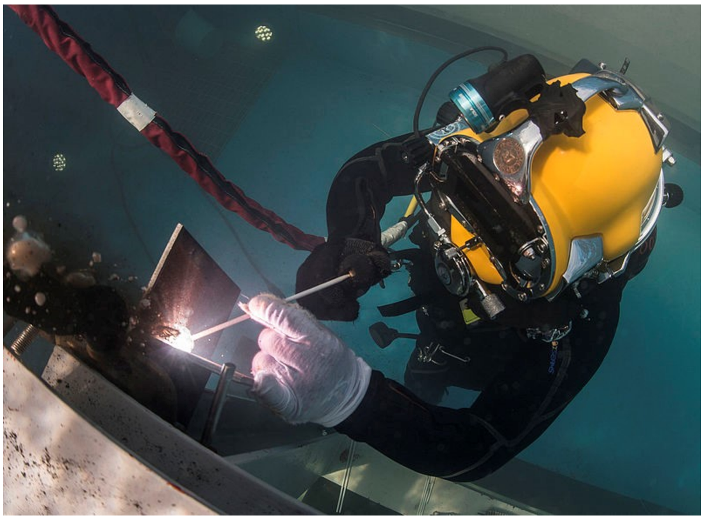

Fig. 4. JINHAE, Republic of Korea (March 15, 2016) U.S. Navy Builder 2nd Class Jesus Saucedo Gomez (right) with Underwater Construction Team (UCT) 2, performs an underwater fillet weld in a training pool at the ROK engineering school at Jinhae, ROK during exercise Foal Eagle 2016. Foal Eagle is an annual, bilateral training exercise designed to enhance the readiness of U.S. and ROK forces, and their ability to work together during a crisis.

(U.S. Navy combat camera photo by Mass Communication Specialist 1st Class Charles E. White/Released)160315-N-GO855-140.

Studies on the influence of Underwater Wet Welding (UWW) factors on the properties of joints made under various conditions are of great significant [6, 7, 8, 9, 10].

The principal significant is ascribed to tests on the welding parameters (linear energy value) on the facility of making joints having demand characteristics and suitable geometry within current research methods purpose attention at welding in dissimilar situations [11, 12].

The unfourable effect of water on joint is ideal visible in Underwater Wet Welding (UWW) [13, 14, 15]. The important developments of covered electrodes for UWW are regarding to the modification of the chemical properties in the electrode coating and core. Advances in coating chemical compositions improve the ionization properties of the coating, reducing the depth influence on the arc stability and decreasing the quantity of spread hydrogen in the joint [16, 17, 18]. The supplement of an suitable amount of alloying ingredient (Ni, Mo) to the electrode core permits restriction of weld solidification cracking and fragile cracking sensitivity.

Reducing joint cooling ratio is tryied by using materials that separate the surface of workpieces from water [19, 20].

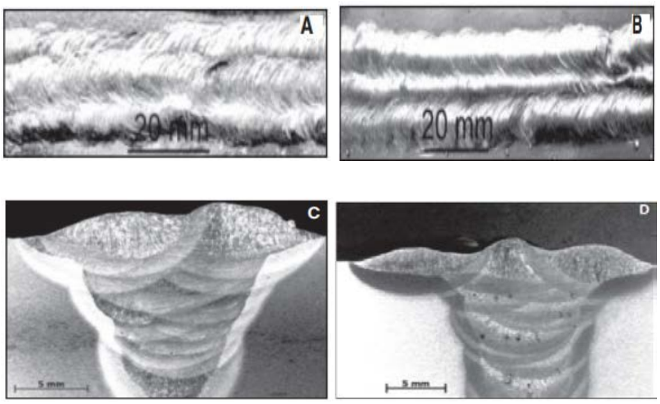

Fig. 5. K. Groove jointswelded at 10 m equivalentdepth. A — Electrode 8A surfaceaspect; B — electrode 2C surfaceaspect; C — electrode 8A transversalsection; D — electrode 2C transversalsection [K] Santos, V. R., et al. "Development of an oxyrutileelectrodeforwetwelding." WeldingJournal 91.12 (2012): 319-328.

The use of multi-welded technologies united with variance of the covering chemical composition render possible it possible to unite unalloyed steel in UWW. The joints met class A requirements according to AWS D3.6M which includes connected to optical testing, radiographic examination and shear strength of a fillet weld, tensile, hardness and toughness needs, i.e. the requirements set for joints made in air [21].

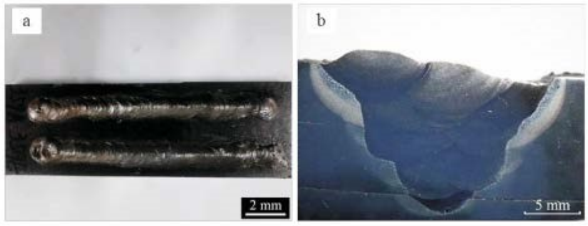

Fig. 6. b. b.Welding of austenitic electrode on the EH40 ship steel plate deposited at 7m immersion depth: (a) weld surface formation; (b) cross section of the multi pass butt-weld joint. [y] Guo, N., et al. " Microstructure and Mechanical Properties of an underwater wet welding dissimilar ferritic/austenitic steel joint." Strength of Materials 47.1 (2015): 12-18.

Wet self-shielding tubular flux cored arc welding; developed with automation and pulsed current in mind for working geometry control [22].

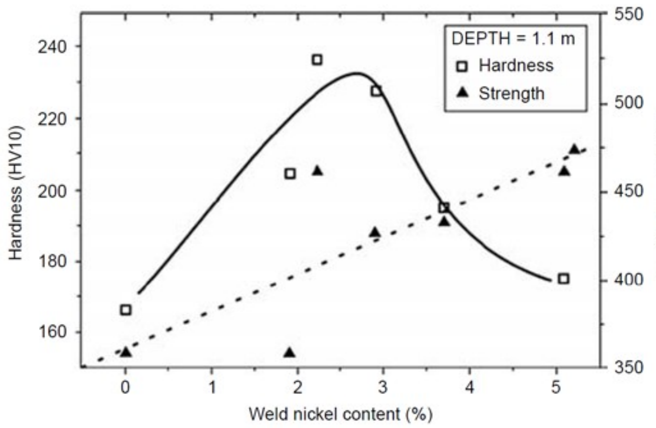

Fig. 7. Influence of nickel content on the properties of wet welding joints [5].

UWW repair work has been tried up to 171 meters. Wavelengths and winds are strong in seas such as the North Sea, so high strength steels are used. Some measures should be taken to prevent cracking caused by hydrogen in high strength steels.

In 1976, Tsai and Masubuchi conducted extensive experiments and studies on UW. The main focus of these experiments and studies was on the development of UWW. This studies focus on; power supply, coating the electrodes, preventing cracking from hydrogen and applying other types of welding in UWW. These studies are still continuing today [3].

3.2. *Underwater Dry Welding(UDW)*

In dry welding, a dry cabin is created near the area to be welded and the welder does the job by staying inside the cabin [23].

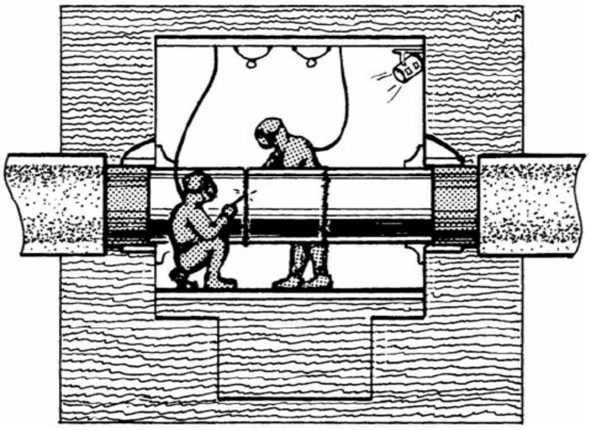

Fig. 8. Schematized UDW [37].

The UDW procedures is first choice when need for larger depths emerge. Using of UDW methods provide completion of full penetration welds with mechanical properties sufficient in normal conditions. Furthermore, Heat treatment is possible after welding for decrease hydrogen content and improve weld properties.

UW in a dry occasion is carried out in cabine sealed around the structure to be welded. The cabin is filled with a gas (helium including 0.5 bar of oxygen) at the prevailing pressure. The gas tungsten arc welding function is used for this process and this method offers high-quality weld that meet X-ray specifications [24, 25].

3.3. *Local Dry Underwater Welding(LDUW)*

LDUW technique is a common combination of the advantages of UDW and UWW techniques. LDUW is ideal for the repair of ships and construction of power plants.

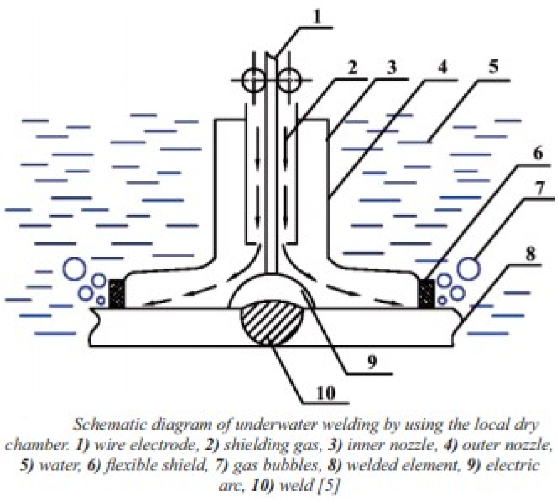

Fig. 9. "Effect of cooling rate on microstructure, inclusions and mechanical properties of weld metal in simulated local dry underwater welding." [30].

4. Literature Review About Underwater Welding

Świerczyńska et al. integrated 4 mm thick S235JR materials with self-shielding cored wire in underwater conditions and measured hydrogen spread into the weld metal. During the studies, they used welding speed as a variable. In their study, they decided the diffusible hydrogen content in the weld metal by using the glycerin process in the Plackett-Burman design, which determines the importance of the effect of free wire length, welding current, arc voltage, welding speed and water salinity. They declared that the outcomes of measurements of diffusible hydrogen content in the weld metal were between 25.85 and 44.12 ml / 100 g [38].

Arias and Bracarense; carried out a study on the spread properties of fatigue cracks in welds produced under conventional conditions (protected welding made in water) and underwater welding conditions (underwater wet welding). In their study, fatigue crack growth rates (d / dN), pore density and distribution, welding process and found to be significantly addicted on variable agents involved to the surroundings. The changes in fatigue crack propagation rate were related to the rate analysis in the stable region of crack propagation. In addition, they found that the UWW procedure produces fatigue-resistant weld metal, which is approriate for use in low-application stresses from those implement outdoors [39].

Shannon et al. ; In order to evaluate the standart of the welds and to grasp the laser / water / material coaction, a research was carried out using 1.2 kW carbon dioxide laser in underwater butt welding of BS 4360 43A and 50D steel. Using a high-speed camera, the temporal action of the melt pool and the "plasma" dynamics surrounded by an aqueous medium were monitored, and experiments were conducted to describe the decaying of the laser beam in water as a function of various focal length optics and water depth. The influence of energy input conditions on weld seam aspect and mechanical properties was also researched [40].

Studies have shown that as a result of the laser beam's interaction with water, the focused beam produces a wave-guiding mechanism that instantly vaporizes the water and directs the beam to the work piece. UW passes show robust microstructures on a number of welding energy inputs due to the formation of a "dry zone sırasında during welding, and when metallurgical analyzes of welds are examined, a slight increase in hardness is reported, although the mechanical properties are similar to atmospheric conditions.

Wang et al.; In their study on characterization of underwater arc welding bubble by visual detection method, they used high speed video camera system to investigate the relationship between arc bubble and process stability under different welding conditions. 8 mm thick medium carbon steel (Q235) materials and 1.2 mm diameter cored wire (AWS A5.36 E81T1ClA4-Ni2) were used for welding. The welding processes were carried out in three different environments: onshore welding, conventional underwater wet welding (UWW) and mechanical constraint assisted wet welding (UWW) [41].

As a result of experimental studies; found that the mechanical restraint applied during welding resists arc bubble separation and holds a larger arc bubble to the weld pool surface for better protection of the weld zone, and that the restraint device plays an important role on arc stability and weld quality. As a result of the microstructure analysis, it was reported that in the joining performed under the same welding parameters, the order of the brittle microstructure in the weld metal was conventional wet welding <UWW with mechanical restraint> coastal welding.

Again Wang et al.; In a study of the effect of ultrasonic vibration on microstructural change and the mechanical properties of the UWW joint, they developed a hybrid method to improve the welding quality using the ultrasonic vibration of the superimposed work piece directly for the purpose of joining underwater. For this purpose, arc welding with cored wire was used. The aim of the study; It is determined that welding microstructure and mechanical properties of welded joints are affected by ultrasonic vibration [42].

As a result of the study, it was concluded that weld metal microstructures consist of preeutectoid ferrite (proeutectoid ferrite), ferrite side plate and acicular ferrite. Another result determined by the study is that ultrasonic vibration affects the size and morphology of the primary austenite grain during the solidification of the weld pool.

It has also been reported that by using ultrasonic vibration, thinner columnar microstructures in the weld metal can be obtained to achieve high tensile strength and excellent stability against impacts, and as a result, the addition of ultrasonic vibration to the method improves the tensile strength and impact resistance of the weld metal during UWW.

In another study, Wang et al.; conducted a numerical study on the temperature range of underwater cored wire arc cutting. In the study, underwater cutting test was performed by using cored wire cutting method and experimental and numerical analyzes were performed to investigate the temperature area during the underwater cutting process [43].

According to the results of the study, it is stated that the thermal cycles calculated during the cutting process with cored wire under water are compatible with the experimental results and the model and boundary conditions in the study are valid for cutting under water. The calculated t8 / 5 value is reported to be less than 0.5 seconds and shorter than open air arc cutting. Furthermore, the importance of optimization of the cutting parameters is emphasized in order to determine the cutting mechanism of the heat affected zone (HAZ) near the cutting gap.

Feng et al.; conducted a study on the dynamic behavior of bubble formation in submerged wet-arc wire arc welding. In this study, bubble exchange behaviors during UWW process were determined by visual perception based on high speed camera method. During the wet welding process, four typical bubble formation modes and corresponding welding electrical information were used to define the bubble behaviour along with arc characteristics [44].

The results showed that the formation of bubbles of the UWW is unstable and complex and requires control by adjusting the welding parameters to achieve a more stable protective effect. They also found an appropriate relationship between the coefficient of variation, weld appearance, and bubble formation mode for some welding parameters. Finally, they report that in wet-cored wire welding, welding parameters need to be well tuned to achieve a more stable welding process, so that the actual bubble growth process can be optimized and controlled.

Shi et al.; duplex stainless steel (S32101) materials UWW cored wire arc welding investigated the formation of pores and microstructures. They used a hyperbaric chamber for this process. The relationship between porosity and microstructure with welding parameters at 20 and 60 m water depths was analyzed comparatively and the relationship between porosity and austenite morphology in microstructures was discussed. As a result of the studies, it was concluded that the cooling speed could be increased by reducing the welding parameters and the resulting microstructures could be corrected. By using a lower welding speed, the molten pool will be held at high temperature for longer so that the porosity of the welds can be reduced by helping the gases leave the weld metal. The low welding stress will make the microstructure thin so that porosity can be avoided [45].

As a result, with a higher welding current at a water depth of 20 m welds have been reported to have lower porosity (at the same weld speed).

Li et al.; They combined high carbon steel (Q460) materials with austenitic additive materials (specially developed Ni-based filler and commercially available ER308) with cored wire arc welding under water and examined the microstructure and mechanical properties of the joints [46].

As a result of the experimental studies, a solid weld was obtained from UW which were combined with Nickel-based additional wire, but solid welds could not be obtained from the commercially available ER308 consumables. Ni-based weld metal has the ability to be diluted with the base metal Q460, while providing excellent mechanical properties compared to austenitic stainless steel weld metal. Austenitic weld metal minimizes ITAB's hydrogen absorption by reducing the tension level between the two parts, thereby reducing the sensitivity to hydrogen-induced cracking. Finally, it has been reported that high tensile strength and excellent ductility joints are obtained by using Ni-based flux cored wires for the UW of Q460 materials.

5. Development of Underwater Welding

5.1. *Development of Underwater Dry Welding*

Although the effect of pressure in UDW conditions is limited, the pressure influence on arc stability is still remarkable. The increase in pressure and arc length is restricted which causes voltage to rise. Even under these difficult conditions, positive welding outcomes were achived at a depth of 550m [26].

Hyperbaric (deep water) welding (UDW) method, the requirment for dry cabinet arranging and special equipment is greater. Therefore, at depths suitable for wet welding, it is much more costly than it [26].

UDW of regular components at higher depths is much more commonplace. Much research has been done on automating the welding process to study on large floating structures that force the improvement of new methots of preparing welding materials for use [26].

These studies are purposed at the improvement of imaging systems capable of examining joint geometry and performing quality control after welding. Dry cabinet design is still an important issue due to the need to weldings of varying shapes and dimension. Coated electrodes and TIG methods are usually used for welding in hyperbaric conditions and intensive testing with MIG and plasma-MIG methods is still ongoing [27, 28].

The current researches about UDW are about corrosion resistant austenitic and duplex type steels, low-carbon martensitic steels, clad steel, titanium alloys and nickel- alloys of weldability.

Other factors that are currently being improvement UDW is welder safety, training of welders, environmental protection, process standardization and joint quality control methods [29].

5.1.1. Development of Local dry underwater welding (LDUW)

In 1976, Hamasaki et al. recommended the use of a LDUW for the repair of a water curtain cover. After that they restored the high-pressure water curtain with slim steel wire to boost the defensive effect [31].

In 1981 Lin et al. advanced a half-automatic CO2 LDUW and decisived that the LDUW quality was upper to the wet weld quality [32].

5.2. Local Cavity Welding(LCW)

Fydrych et al. determined that LCW has superior capacity for underwater use. In this technique, an operator or welder dives under water and performs welding in a chamber used to form a spring in the water-free area [30].

According to Rogalski et al. LCW technique has a lower cooling rate, lower welding porosity, more stable welding process and higher welding quality check against to other welding types. On the other hand the cost of LCW is cheaper than other types of welding [33].

Fydrych, Dariusz, GrzegorzRogalski, and Jerzy Łabanowski. "Problems of underwater welding of higherstrength low alloy steels." Institute of WeldingBulletin 5 (2014).

Gao and Hu (2017) have studied the microstructure, coating and mechanical properties of LCW with the aid of a simulation. Along with this study, they found that alloy metals have a major role on the mechanical strength of the weld [34].

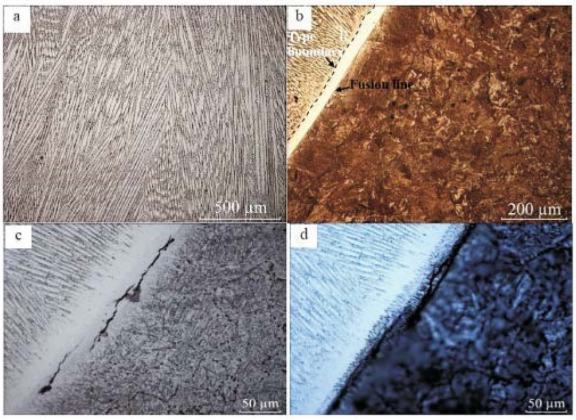

Fig. 10. z. Optical micrographs of joint: (a) weld metal (b) CGHAZ around the fusion line; (c) chromic acid electrolytic/nital etched surface; (d) chromic acid electrolytic/nital/ferric chloride electrolytic etched surface with a martensitic microstructure earthfusion boundary [z]GUO, N., et al. Microstructure And Mechanical Properties of an underwater wet welding dissimilar ferritic/austenitic steel joint. Strength of Materials, 2015, 47.1: 12-18.

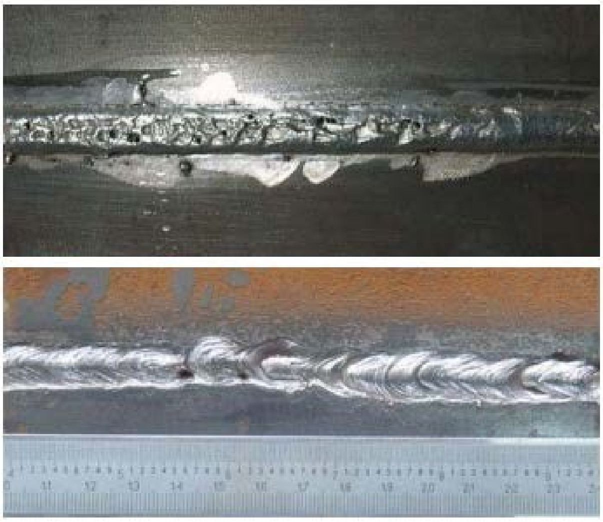

Fig. 11. . Joints welded underwater: a) S355J2G3 steel, flux core darc welding using the local dry chamber method, visible numerous gaspores; b) S420G2+M steel, wet MMA welding, visible undercut sandgaspores[x]

6. Newer Techniques for Underwater Welding

6.1. Laser Beam Welding(LBW)

Laser beam welding (LBW) is a kind of radiant energy welding process in which the material is melted using laser beam. LBW have high electromagnetic energy and are highly consistent. The laser light is focused on a spot and welded by sending high-energy electrons onto the part.

The laser light can melt the workpiece in a very short time and it becomes quicker to switch to other workpieces. Due to its monocromatic and intense structure, the laser light can easily focus on very small spots. The reason for Lazar beam welding being used underwater is that the laser light can melt all metals and is easily automated and has high welding quality. Underwater trials of LBW are underway [23].

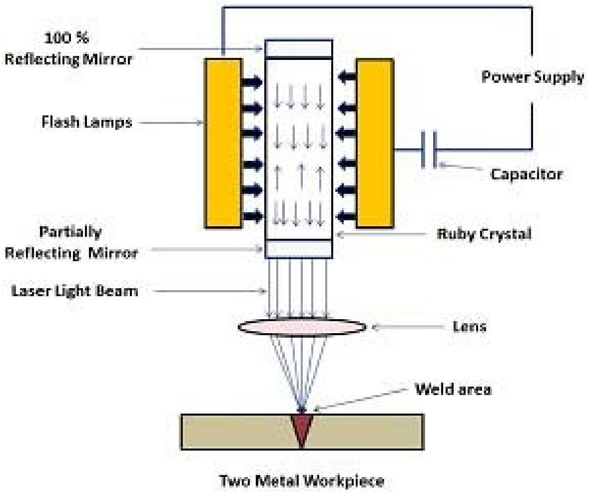

Fig. 12. "Effect of shielding conditions of local dry cavity on weld quality in underwater".

6.2. Robotic Studies and Developments for Underwater Robot Welding(URW)

The most important point in URW is the precise working rates. URW can weld more reliable and higher quality than man-made welding. on the other hand, when the robots are coded correctly, they can easily be used for repeated welding. for these reasons, serious studies are underway for the application of the URW [23].

According to Lintao Xiang et al. with the advancement of technology, robots began to replace people. But more robotic movements need to be better controlled in order to expand their work. In order for the robot to perform UW effectively, it must be placed in a proper trajectory and angle. The URW is created by a mathematical parameter method called D-H. After that, kinematic equations containing the motions of the robot are created. Some coordinate systems and calibrating methods are used to correctly adjust the trajectory. It has been determined that the quality of URW studies [35, 36].

URW systems need to be reconditioned in low-radiation areas at a depth of 30 meters.For the purpose of make these applications, a robotic arm is being studied.The features of this robot; cutting, welding and analysis. This robot arm must be lowered to the area to be welded by using an lift. The robot must be designed to repair and move when it reaches the welding zone and the working depth. Various robotic arms have been improved for such operations. These robotic arms are tested using three-dimensional simulation chambers [23].

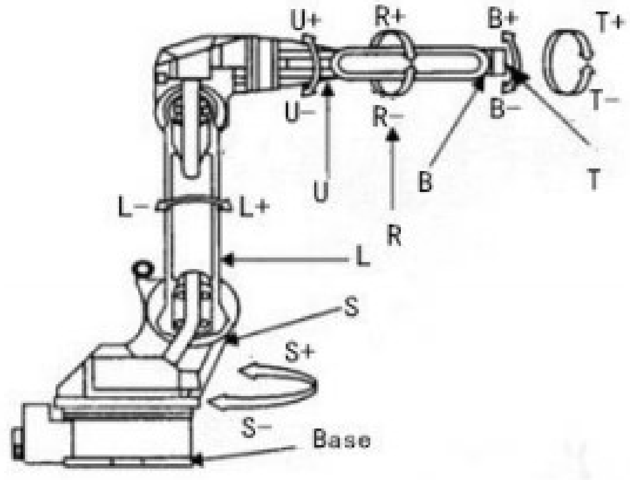

Fig. 13. The UW robot used in this study belongs to the family of six degree-of-freedom joint robots having six axes: S, L, U, R, B and T.

The movement control of URW system will be analogous to the movement control of a standard robot. Operator supersede control permit real-time operation setting. This system will also work in tele-operational mode to perform control and small processing responsibility. UW robots have 6 or more axes of motion & capable of approaching the points in work envelope from any angle [36, 23].

7. Future Underwater Welding

- Researchers should do experiments on automatic pie alignment and automatic welding.
- Inventing different types of welding and applying to underwater welding.
- Ultrasonic testing of welding parts of complex structure and the possibility of using robots.
- Improve the automation of underwater welding.
- Explosive welding should be tested in deep sea
- Facilitation and diversification of inspection procedures.
- Researching of using and examination of advanced techniques such as friction and laser welding.
- Improve the weldability of large floating structures
- Development and applying TIG Hyperbaric Orbital Robot.
- Development of non-submersible Hyperbaric welding process [23].

8. Conclusion

In the last century, there have been serious developments in welding technology. These studies have significantly increased the quality of the underwater welding. The development and investigation of underwater welding technologies has contributed greatly to the reduction of porosity of the weld, adjustment of the hydrogen content, removal of cracks, weldability, weld quality and better understanding of the microstructure. Today, underwater welding is done with the help of robots. The use of robots underwater has made welding easier and higher quality.

References

[1]C, Shawn. Development of a human and organizational factors (HOF) annex for underwater welding. California University Berkeley Dept Of Civil engineering, 1997.

[2]Łabanowski, Jerzy, Dariusz Fydrych, and Grzegorz Rogalski. "Underwater Welding-a review." Advances in Materials Sciences 8.3, 2008, 11-22.

[3]M. Rowe, and S. Liu. "Recentdevelopments in underwater wet welding." Science and Technology of welding and Joining 6.6, 2001, pp.387-396.

[4]H. Ozaki., J. Naiman, and K. Masubuchi. "A study of hydrogencracking in underwatersteelwelds." Welding Journal 8, 1977, p. 231.

[5]A. CHHANIYARA. Underwater Welding. International Journal of, 2014.

[6]H. C. Cotton. Weldingunderwaterand in thesplashzone – a review. Proceedings of the International Conference “Underwater Welding” Trondheim, Norway, 1983.

[7]D. Fydrych., Rogalski G. Badania proceso´w spawania pod woda. Gdansk: Pracanie publikowana, Politechnika Gdansk; 2007.

[8]S. Liu. "Fundamentals of underwaterwelding." Underwaterwetweldingseminar. Ciudad del Carmen, Mexico. 1999.

[9]H. Ozden. "Underwater Weldıng In Hyperbarıc Condıtıons-HuseyinOzden (Ege University) studies the parameters for underwatergas tungsten arc weld edjoints." Sea Technology 49.6, 2008, pp. 52-54.

[10]M. Rowe., S. Liu, and Reynolds TJ. Theeffect of ferro-alloyadditionsanddepth on the quality of underwater wet welds. Weld J. 2002, p. 8.

[11]B. Chen., J.C. Feng. Modeling and analysis of underwater wet weld process based on regression method. Advanced Materials Research. 2013: pp. 690-693.

[12]B. Zhao. "Numeric alanalysis of the weld bead profiles in underwater wet flux-cored arc welding." Acta Metall Sin 49.7, 2013, pp. 797-803.

[13]S. Liu. "Fundamentals of underwater welding." Underwater wet welding seminar. Ciudad del Carmen, Mexico. 1999.

[14]N. Christensen. "Themetallurgy of underwater welding." Pergamon Press, 1983, pp.71-94.

[15]S. Ibarra, and D. L. Olson. "Underwaterwelding of steel." Key Engineering Materials. Vol. 69. Trans Tech Publications, 1992.

[16]V. R. Santos, M. Monteiro, F. Rizzo, A. Q. Bracarense, E. C. P. Pessoa, R.R. Marinho, L. A. Vieira, "Development of an oxyrutile electrode for wet welding." Welding Journal 91.12, 2012, pp. 319-328.

[17]C, W. Jun., C. B. Gui, and J. Sun. "Preparation of water-resistant electrode coating with palmitic acid by micro wave reaction." Advanced Materials Research. Vol. 228. Trans Tech Publications, 2011.

[18]F. Dariusz, and G. Rogalski. "Effect of shielded-electrode wet welding conditions on diffusion hydrogen content in deposited metal." Welding International 25.03 2011, pp.166-171.

[19]D. Fydrych,, G. Rogalski., A. Kunowski., & D. Miś. Zastosowanie izolacji cieplnej przy wykonywaniu złączy w warunkach spawania izobarycznego. Welding Technology Review, 84, 2012.

[20]V. Chigarev., and A. V. Ustinov. "Design-experimental estimation of the possibility of reduction of the HAZ metal cooling rate in wet underwater welding." The Paton Welding Journal (Ukraine) 5, 2000, pp. 25-30.

[21]D. Fydrych., G. Rogalski, and J. Łabanowski. "Problems of underwaterwelding of higher-strength lowalloy steels." Institute of Welding Bulletin 5, 2014.

[22]Zhu, Jie, et al. "Effect of arc current ultrasonic-frequency pulsation on underwater water welding quality" Advanced MaterialsResearch. Vol. 763. Trans Tech Publications, 2013.

[23]V. Ketan, and H. K. Garg. "Underwater Welding-Recent trends and future scope." International Journal on Emerging Technologies 3.2 (2012): pp. 115-120.

[24] A. S. Azar. "Dry Hyperbaric Gas metal arc welding of subsea pipelines: Experiments and Modeling, 2012.

[25]L. F. Silva. " Influence of molybdenum in metal weld properties in welding wet with oxy-rutile electrodes." Soldagem & Inspeção 18.2, 2013, pp. 102-109.

[26]P. Szelagowski, and I. Pachniuk. "State of the art andpractice of underwater hyperbaric dry welding." International workshop on underwater welding of marine structures. New Orleans, USA. 1994.

[27]H. W. Mishler., J. R. Gordon, and Y. Ogawa. "Advanced technology and challenges in underwater welding." International workshop on underwater welding of marine structures. New Orleans, USA. 1994.

[28]X. Zhang. "Effect of shielding conditions of local dry cavity on weldquality in underwater Nd: YAG laser welding." Journal of Materials Processing Technology 174.1-3, 2006, pp. 34-41.

[29]M. R. Johnsen."Keeping Shipshape Through Underwater Welding." Welding journal 80.11, 2001, pp. 54-57.

[30]D. Xinjie. " Effect of cooling rate on microstructure, inclusions and mechanical properties of weld metal in simulatedlocaldry underwater welding." Materials & Design 88, 2015, pp. 505-513.

[31]H. Masanobu., J. Sakakibara, and A. Yoshiaki. "Underwater Mıg Weldıng-ıigh-Pressure Chamber Experıments." Metal Construction 8.3, 1976, pp. 108.

[32]L. Tianhu., S. Shangyang., S. Baotian."A Study and Application Of Local Dry Co_2 Gas Shielded Semi-Automatic Underwater Welding [J]." Transactions of The China Welding Institution 1, 1981.

[33]G. Rogalski. "Bead-on-plate welding on S235JR steel underwater local dry chamber process." Polish Maritime Research 21.2, 2014, pp. 58-64.

[34]H. Gao. "Study on remote control underwater welding technology applied in nuclear power station." Procedia Engineering 15, 2011, 4988-4993.

[35]L. Xiang., X. Xiaopeng, and L. Xiaohui. "An optimal trajectory control strategy for underwater welding robot." Journal of Advanced Mechanical Design, Systems, and Manufacturing 12.1, 2018.

[36]G. Bingtuan, et al. "Developing an efficient calibration system for joint off set of industrial robots." Journal of Applied Mathematics 2014.

[37]Cotton H. C., Welding under water and in the splash zone – a review. Proceedings of the International Conference „Underwater Welding", Trondheim, Norway 1983.

[38]Świerczyńska, Aleksandra, Dariusz Fydrych, and Grzegorz Rogalski. "Diffusible hydrogen management in underwater wet self-shielded flux cored arc welding." International Journal of Hydrogen Energy 42.38, 2017, 24532-24540.

[39]Arias, Ariel Rodríguez, and Alexandre Queiroz Bracarense. ."Fatigue crack growth rate in underwater wet welds: out of water evaluation." Welding international 31.5, 2017, pp. 348-353

[40]Shannon, G. J., J. Watson, and W. F. Deans. "Investigation into the underwater laser welding of steel." Journal of Laser Applications 6.4, 1994, pp. 223-229.

[41]J. Wang, Q. Sun, S. Zhang, C. Wang, L. Wu, J. Feng, "Characterization of the underwater welding arc bubble through a visual sensing method." Journal of Materials Processing Technology 251, 2018, pp. 95-108.

[42] J. Wang, Q. Sun, L. Wu, Y. Liu, J. Teng, J. Feng, "Effect of ultrasonic vibration on microstructural evolution and mechanical properties of underwater wet welding joint." Journal of Materials Processing Technology 246, 2017, pp. 185-197.

[43]J. Wang, J. Shi, J. Wang, W. Li, C. Liu, G. Xu, S. Y. Maksimov, Q. Zhu, "Numerical study on the temperature field of underwater flux-cored wire arc cutting process." The International Journal of Advanced Manufacturing Technology 91.5-8, 2017, pp. 2777-2786.

[44]J. Feng, J. Wang, Q. Sun, H. Zhao, L. Wu, P. Xu, "Investigation on dynamic behaviours of bubble evolution in underwater wet flux-cored arc welding." Journal of Manufacturing Processes 28, 2017, pp. 156- 167.

[45]Y. Shi, Y. Hu, Y. Yi, S. Lin, Z. Li, "Porosity and microstructure of underwater wet FCAW of duplex stainless steel." Metallography, Microstructure, and Analysis 6.5, 2017, pp. 383-389.

[46]H. Li, D. Liu, Y.Yu Song, Y. Yan, N. Guo, J. Feng, "Microstructure and mechanical properties of underwater wet welded high-carbon-equivalent steel Q460 using austenitic consumables." Journal of Materials Processing Technology 249, 2017, pp. 149-157.