UNDERWATER WELDING

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Contents

Summary

Underwater technologies take special role in modern offshore facilities, pipelines, ships and floating objects repair and maintenance. Huge numbers of underwater structures which are used in oil and gas production, as well as increasing intensity of naval transport present the technological cornerstone of the economical development and strategic issues. On the other hand, almost daily we are witnessing various cases of environmental pollution that are caused by means of improper usage of these installations or inadequate maintenance. Maintenance of structures or eventual repairs under the water line demands application of sophisticated technologies such as underwater welding, in wet or dry environment. Underwater welding is unique process which integrates several, on the first sight, contradictory phenomena as water or gas at high hydrostatic pressure, electricity and electric arc as a heat source and metallurgical transformations during solidification of weld metal, everything constricted in a small space and short time. Interactions of mentioned physical phenomena in, what is considered normal conditions, presents not only the huge risk for the weld quality but life threatening safety risk for the welder. So, the question arises, how is it possible to weld underwater and achieve good and solid weld joint, able to perform all the tasks in harsh environment? Due to high safety risks, great importance and responsibility in performing of these activities is on the highly trained and educated human resources, including divers and organization team on the surface. Specially designed equipment is necessary for successful accomplishing of practical tasks. In global aspects

investigations for improvement and application of underwater welding and NDT techniques have been highly intense through recent decade. In this chapter main issues about underwater wet and dry welding are described giving basic knowledge and understanding of these, very often misunderstood, sophisticated technologies. Technological variations, consumables and weldability problems are presented through analysis of basic physical and chemical processes. Besides, brief scope of underwater NDT techniques is given in order to help understand how difficult and important quality evaluation of welds on underwater structures is.

1. Introduction

The concept of conducting underwater welding involves welding performed below the water surface at a certain depth, in a dry or wet environment. Wet underwater welding implies that the welding process is carried out directly in the water without any kind of insulation barrier to prevent the contact of the ambient water with the place of work, the weld pool, the electric arc, the filler material and the welder. It is clear that in such conditions there are a number of parameters that considerably hamper the actual welding process and also affect the quality of welded joints. In case of dry underwater welding there is no direct contact of surrounding water on electric arc and weld pool as it is divided by mechanical barrier which ensure dry environment under atmospheric or hyperbaric pressure, depending on water depth and object shape or type involved. The search for offshore hydrocarbons has taken the oil industry into increasingly deep water. Over the 2000s activities have gone beyond the continental shelf in the Gulf of Mexico, Brazil, West Africa, northwest Europe and the Mediterranean Sea. Oil is now being produced from fields far below 1000 m water depth, with field developments in progress to double these depths. Importance of the underwater welding and inspection technology is well proven in numerous cases of installation, repair and maintenance of naval objects. Moreover, as exploitation of oil and gas seems to move in deep waters, technical level of those techniques demands further investments and development. Although it is clear that automation is unavoidable, conventional diving is irreplaceable in certain activities and following that, great importance is on the field of education and training of human resources. Also, it is obvious that development level reached the point where application of these technologies is possible and applicable in different situations. It is well known that in last 30 years, number of projects was profiled in order to develop underwater technology in “fit-for-service” level. Some of those projects gave good results, but a number of projects collapsed due to large cost and poor flexibility. Underwater wet welding technique was misunderstood for a long time, and it was a synonym for low quality weld full of porosity and cracks with poor mechanical properties like low ductility and due to micro structural issues prone to cracking. This lack of experience and knowledge was present in companies which did not understood all underwater welding issues which caused development of inadequate welding procedures, poor welder technique and inappropriate filler materials. Through time, that status has been changed, and today underwater welding projects, both dry and wet, are used in most complex and difficult objects with a high level of quality assurance.

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2. Classification of Underwater Welding

Underwater welding can be divided in two main types with sub classification as follows:

1. Wet underwater welding is considered as welding at the ambient pressure where there is no mechanical barrier between welder-diver and surrounding water.
2. Dry underwater welding is considered as welding in dry ambient atmosphere under atmospheric or hyperbaric pressure where welder-diver is divided from surrounding water by means of mechanical barrier which could be designed according AWS D3.6 in several alternatives as follows:
    - Dry welding at one atmosphere; welding in a pressure vessel in which the pressure is reduced to one atmosphere independent of water depth.
    - Dry welding in a habitat; welding at ambient pressure in a large chamber from which water was displaced and where such atmosphere is achieved that welder has no need to use diving equipment.
    - Dry chamber welding; welding at ambient pressure in a simple open bottomed dry chamber that at least accommodates the head and shoulders of a diver-welder in full diving equipment.
    - Dry spot welding; welding at ambient pressure in a small, transparent, gas filled enclosure with the diver-welder outside in the water.

While in underwater wet welding MMAW-manual metal arc welding process is common and widely used in dry underwater welding there is greater flexibility over the welding process selection where MMAW, TIG-tungsten inert gas, FCAW- flux cored arc welding and MAG-metal active gas are possible to engage depending on water depth, material type and thickness and other object requirements.

3. Underwater Wet Welding

Underwater wet welding is flexible and applicable on various types and shapes of underwater structures. Diver-welder and electric arc are in direct water environment which causes number of negative impact factors not only for weld quality but also for welder safety. These problems appear proportionally with depth and therefore the depth is a limiting factor when taking in account wet welding procedures operational accessibility. On the other hand, equipment and other technical facilities are far more complex and cheaper compared to underwater dry welding procedures so very often underwater wet welding is proper technology to use for maintenance of underwater structures and repair of ships.

3.1. Physical Fundamentals, Weldability and Metallurgical Issues

Wet underwater shielded electrode manual arc welding is characterized by the following:

- Electric arc instability, which causes irregular geometry in the welded joint, slag inclusions, porosity and insufficient penetration. Ambient pressure has a significant influence on the behavior of a welding arc, the performance of the welding process and the resultant weld properties. Increasing pressure leads to

destabilization of the arc plasma resulting from escalating turbulence in the arc column.
- The rapid cooling leads to great hardness in the heat-affected zone, low toughness in the welded joint and the appearance of porosity due to the capture of gas bubbles.
- The high content of hydrogen in the column of the electric arc, molten metal in the transfer and in weld pool, which results in hydrogen capture in the metal of the weld and in the heat-affected zone. This increases the susceptibility to the appearance of cold cracks, brings about porosity and degrades the mechanical properties of the joint.
- The high oxygen content in the electric arc column, molten metal in the transfer and weld pool, which leads to oxidation, reduction of the proportion of alloy elements and the degradation of mechanical properties.
- The disintegration and dissolving of the coating of the electrodes, which results in electric arc instability and the appearance of porosity.

The inferior mechanical properties of underwater wet welds are a direct consequence of the aquatic ambience. When conditions for the formation of an electric welding circuit and the establishment of an electric arc are met, it is possible to start the welding process. The active parts of the electric arc, the column and the cathode and anode spot are not in direct contact with the fluid. In the case of wet underwater welding with a coated electrode, the energy of the arc is so great that all the water around the electric arc evaporates in an instant, and relatively stable bubble is created around the tip of the electrode. The bubble is retained until the moment the electric arc is interrupted. The dissociation of water in the case of wet underwater welding is carried out according to reaction (1) and the partial pressures of hydrogen and oxygen in the electric arc increase:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{1}$$

In addition, the carbon which partially emerges from the combustion of the electrode coating and oxygen create carbon dioxide, which also dissociates, according to reaction (2):

$$2CO_2 \rightarrow 2CO + O_2 \tag{2}$$

According to these reactions, through the evaporation and dissociation of water and the combustion of the coating, the following gases are created:
- 62-82% H_2 (hydrogen)
- 11-24% CO (carbon monoxide)
- 4-6% CO_2 (carbon dioxide)
- O_2 (oxygen)
- N_2 (nitrogen)

Because of the rapid cooling, locally quenched structures of great hardness are formed in the welded joint. Their hardness reading sometimes exceeds 350 HV10 in the heat affected zone. In addition, the high proportion of diffusible hydrogen, which ranges

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from 30 to 80 ml H_2/100g of the weld metal, makes such a structure susceptible to the appearance of hydrogen brittleness, i.e. it leads to the incidence of cold cracks caused by hydrogen. The number of micro pores that appear because of rapid solidification and the impossibility of degassing the metal of the welded joint also contribute to the occurrence of cold cracks. The hydrogen content in the material also rises because of the employment of cathodic protection (CP), where hydrogen is created on the surface of the metal. The created hydrogen subsequently diffuses rapidly into the lattice of the metal. The increased proportion of hydrogen in the joint is the consequence of the raised partial pressure of hydrogen in the electric arc. The main source of this hydrogen is water vapor, which decomposes at high temperatures into hydrogen and oxygen. Hydrogen can also penetrate into the weld from the coating of the electrode, particularly if the coating is contaminated with moisture during production or handling. Cooling times from 800 to 500°C($t_{8/5}$), depending on the welding conditions and parameters, are between 2 and 4 seconds, as shown on Figure 1. Numerous investigations into how to extend these times have been carried out. Special insulation materials or welding procedures have been used in such approaches which impose increasing demands during the execution in realistic conditions and are not applicable for all forms of construction.

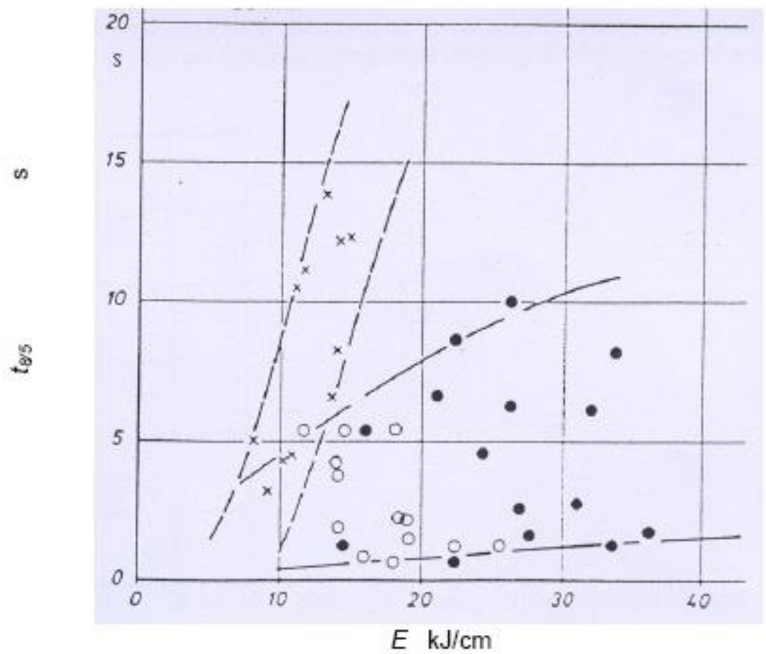

Figure 1. Dependence of cooling time $t_{8/5}$ on the heat input in normal conditions and in wet underwater MMA welding; base material St 37-2, thickness 20mm; underwater wet welding of ○- rutile-celulose coating, ● rutile coating ; *x*-welding in normal conditions, rutile coating [5]

Apart from this, rapid cooling in wet underwater welding increases the deformation of the crystal lattice in the heat-affected zone and causes the appearance of brittleness due to the increased amount of hydrogen coming from the metal of the weld. Rapid cooling is the cause of the creation of brittle, quenched structures that increase the risk of the incidence of cracks. In almost all underwater welds it has been noted that martensite

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structures are locally formed right along the fusion line. The width of this intermediate belt does not usually exceed 0.5 mm. This intermediate layer in the welded joint greatly increases the danger of the incidence of cold cracks due to the structural brittleness of this layer and the maximum hydrogen concentration in this area after welding. Since the diffusion coefficient of hydrogen in martensite is low, the diffusion of hydrogen from the weld metal is considerably higher than the diffusion of hydrogen further into the base material. Martensite thus acts as a barrier preventing the diffusion of hydrogen. Typical underwater wet welding steel microstructure is presented in Figure 2. It presents fusion line with coarse grained high temperature heat affected zone with visible martensite and bainite constituents.

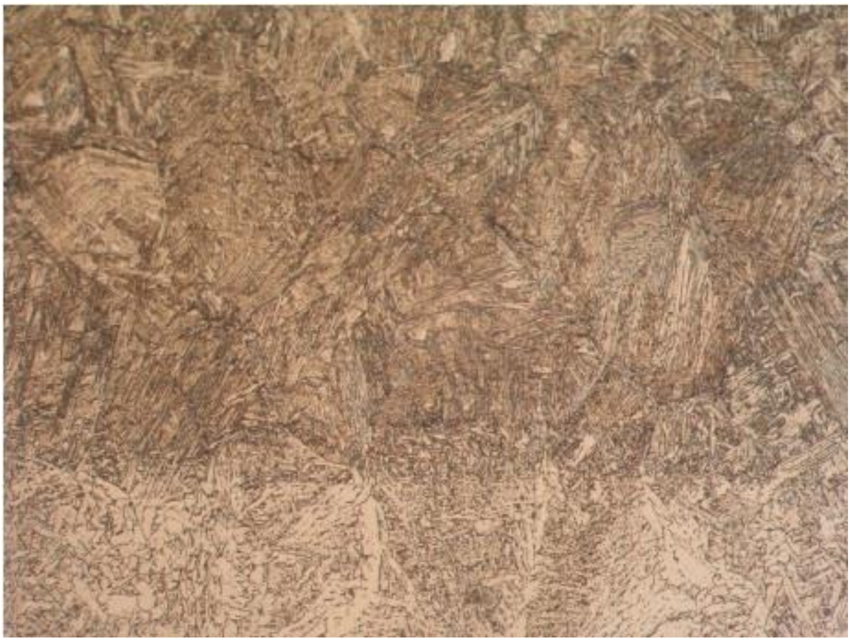

Figure 2. Typical coarse grained martensite and bainite microstructure in MMAW underwater wet weld [18]

The acceptability of the base material for wet underwater welding is defined on the basis of determining the CE- carbon equivalents, according to the standard **AWS D3.6M:1999: Specification for underwater welding** according to the following expression:

$$CE = [\mathrm{C}] + \frac{[\mathrm{Mn}]}{6} + \frac{[\mathrm{Cr}]+[\mathrm{Mo}]+[\mathrm{V}]}{5} + \frac{[\mathrm{Ni}]+[\mathrm{Cu}]}{15} \qquad (3)$$

Engineering steels with less than 0.1% C and steels with carbon equivalent less than 0.4% are suitable for wet underwater welding. Steels with carbon equivalent greater than 0.4% have high sensitivity to hydrogen induced cold cracking (HICC) and can be wet underwater welded only if special welding filler material and welding techniques are used. The sensitivity to the occurrence of hydrogen-induced cracks can be reduced by applying electrode oscillation or by applying runs with heat processing of the metal weld. If heat treatment by means of additional runs is applied, then it is necessary to keep an interval between the applications of two layers shorter than 1 minute. In combination with multi-run welding, this is the most cost-efficient technology which significantly improves the properties of the welded joint.

When welding involves steels with carbon equivalent CE greater than 0.4%, the heat affected zone of the base material is sensitive to hydrogen-induced cold cracking and to undesired high hardness. In underwater dry welding, it is possible to implement pre-heating and maintenance of inter-layer temperature in order to reduce the humidity volume. Sometimes special regimes of heat treatment may be required in order to improve toughness and reduce hardness in the heat affected zone.

In wet underwater welding, it has been proven that electrode oscillation and multi-run welding can substantially improve the mechanical properties by reducing hardness and increasing toughness. The risk of hydrogen-induced cold cracking is also reduced, since every subsequent run treats thermally the previous layer, but this also enables diffusion of the hydrogen in the weld metal. In that case it is better to use smaller diameter electrodes, for better control of weld pool and operative properties. It is possible to implement subsequent heat treatment, but this procedure is expensive and not cost-efficient.

With higher cooling rates, which increases hardness and reduces toughness of the welded joint, the porosity represents also a big problem in wet underwater welding.

Gas absorption of the molten metal depends directly on the ambient pressure and temperature. The higher the pressure and the temperature the more gas absorbed into the weld metal. This is a reversible process. High cooling rates cause capturing of gas in the solidified material since solid metal features lower solubility of certain gases. During solidification, the captured gas from the warmer central part cannot diffuse through the solid metal. This leads to the creation of pores in the weld metal. The greater the depth the higher the probability of pore occurrence. Therefore, the depth in underwater welding has crucial impact on weld metal integrity.

It should be mentioned that the underwater wet welding procedure needs to be checked on a material in which CE and carbon share do not exceed CE and carbon share of the base material to be welded.

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Ivica Garašić was born on 4th of May, 1973 in Zagreb. He finished elementary school in Sveti Martin pod Okićem and completed his secondary education in CUO "Ruđer Bošković" in Zagreb. He graduated at Faculty of Mechanical Engineering on Chair of welded structures 1999. During studies he received Rectors award for student work on area of underwater welding filler materials development. Since year 2000. he is employed as scientific assistant on Chair of welded structures, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. In 2000 he enrolled postgraduate studies at the division of Manufacturing Engineering. In 2004 he received Vera Johanides award form Croatian Academy of Technical Science for his research work. He received his PhD in 2008, when also was appointed as Head of welding laboratory at Faculty of Mechanical Engineering and Naval Architecture. He is active participant in scientific projects and also included in education of students while as member of Croatian Welding Society he is active through organization boards of international conferences and he also participate in IIW education courses for welding personnel. In 2007 he finished specialization according IIW/EWF programs and received IWE/EWE degree. In IIW he is included in work of two commissions Com II-arc welding and filler materials and Com XI-pressure vessels and pipelines.
Through participation in research project 0120018 Development of underwater welding and inspection he published more than 40 papers in conferences and journals. Beside that, he is involved in Euraka projects-Welders Passport, European Welder and European Welding Consultant. In Leonardo program he is included in Hamster project. He is coauthor of several projects and expertise which deal with issues of spherical tanks welding, weldability testing for pipeline steels, underwater welding repair of off-shore platforms, assessment of gaslines in exploitation, underwater inspection of off-shore platforms and design of synergic curves for welding power sources and introduction of robotic welding.