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Underwater Welding : A Review Paper

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Abstract

This paper sheds lights on the development of underwater welding. A brief history of underwater welding is touched upon, followed by the different types of underwater welding and the various welding processes used. The various challenges associated with underwater welding, emphasizing on the influence of cooling rate, depth of water on the mechanical properties, microstructure and corrosion properties, is discussed. The characteristics of electrodes used for underwater welding and the metal transfer technique associated with underwater welding are also investigated. The specification for underwater welding AWS D3.6 is also introduced. Finally, the paper explains some of the extremely important safety issues associated with underwater welding.

Keywords: Underwater welding; dry welding; wet welding; metal transfer; safety in underwater welding; challenges of underwater welding.

1.0 Introduction

A Russian welding engineer named Konstantin Konstantinovich Khrenov, in 1932, invented underwater welding and cutting techniques. For this invention, Konstantin Konstantinovich Khrenov (**Fig. 1**) was awarded the prestigious State Stalin Prize in 1946. Underwater welding, long considered impossible due to welding in water, attracted attention of all countries due to its wide application in repairing underwater pipelines, ships and submarines, installation of underwater pipes and structures, etc. It is also widely used to lift sunken ships from the bottom of the ocean. In 1936, Russians used underwater welding to lift ship Boris from the bottom of Black Sea. The main contribution of Konstantin Konstantinovich Khrenov was the invention of waterproof electrodes and a stable power source for underwater welding [1-2].

Fig.1 : Konstantin Konstantinovich Khrenov [3]

2.0 Types of Underwater Welding

There are basically two types of underwater welding, namely, wet welding and dry welding. When welding is performed in atmospheric pressure inside a chamber from which water is displaced, it is known as dry welding. The welder can either be completely or partially in the chamber, depending on the chamber size and configuration. During welding, the welder wears all necessary welding gears and diving gears. The chamber of dry welding is also known as hyperbaric chamber. It not only provides a dry environment suitable for welding, but also maintains the chamber temperature between 25–35 °C. The pressure inside the chamber depends on the depth at which the welding is carried out. Pressure inside the chamber can vary between 0 to 25 bar. All necessary safety precautions shall be taken prior welding to prevent electrocution hazards. Both alternating and direct current can be used for dry welding [3-7]. The type of current, installation ripple factors (if direct current is used), electrical power supply and its control devices, responsiveness of the trip devices, maximum voltage etc. should be considered prior to the commencement of the welding process. Air is normally used as the breathing gas for splash zone operations, but it should not be used at greater depths. Argon gas being a breathable gas, is also used in chambers for underwater welding operations. At larger depths, where the pressure is higher, argon gas can have a narcotic effect on divers and hence, it is hazardous. When argon is used as a shielding gas in welding processes like TIG welding, its concentration in the chamber needs to be constantly monitored. If the concentration is more, it has to be flushed out. Helium is also used as a breathable gas but it is more expensive than argon and its density is one-tenth as that of argon. The major benefit of using helium chamber gas is that it is similar to the gas mixtures breathed by divers, when in saturation, at depths greater than 50 meters. Breathable diving gas consists of helium, mixed with oxygen at a partial pressure of 0.5 bar irrespective of depth. The mixture is not hazardous to the diver and also less flammable due to low concentration of oxygen. However, due to the high thermal conductivity of helium, weld pool cooling rate is increased [6].

In wet welding, the welder establishes physical contact with the surrounding water. Hazards associated with wet welding are very high. All necessary precautions shall be taken prior to welding to ensure safety of the welder. Severe electrocution injuries to welder can occur if lethal electric current is engaged at very close distances, which may result in cardiac arrest or even death. Care shall also be taken to ensure that temperature in excess of 10,000°F is not produced, either due to spark or from the electrode tip. Temperature greater than 10,000°F can trigger catastrophic explosion, as it provides an ideal condition for combination of oxygen and hydrogen rich gases [6].

2.1 Common Welding Process for Underwater Welding

Almost all common welding processes used in normal conditions are also used in underwater welding. Most

Fig.2 : Hyperbaric Welding Chamber [9]

commonly used welding processes are shielded metal arc welding (SMAW), Gas Metal Arc Welding (GMAW), Flux Cores Arc Welding (FCAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), Friction Welding and Stud Welding. AWS D3.6 specifies SMAW, GTAW, FCAW, GMAW and PAW. Friction Welding and Stud Welding are employed at depths where fusion welds are not possible. SMAW is the most commonly used welding. For FCAW, GMWA and other processes, external shielding gases are supplied, which also reduces the partial pressure of unwanted gases [4-9, 11].

2.2 Electrodes in Underwater Welding

SMAW is the most commonly used welding process. The electrodes E6013 and E7014 are provided with a waterproof coating to protect the electrodes when used for underwater applications. Rapid quenching and the abundance of hydrogen and oxygen in underwater causes embrittlement and inferior weld properties. This results in welds with porosity, poor impact and inferior fatigue properties. The main shortcomings of using normal electrodes in underwater welding are porosity, hard microstructure and low toughness of the welds produced. In order to increase the impact toughness property and other technical properties, the presence of acicular ferrite in the microstructure shall be increased. Acicular ferrite, due to its interwoven shape of fine ferrite will have superior mechanical properties than ferrite [11-15].

Addition of Boron and Titanium, will suppress the formation of primary ferrite and enhance the formation of acicular ferrite. But this addition will not yield the expected increase in hardness values [11].

The addition of Nickel, also increases the acicular ferrite and grain boundary bainite content in the weld, and thereby improves the impact toughness. Nickel also prevents hydrogen cracking in the welds as it reduces the lattice diffusion of hydrogen. Thus, the hydrogen absorption and the Ac1 temperature are lowered. However, it is reported that addition of more than 1% Nickel will reduce the environment assisted cracking (EAC) resistance of the steel and improves the pitting resistance. Nickel is a well-known austenite stabilizer and thus increases the austenite content [14].

During the selection of elements for electrodes, slag forming constituents are selected because slag formed will have higher surface tension and are easily detachable. The weld profiles are thus made smooth, which improves the fatigue life of the weld. Fluxes selected shall also be such that the microstructure formed will have more acicular ferrite. The waterproofing material shall not degrade the characteristics of electrode [11-15].

In some cases, general purpose electrodes like E6013 were covered with insulation tapes and then used to weld in underwater. Though it produced results better than uncoated or unprotected E6013, the welds lacked acceptable features. Thermoplastic coatings and polyethylene coatings provided better waterproofing and reduced water absorption, with no noticeable performance deterioration [11,16].

For underwater repair welding, identification of steel may not be always possible for instances where the engineering drawings of the structure are not available. In such cases, an in-situ experiment of tee welding and hammering the weld, may help to identify the material. If the tee weld breaks easily, it means that the base metal is a high strength steel with high carbon content. If it bends a great deal before it breaks, it means that the base metal is most probably a low carbon steel. For repair welding of high carbon steels, austenitic stainless-steel electrodes can be used safely. However, it is not advised to repair welds of very high strength steels like HY-80 since it is more prone to cracking, when cooled suddenly [6].

3.0 Challenges Associated with Under-water Welding

The most common problems associated with underwater welding are porosity, rapid cooling, effect of pressure, effects of gases, hydrogen cracking, etc.

Porosity in welds is mainly due to the gas content in the weld pool. As depth of underwater welding increases, the effect of gases increases as more gases get dissolved in water. When arc is initiated, it vaporizes water and forms bubbles which contain dissolved gases, namely hydrogen, carbon monoxide, carbon dioxide, nitrogen, oxygen and other gases. As depth increases, the amount of gases increases due to increase in partial pressure of gases. Absorption of oxygen and other gases also reduces the impact properties and makes the microstructure brittle.

Rapid cooling of the weldment is caused due to heat loss by convection of the water around the weld pool. Rapid cooling results in brittleness because of transformation of austenite to some undesirable microstructures. It results in diffusionless shear transformation of austenite to martensite. Other phases formed due to fast cooling are bainite and grain boundary ferrite with side plates. Typically in underwater welding, the HAZ will have martensitic phase having increased hardness and reduced notch toughness. The martensitic phase is also prone to hydrogen cracking. The effect of cooling rate especially from 800°C to 500°C can be slowed down either by increasing the arc power or reducing the speed of the welding, so that detrimental phases are not formed due to rapid cooling [17-28].

Hydrogen cracking is formed due to the combination of several factors namely, a susceptible microstructure, presence of hydrogen, tensile stress, time and temperature. Temperature range for HIC (Hydrogen Induced Cracking) is normally in the range of -50°C to 150°C. Below temperatures of -50°C, the diffusion of hydrogen is less and above temperatures of 150°C, the diffusion is high. Thus, the hydrogen escapes easily from the metal and without initiating a crack. The formation of a crack usually occurs within 48 hours [17-28].

Poor fatigue property of underwater welds is mainly due to inferior weld profiles. The toe and the convex welds produced underwater, are areas of stress concentrations which are detrimental to the fatigue life. Weld defects like inclusions, porosity and incomplete penetration also reduces fatigue strength. However, rarely it is found that the porosities can sometimes arrest the crack propagation and thereby increase fatigue life. Underwater welds also show lower ductile properties. Temper beading technique can also be used to improve the weld metal and HAZ properties [17-28].

4.0 Metal Transfer in Underwater Welding

The most challenging part of underwater welding is maintaining the arc in water. For enabling steady and continuous arc, it is normally found that the welding is performed with short arc length. So, naturally, the most preferred modes of metal transfer are short circuit transfer and globular metal transfer, mostly a combination of the two modes. The metal droplet in underwater welding experiences forces such as, electromagnetic force, drag force of the shielding gas, arc pressure, surface tension force of the molten

Fig. 3 : Wet Underwater Welding [10]

metal, vaporization pressure of the water molecules and the drag of the water around. The metal transfer in welding will depend on the arc stability. It also influences the weld properties, weld pool shape and also weld defects [29-35].

In underwater welding, the electric arc is formed inside a bubble, generated by vaporization of water and the gas formed from the electrode. The gas bubbles formed rises up and move in the direction opposite to the arc motion. This causes a gas drag force on the molten droplet formed from the electrode, which is unique in underwater welding. Along with the gas drag force, other six forces which act on the droplet are plasma force, gravitational force, buoyant force, surface tension, vaporization force and electromagnetic force. The forces such as gas drag, electromagnetic force, buoyant force, vaporization force and surface tension forces act as repelling forces and prevent the droplet from detaching. This causes the droplet to increase in size as the detaching force exceeds the repelling force. The repelling forces shift the droplet away from the axis of the wire and thereby induce a rotation. In underwater welding, it is observed that, the droplet rotates around the electrode every-time before it detaches from it. The metal transfer mode is usually a combination of globular repelled mode and short circuit mode. The droplet attains a large size but the frequency of its formation is low. This is followed by formation of small droplets at a slightly higher frequency [29-35].

It is observed that, as the welding speed increases the combination metal transfer becomes less of a short circuit mode and more of a repelled globular transfer. The effect of welding speed will influence more on metal transfer for an increased arc length. It is observed that as welding speed increases the arc constricts and thereby increasing the arc energy density, which eventually increases the weld depth and also decreased the weld width [29-35].

5.0 Introduction of AWS D3.6

AWS D3.6, Specification for Underwater Welding is the most commonly used specification for underwater welding. The specification classifies weld based on their serviceability and properties. Accordingly, there are four classes of weld namely

a) **Class A -** Welds capable of meeting design stress and comparable to air quality welds. Section 7 of Code D3.6 mentions about the requirements

b) **Class B -** Welds capable of meeting less critical applications where porosity, discontinuity etc can be tolerated. Section 8 of Code D3.6 mentions about the requirements

c) **Class C -** Welds where load bearing is not the primary requirement. Section 7 of Code D3.6 mentions about the requirements

d) **Class D -** Welds intended to meet requirements of some other codes like ASME Section IX etc. Section 10 of Code D3.6 mentions about the requirements [36].

6.0 Safety Aspects of Underwater Welding

Underwater welding was long considered impossible due to difficulty of producing a stable arc in water. The main hazards associated with underwater welding are drowning, electric shocks, gas explosions due to oxygen and hydrogen gas bubbles formed which can explode in a spark or in contact with electrode tip which is at very high temperatures, water currents, low visibility, unstable footing, low temperatures, fall of objects, other work specific hazards and even attacks of marine life [37].

Most of the accidents are formed when the underwater works are hurried. It is recommended not to hurry the underwater cutting or welding. When cutting is speed up by firing deep into the metal there is a high possibility for explosion to happen.

The possibility of electric shocks is more when the underwater cutting/welding is done in the splash zone, or at a location partially immersed in water. However, splash zones are the locations which are more prone to damages due to corrosion because of exposure to two mediums namely water (saline) and air, supply of oxygen, salt spray, temperature changes, exposure to ultraviolet radiations and also due to loads of the splash or waves. It is known that the sacrificial anodes cannot work effectively in splash zone because there is no stable electrolyte around the metal in the splash zone to enable the anode to function. The most important factor is the dry-wet alteration. The splash zones are also prone to microbiologically induced corrosion as well [39].

The possibility of drowning is the most dangerous hazard associated with underwater cutting/welding. The personal

Fig. 4 : Splash Zone Corrosion [38]

involved with the underwater cutting/ welding activities shall qualify as a commercial diver and have a valid certificate for the same [37].

One of the most dangerous hazards associated with underwater cutting and welding are the explosions caused due to gas entrapments. During underwater cutting/welding, the water molecules dissociate to oxygen bubbles and hydrogen bubbles. When these gases combine or when comes in contact with a high temperature or electrode tip at high temperature, it can cause explosion. Explosive gases can also entrap at cavities like sea chest, pipelines, shaped structures or tubular structures etc from other means also. For examples petroleum products can release explosive gases, decaying marine or biological materials can cause methane and other explosive gases, discharges from paints and adhesives, from bulk explosives or ammunitions, or unburned gas of underwater cutting [37].

Prior to commencing any underwater cutting/welding activities, the structural drawing shall be fully understood to identify pockets of gas entrapments. Also, it is advised to open the valves located near the cavities like sea chest or any pipelines where the underwater cutting/welding is to be done so that the gas can escape out. It has to be ensured that the gas entrapped are ventilated prior any cutting/welding operation. The start of the work shall be preferably from the top and then proceed down so that even if some unburned gas is released, it will not accumulate at the top, instead, it can vent out from the top. A tube can also be used to directly vent the gas to outside. Similarly, when cutting a thick section, like propeller shaft, the cutting/ welding shall be performed from outside through circumference to inside to avoid gas entrapment inside the holes. Also, it has to be ensured that the electrode/torch shall be withdrawn after some seconds to avoid gas bubble accumulation [37].

Another major hazard associated with underwater cutting/ welding is electric shock. It is advised strictly not to depute AC current for underwater cutting/ welding applications. AC current can cause severe electric shocks causing burns, cardiac arrest, muscle contractions, etc. which can be fatal. Every diver shall be trained in first aid safety and also CPR to render prompt assistance in case of any accident. It is reported that the welder experiences a tingling sensation when the welding arc is

Fig. 5 : Gas formations and bubbles in Underwater welding [40]

It shall be ensured that only an approved manufacturer's equipment is used and the equipment shall also be tested for safe performance prior using for underwater welding/cutting. The installation and operation of the equipment shall be done by a competent and an experienced personal in accordance with an approved plan. The operation of the equipment shall be as per the manufacturer's recommendation. Prior underwater welding, the welding machine and its supporting structure shall be grounded. Grounding is very important for the enclosure of the welding equipment so that any leakage current will be dissipated to the earth through a cable which is capable to pass maximum current and also ensures that the enclosure and the ground are at the same potential. It also ensures that the terminals of the welding machine are not short circuited with the enclosure at any moment of time [37, 40-41].

A knife switch arrangement is always used to ensure that current is switched ON only when the diver is ready to weld. It is imperative that electric current shall not flow when underwater welding is not in progress. The amperage of current in underwater welding is very high compared to welding in open atmosphere. The knife switch shall be mounted on a non-conducting base preferably a wooden base. The switch shall be rated to conduct maximum welding current. The switch shall have an open circuit voltage of 80 volts between the poles. The switch shall be vertically mounted and also be positioned in the welding lead side of the circuit. It shall be strictly positive-acting switch for opening and closing the switch. Care shall be taken to ensure that the switch is not bypassed due to failure of insulation in any part of the circuit. A proper communication shall be established such that the knife switch is ON only when the electrode is positioned and ready

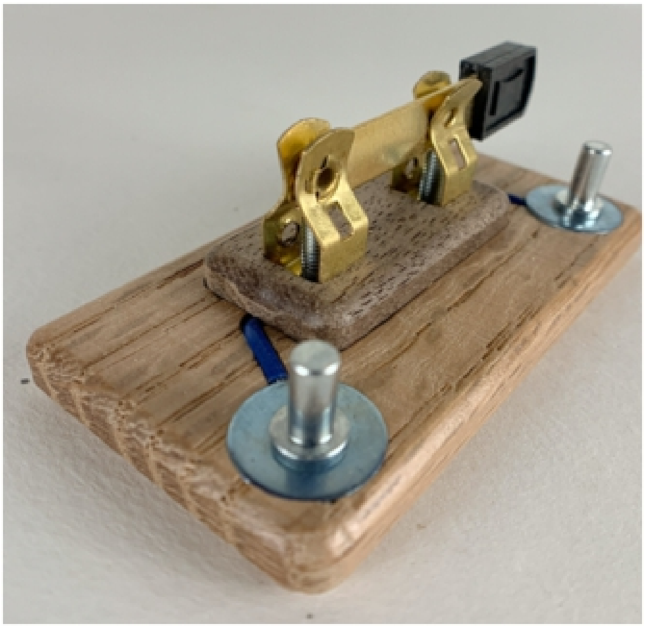

Fig. 6 : Knife switch [42]

Fig 7 : Risk of attack of marine predators [40]

and OFF in all other cases. Diver shall ensure that the circuit is OFF when he changes the electrode. It is common that the diver carries with him metallic tools like chipping hammer, wire brush etc. The diver shall be careful that neither any part of his body nor the metallic tools are not in contact with the live electrode or workpiece. The diver shall also not point the electrode towards his body while welding as any explosive gas formed will directly impact on his body [37].

In underwater welding, normally the polarity used is DCEN, or Straight Polarity. The easiest way to identify the negative pole is that bubble start coming from the negative terminal. If DCEP was used, the bubbles will come from the work piece plate [37].

Several other precautions regarding electrical hygiene shall be ensured for a safe underwater cutting/ welding operation. Only torches and holders specifically designed for underwater use shall be deputed for underwater cutting/welding operation. Ensure that all the current carrying components are fully insulated and all connections are tightened properly. When length of the cables is to be increased by connectors, the connectors shall be selected such that the current carrying capacity of the connectors is same as that of the cable. The diver at no point of time shall come in between the ground point and the electrode and shall not become part of the circuit. Any additional lights carried underwater for better vision shall have proper grounding and also not be part of the welding circuit. It is advised not to carry lengthy cables inside water as it can be entangled and even entangle the diver due to water currents. Care shall also be taken by the welder so that the diving umbilical cables are not damaged or entangled while welding/cutting [37].

In addition to these operational hazards, other hazards like fall of objects on the diver while performing overhead underwater cutting/ welding poses a risk. The bubbles produced during the welding/cutting operation reduce the visibility and thereby also delays the movement of the diver from a falling object. At the same time the diver is prone to decompression sickness. The high intensity radiations produced by the welding/cutting operation can attract marine life towards the welder and are also at the risk of attacks of marine predators [40].

Prior commencing of any welding, the surface has to be cleaned of rust, marine growth, paint, grease and other foreign materials by chipping, grinding or any other means. Also, for multiple pass welds, each pass shall be cleaned and inspected before depositing other welds. As it is known that underwater welding is difficult and risky and also definitely inferior to normal welding in open atmosphere, it is always better to do minimum welding in underwater, that is, do maximum welding of a prefabricated structure outside rather than doing welding inside the weld. Also avoid as much overhead welding as possible as it can also cause fall of molten metal on the diver-welder. It's always preferable to measure the current in underwater using a tong ammeter which can measure the current without establishing an electric circuit [37].

Hazards associated with diving operations:

The valves of the gas cylinders shall be opened only gradually to avoid diesel effects in the hoses. Diesel effect is an explosion in the hose formed due to cavitation with certain oil content in the hose (due to trapped air molecules in the gas) because of high pressure. Diesel effect increases pressure in hoses and damages the hose, tightening of seals, O-rings etc.

Divers are regularly exposed to noise and noise of 120 dB (A) is measured during ventilation of a hyperbaric chamber. Ear canal may squeeze, possibly with drum perforation, may result in transient conductive hearing loss [37,43].

7.0 Conclusion

With the increased dependency on offshore structures and pipelines for various energy needs and also with the increased use of steel structures for the construction of various underwater structures, the requirement of regular upkeep of underwater structures to ensure safety of the equipment has become very critical to ensure not only uninterrupted energy supply but also to comply with marine pollution standards. Underwater welding has gained wide acceptance due to the versatility of the process and the speed with which installations and repairs can be performed. The advancements in electrode manufacturing and power supply devices are improving the quality of underwater welds and thereby increasing the employability of the process to perform difficult and critical repairs demanding high quality weld joints. In the market, electrodes are available that are capable of producing Class A welds as per AWDS D3.6. The major challenge associated with underwater welding is the safety of the personal engaged in it. It shall be ensured that all standard practices are followed strictly for a safe underwater welding operation.

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