International Journal of Innovative Research in Engineering and Management (IJIREM)
ISSN(Online): 2350-0557, Volume-11, Issue-6, December 2024
https://doi.org/10.55524/ijirem.2024.11.6.18
Article ID IJIR3053, Pages 165-174
www.ijirem.org

Underwater Welding: A Comprehensive Review of Techniques, Applications, Challenges, and Safety Practices

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Received: 2 December 2024 Revised: 17 December 2024 Accepted: 29 December 2024

ABSTRACT- Underwater welding plays a special role in the repair and maintenance of modern oil platforms, pipelines, ships, and floating objects. This paper provides a classification of underwater welding and discusses the advantages and disadvantages of various underwater welding techniques. Additionally, the paper covers the techniques that can be used underwater, the history of underwater welding, the equipment used, application areas, working principles, challenges, and problems related to underwater welding. As in any field, safety is very important in underwater welding, and information is provided about the safety measures that should be taken during underwater welding.

KEYWORDS- Welding, Underwater Welding, Dry Underwater Welding, Wet Underwater Welding, Underwater Welding Working Principles

I. INTRODUCTION

Until the end of the 19th century, the only known welding method was the process of heating and forging metals, primarily used by blacksmiths. Electric arc welding and oxy-gas welding were the first methods to be developed at the end of the century, followed by resistance welding. Welding technology rapidly advanced during the early 20th century, particularly during and after World War I and World War II, to meet increasing demands. It became one of the most reliable and cost-effective methods.

After the wars, various modern welding techniques emerged, including manual methods (manual metal arc welding) and semi-automatic and automatic methods (gas metal arc welding, etc.). Advances continued into the second half of the century with the invention of laser beam welding and electron beam welding.Additionally, underwater welding has gained significant importance since the years of World War I At that time, underwater welding was primarily used to temporarily repair damages or seal holes in warships. With technological advancements, underwater welding(see figure 1) now plays a crucial role in constructing and repairing offshore structures, pipelines, and drilling platforms used for exploring oil and natural gas beneath the seas. It is of great significance for underwater structures and repairs.

A. Definition of Welding

In general, welding can be defined as the process of joining parts by applying heat, pressure, or both, or covering surfaces with an additional metal. In practice, it is possible to observe applications where additional metals are used or not used during these processes. Welding can be described in two ways: macroscopically and microscopically.

- **Macroscopically**, welding is the process of joining two or more materials in a way that ensures continuity by applying external energy, with or without the use of filler material.
- **Microscopically**, welding involves bringing the atoms of the parts to be joined into regions of mutual attraction.

Figure 1: Underwater Welding Experiment

B. Classification of the Welding Process

The welding process can be classified based on the welding method as manual, semi-mechanized, fully mechanized, and automatic. Another classification is made according to how energy is delivered to the welding site. In practical applications, the required energy for welding is delivered to the site as heat, pressure, or a combination of both. Based on the type of process, welding operations are divided into two groups;

- **Fusion Welding:** In this method, energy is delivered to the welding site in the form of heat energy.
- **Pressure Welding:** In this method, energy is delivered to the welding site as pressure or as a combination of heat and pressure.

These two main groups encompass many welding types. In practice, the most commonly used welding type is electric arc welding, which is a subset of fusion welding. The energy required for the welding process in this method is supplied by welding machines.

The welding methods included in these two groups are:

- **Fusion Welding Methods**
  - Resistance Fusion Welding
  - Electric Arc Welding
- **Pressure Welding Methods**
  - Ultrasonic Welding
  - Friction Welding
  - Electric Resistance Welding

II. UNDERWATER WELDING

At the beginning of the 20th century, the idea of a diver creating an electric arc underwater was considered suicidal. While professional diving had already become an established industry, underwater welding was not. This changed when Soviet engineer Konstantin Khrenov invented a method for joining and cutting metals underwater.

"Underwater welding was first used during World War I when naval personnel temporarily repaired damages on British warships.

These repairs involved leaking rivets on the hulls of the ships. Initially, underwater welding operations were limited to salvage operations and emergency repairs only. Additionally, they were restricted to a depth of just 10 meters."

The underwater welding process was improved in 1946 with the use of special waterproof electrodes developed by Vander Willigen. In the initial stages of underwater welding, repairs such as welding and patching were carried out. Over time, as more experience was gained, ambitious individuals and companies worked to improve the results and develop more accessible features [9].

A. Description

Underwater welding is generally used in areas such as port construction and repairs, the construction of bridge piers, the construction of canal reservoirs, the repair of ships and submarines, and the construction and repair of underwater pipeline connections. Underwater welding has been widely implemented, especially by the U.S. Navy and salvage companies. While its primary use is for the emergency repair of ships, it is also employed in the manufacturing and maintenance of drilling platforms and associated equipment, as drilling for oil and natural gas in the seas has developed. This type of welding is performed either in a completely wet environment, in underwater areas where only specific points are protected from water, or in a dry environment under high pressure within water. Compared to welding performed under atmospheric conditions, underwater welding tends to result in lower mechanical properties, especially in terms of elasticity. For this reason, until recent times, underwater welding was mainly used for temporary repairs and salvage operations. The underwater welding techniques currently in use are performed with covered electrodes.

Underwater welding with covered electrodes is attractive in many respects. Although the fundamental principles that ensure the quality of structural steel welding might seem violated here, it is often not emphasized as long as the requirements for a quick repair have been effectively met. Perfection can be sacrificed in favor of practicality.

Moreover, temporary or provisional work does not really need to be perfect. The main thing is that quickly.

In fact, underwater welding provides the opportunity to perform simple repairs at low cost in many cases, and the results obtained are in favor of the principle of "fitness for use.

The exploration and discovery of hydrocarbons in open seas have further developed the oil industry. With new exploration techniques, oil is now extracted from depths of 1,000 meters, and advancements are being made to extract oil from even deeper areas. The importance of underwater welding and inspection technology has been proven through the installation, repair, and maintenance of many naval objects.. Moreover, as the operation of oil and gas fields moves into deeper areas, investments have increased for the further development of underwater welding techniques. It is clear that the level of development has reached a point where these technologies can be applied and used in various situations. Recently, underwater welding has become an important tool in many applications, including underwater structures, pipelines, ships, and in manufacturing industries, as well as on offshore platforms. Some structures, however, may encounter unforeseen accidents and malfunctions during normal use, such as storms or collisions.. Underwater welding is used to repair these damages [10].

Figure 2: A Welding from Underwater

B. Applications of Underwater Welding

Underwater welding is used for the following purposes(see figure 2)

- The construction and installation of offshore marine structures, submarine pipelines, and port facilities
- Maintenance and repair
- Repair of accidents and damages occurring on offshore oil platforms
- Repair or replacement of damaged underwater pipes
- Repair of holes in ship hulls
- Repair of corrosion damage in port facilities
- Generally, the repair of ships, offshore oil platforms, and pipelines
- Underwater welding is typically used on materials such as steels, stainless steels, copper, and aluminum. [9]

C. Classification of Underwater Welding

Underwater welding is divided into two main types:

- **Wet Underwater Welding**
- **Dry Underwater Welding**
- **Robotic Underwater Welding**

In wet welding, the welding is performed directly in a wet environment without any protection between the welding area and the water.

In dry welding, a dry chamber is created around the area where the welding will be done, and the welder performs the welding inside the chamber [7].

- **Wet Underwater Welding**

It is performed directly under underwater pressure, where the welder uses a special electrode with protection, and there is no physical barrier between the welding arc and the water. A special electrode is used, and the welding is done using electric arc welding, just as in open-air welding[6].

Special precautions must be taken to protect from water when welding is to be performed. Wet underwater welding does not require any complex setup, is economical, and can be applied immediately in emergencies or accidents, as there is no need to drain the water. High mobility, efficiency, and economic feasibility are important advantages of wet welding. However, some of the significant disadvantages include low visibility in water, the conductivity of water, bubbles formed in the water, low weld quality, and the difficulty of the welding process[2].

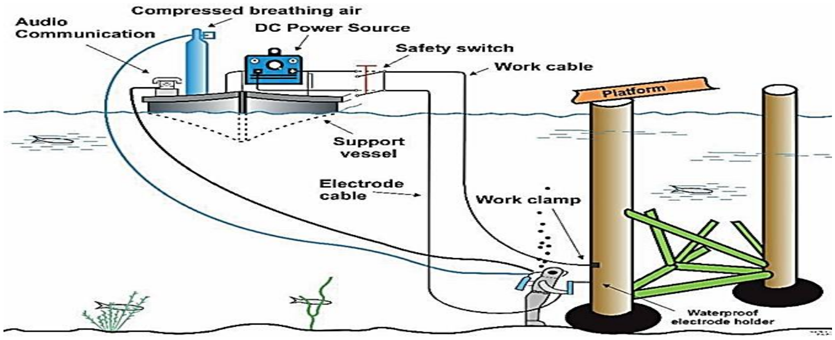

Figure 3: Underwater Welding Equipment and Underwater Welding Construction [11]

The diver-welder and electric arc in direct water environments have negative effects not only on the quality of the weld but also on the safety of the welder. These problems arise in proportion to the depth, and therefore, when considering the operational accessibility of wet welding procedures, depth becomes a limiting factor. On the other hand, the equipment(see figure 3) and other technical facilities are not as complex as those of underwater dry welding methods and are cheaper. For this reason, underwater wet welding is more preferred for the maintenance of underwater structures and ship repairs[8].

FCAW (Flux-Cored Arc Welding) with covered electrodes can be performed in a wet environment up to a depth of 100 meters(see figure 4). In wet welding in a water environment, the cooling rate is much higher than that achieved in dry welding.
The temperature range can vary from 800 to 500 °C, changing from 415 to 56 °C/s. This leads to a loss of ductility in the weld metal and the heat-affected zone. It is also known that underwater wet welds contain high amounts of porosity.

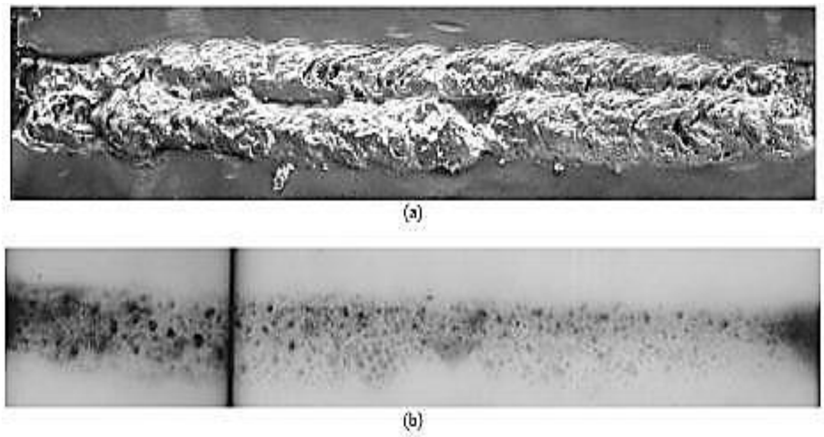

Figure 4: Wet Underwater Welding at a Depth of 100 m (a) and the X-ray Image (b)

The power source for welding is located on the surface and is connected to the diver/welder via cables and hoses. In wet welding, electric arc welding is used.

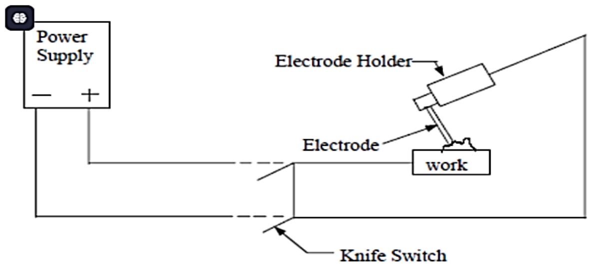

Figure 5: A typical underwater wet welding diagram Power source used: DC[11]

When a DC power source is used with +ve polarity, electrolysis occurs, leading to rapid degradation of the metallic components in the electrode holder. AC is not used for wet welding because of electrical safety concerns and the difficulty in maintaining a continuous arc underwater. The power source should be a DC machine with 300 or 400 amps (see figure 5). The welding machine must be grounded. The welding circuit must include a positive switch, usually a knife switch, which is operated on the surface and controlled by the diver-welder. The welding circuit must include a knife-type switch, which is operated on the surface and controlled by the diver-welder. The knife-type switch in the electrode circuit can cut off the welding current and is used for safety reasons.

The underwater welding electrode holder uses a twisted head to hold the electrode.

It accommodates two sizes of electrodes. The electrodes must be waterproof. All connections must be thoroughly insulated to prevent water from making contact with metal parts. If the insulation leaks, seawater will make contact with the metal conductor, and the arc will not form. Additionally, rapid degradation of the copper wire will occur at the leakage point [4].

C. Dry Underwater Welding

The working area must be free of water for the process to take place. This welding is performed using a controlled atmosphere and pressure in a chamber. Compared to wet underwater welding, it provides higher quality results but requires more equipment and costs. In many cases, dry welds have mechanical properties equal to similar welds performed on the surface. The estimated cost and time for repairs using dry welding are twice as much as for repairs using wet welding. Almost all standard welding methods can be used in dry conditions. Welding can be performed at depths of up to 300 meters[3].

Additionally, it is possible to reduce hydrogen content or improve welding properties by preheating or performing post-weld heat treatment. When dry underwater welding is applied, visibility similar to that of normal open air is achieved, and communication between welders and other workers greatly enhances the progress and safety of the work. Furthermore, the ability to handle equipment and workpieces, surface cleaning, and welding preparation conditions are better. Welding is completed in a shorter time compared to wet welding. Problems normally expected, such as brittle microstructure prone to cracking, are completely avoided by using underwater wet welding. On the other hand, setting up the materials and equipment for dry underwater welding and preparing the suitable conditions takes more time and is more costly compared to wet underwater welding. More workers are needed compared to wet welding. However, dry underwater welding is widely used in the maintenance and assembly of underwater structures[10].

Dry underwater welding can be done in various ways[5]. These are:

- Dry Habitat Welding
- Dry Chamber Welding
- Dry Spot Welding
- Dry Welding At One Atmosphere
- Hyperbaric Welding

- **Dry Habitat Resource**

The workpiece to be welded is placed inside a specially designed, sealed, and spacious chamber, and all water is removed. Under these conditions, the welder performs the welding process without using any diving equipment. As shown in the figure, welders operate in a completely dry environment, and welding is performed under normal conditions. However, preparing and leveling the area for welding takes time. This process is referred to as dry habitat welding. (see figure 6)[2].

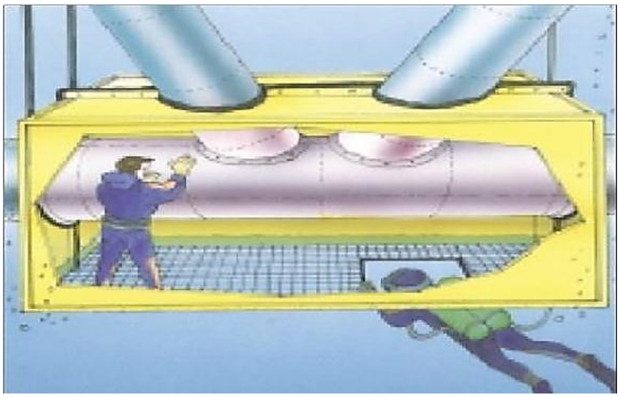

Figure 6: Dry Habitat Welding Process

- **Dry Chamber Welding**

The workpiece to be welded is placed inside a small, water-free chamber. The diver/welder performs the welding process while wearing all necessary diving equipment, with at least their head and shoulders inside the chamber. The diver/welder may be partially submerged in water, but the welding is carried out in a dry environment. The setup is smaller and less complex compared to the dry habitat welding. Due to the smaller size of the chamber, the preparation and other pre-welding procedures are less costly than those for dry habitat welding (see figure 8)[7].

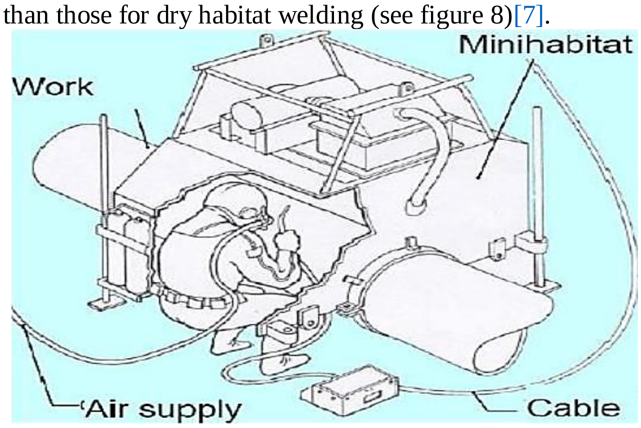

Figure 7: Dry Chamber Welding Process

- **Dry Spot Welding**

This type of welding is performed by a diver/welder inside a small, transparent chamber filled with gas, under the pressure of the surrounding environment. The welding occurs within the dry chamber, and the diver/welder is outside the welding area. Welding is performed in a container where the pressure is maintained at approximately one atmosphere, regardless of the water pressure in the external environment. The welding area is physically separated by a transparent barrier. The equipment is much smaller than that used for dry habitat and dry chamber welding, but issues such as welding fumes and visibility problems may arise(see figure 8)[10].

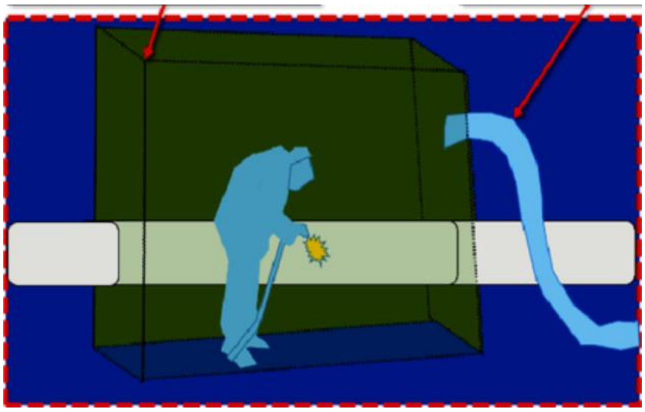

Figure 8: Dry Chamber Welding Process

- **Dry Welding Under One Atmosphere Pressure**

This type of dry underwater welding is performed by the welder in a dry environment within a cofferdam. Aluminum is typically used as the material for this box-like structure, which is employed to isolate the internal environment from the surrounding water[2]. The cofferdam has an air inlet pipe that extends above the sea surface. Therefore, the welding process is carried out at the open-air atmospheric pressure of the sea surface. This eliminates diving problems, the effects of increased pressure, and other factors that can affect the welding process. The cofferdam is fixed to the structure to be welded, and the welding is done inside it. Before underwater assembly, polymeric foam is applied to the corners and contact surfaces of the cofferdam to prevent water entry. Once the cofferdam is placed and fixed, water is pumped out of the cofferdam using a special pump[10].

After the necessary safety precautions are taken, the individuals who will perform the welding in the dry environment are lowered into the cofferdam through the air pipe. A specific problem with working in such a confined space is the potential formation of explosive and harmful gases. Therefore, a sufficient ventilation system with clean air support is required(see figure 9).

Compared to wet underwater welding, the major advantages of this process are better quality, flexibility in the selection of welding procedures, and higher operational safety. The disadvantages are the high cost of building and positioning the cofferdam, and the issues related to the impermeability of the structure.

This concept is frequently used, and there are examples of the application of this technology.

After setting up the cofferdam, it is necessary to secure a monitoring system, install appropriate sensors to detect water leakage, and establish a system to pump out the water. Leakage problems may often occur. These issues depend on the design of the cofferdam, its construction phase, cost, and the responsibility of the investor. On the other hand, in terms of welding, it is more suitable compared to wet underwater welding, as it allows for more productive cutting and welding operations.

In addition to electric arc welding, MAG and flux-cored wire welding can also be considered. However, electric arc welding is recommended due to potential problems, such as the use of separate filler wires and the contamination of the working environment with protective gases. When the cofferdam is used, diving equipment is prepared, assembled, and removed once the work is completed. Additionally, to ensure the continuity of external monitoring activities, the diver is responsible for detecting any leakage problems that occur during the placement and fixation of the cofferdam[10].

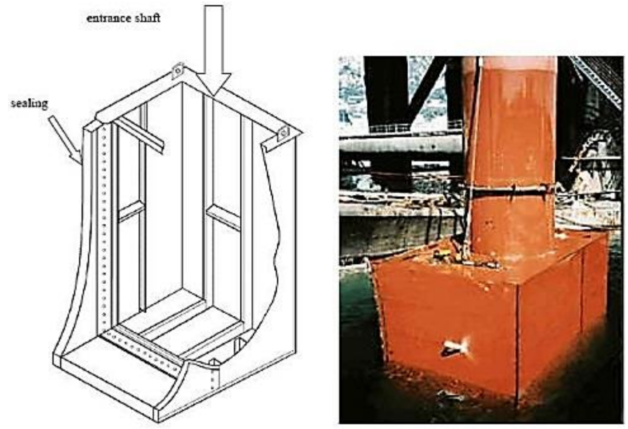

Figure 9: The Cofferdam Used in Welding Performed Under one Atmosphere Pressure[10]

- **Hyperbaric Welding**

Hyperbaric welding, like other examples, is performed by enclosing the structure to be welded within a chamber. The chamber is filled with a gas (usually helium gas containing 0.5 bar of oxygen) under the existing pressure. The chamber is connected to a breathable pipeline and filled with oxygen and helium at the pressure of the welding environment or slightly above it. This method produces high-quality welded joints that meet x-ray and regulatory requirements. The TIG welding method is used for this process. The bottom of the working environment is exposed to water. Thus, the welding is carried out with the hydrostatic pressure of the seawater surrounding the working environment(see figure 10)[6].

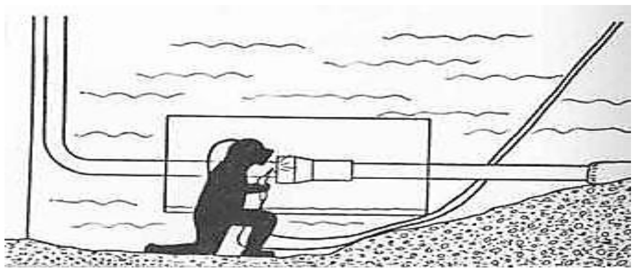

Figure 10: Hyperbaric Welding Process

- **Robotic Underwater Welding**

Robotic underwater welding is an advanced method that employs automated robotic systems to perform welding operations in submerged environments. This technology is increasingly used in the construction and maintenance of offshore oil platforms, ship hulls, underwater pipelines, and other marine infrastructure. It addresses the inherent risks and limitations faced by human divers in underwater welding.

- **Challenges**

While robotic underwater welding offers significant benefits, it also presents several challenges:

- **Environmental Factors:** The conductivity of water and varying pressure levels make it challenging to maintain arc stability and weld quality.
- **High Costs:** The design, deployment, and maintenance of robotic systems are expensive.
- **Material Issues:** Welding underwater can lead to issues such as hydrogen-induced cracking, requiring specialized welding techniques and materials.

- **Future Prospects**

Robotic underwater welding is set to revolutionize marine engineering by combining robotics with advanced sensor technologies and artificial intelligence. These advancements will not only enhance the safety and reliability of underwater welding but also expand its applicability in deeper and more complex underwater environments. Future innovations, such as the integration of augmented reality for remote operators and AI-driven predictive maintenance systems, promise to further optimize this cutting-edge technology.

D. Preparation for Underwater Welding

Surface preparation and fitting of the parts are extremely important in underwater welding. Strong welds cannot be obtained on thick paint, rust, seaweed, or similar layers. Chisels, hammers, files, and wire brushes should be applied with force. Pneumatic tools can assist in this process. In shipyards, due to the slope, fitting is often problematic. The patch plate will be adjusted to match the slope of the vessel as much as possible. If the remaining gap cannot be completely eliminated, it will be kept as small as possible. A gap of 1.6 mm will be considered the maximum permissible. The diver/welder is required to establish a stable working platform. In cases where the water is rough and the work can be delayed, this alternative should be chosen. It is preferable to connect the platform to the ship to be welded rather than attaching it to the diving platform, rescue ship, or buoy.

In underwater welding, the management of the electrode is quite difficult for various reasons, and to overcome this, the electrode must be pressed strongly at the base of the joint, as with "contact" electrodes.

Indeed, this "self-consuming" pulling (contact) technique is preferred in underwater welding. Once the arc is ignited, the electrode is pressed against the workpiece with enough pressure to allow for "self-consumption." Using this technique, a 5mm fillet weld can be completed in a single pass with a 5mm electrode, and the resulting weld will have approximately the same strength as a three-pass weld.

After the first weld, the guiding groove disappears, making multi-pass welding truly difficult. When butt welding is done on the ground, a gap is opened, and V-groove welding should be avoided.

Moreover, when the work aligns with the mechanical strength to be achieved, this butt weld's advantages include saving time, eliminating the need for cleaning the seam between passes, and not requiring the maintenance of a groove to guide the electrode throughout the joining process. The butt weld can replace the joint, but if the butt is oriented downwards (Figure 11(a)), gases will not escape properly and will disturb the welder. In this case, a sufficiently open weld pool will form (Figure 11(b)).

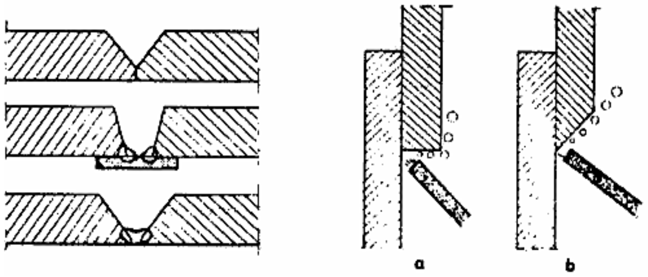

Figure 11: Process of Underwater Welding

In vertical welding from top to bottom, the process is supported and easier to apply; however, in vertical welding from bottom to top, molten metal tends to accumulate in clumps that do not adhere to the base metal. The same difficulties are encountered in overhead welding. In air welding, the angle of the electrode is determined by the need to prevent the arc plasma pressure from forcing the molten metal outside the joint. If the electrode is too upright, the tip of the electrode dips too deeply into the pool of molten metal. The same situation occurs underwater, but here the arc penetrates deeper, so a greater angle is desired.

E. Underwater Electric Arc

Underwater arc, like in air, is initiated by contact between the electrode and the workpiece, but it is much harder to maintain. At the tip of the molten electrode, a deeper crater forms than what occurs in air, making it significantly harder to reignite such a partially melted electrode. The arc also penetrates deeper underwater, and the marks left by ignition become actual pits[1].

The main characteristic of the arc underwater is the formation of a pocket around it, consisting of gas, smoke, and vapors. From this pocket, small or large bubbles continuously rise to the surface, where they burst.

The vapors, along with small white smoke, produce brown or leaden clouds. Some bubbles, when bursting, release solid particles that gradually cause the water to become turbid. The vapors rise vertically from the arc directly to the water surface (see figure 12).

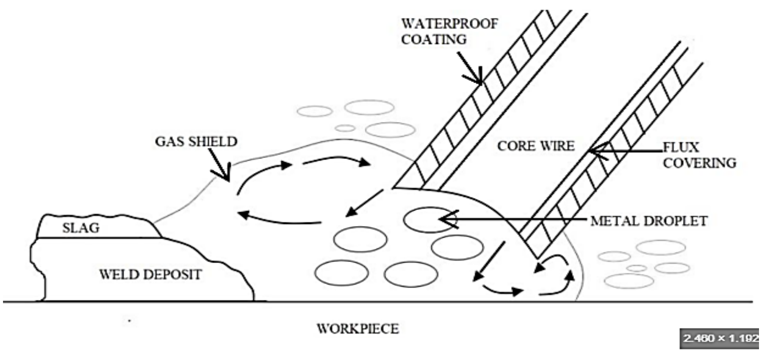

Figure 12: Metal Droplets and Vapor Bubbles In Underwater Welding

Just like in the air, but this time much more, molten metal spattering occurs underwater. Some of these droplets stick to the workpiece at a distance of 15 to 20 mm from the joint.

These can only be removed with a chisel. In figure 13, there is a metal droplet surrounded by a vapor bubble. The diameter of the droplet varies between a few microns and approximately one millimeter. Likewise, red droplets are also dragged towards the surface inside a large gas bubble (b). The droplets move quickly within the bubble. Any contact of the droplet with the bubble's wall likely creates a small force that pushes the droplet (c). Some droplets directly reach the molten pool, but sometimes they roll over the molten area without falling into it. These last ones accumulate in front of the electrode and form pellets that disturb the welder (d). This phenomenon occurs only with certain electrodes. Additionally, there are light particles that are generated from the electrode's insulating outer coating and move slowly.

III. PARAMETERS AFFECTING WELDING

A. Electrical Parameters

- **Current (Amperage):** The current used during welding directly affects the quality of the weld seam. High current can produce a deeper and wider weld seam, while low current produces a finer and narrower seam.
- **Voltage:** Voltage affects the length and stability of the arc. Higher voltage leads to a shorter, more concentrated arc.
- **Welding Speed:** The speed of the welding process affects the morphology and mechanical properties of the weld. Too high of a speed can cause an irregular seam with cracks, while a slow welding process can result in excessive heating, melting of the metal, and deformation.

B. Airflow and Gas Flow

- **Shielding Gases:** In welding types such as TIG and MIG, shielding gases are used to prevent the welding metal from oxidizing. The type of gas used (argon, carbon dioxide, helium, etc.) impacts the quality of the weld.
- **Airflow:** In underwater welding, the water pressure and underwater currents can influence the efficiency and safety of the welding process.
- **Electrode and Material Selection:** The type and quality of the electrodes used (such as tungsten or copper-coated) affect the stability of the arc and the durability of the weld seam. Additionally, the chemical composition and properties of the welding material also determine the strength of the weld.
- **Temperature:** The temperature of the welding metal, especially in underwater welding, can affect the shape and durability of the seam. Temperature influences the risk of cracking. Moreover, the ambient temperature in underwater welding is also crucial, as low temperatures cause the metal to cool faster, increasing the risk of brittleness.
- **Pressure:** In underwater welding, the pressure of the water affects the efficiency of the welding process. As the depth increases, the pressure rises, which can cause the metal to cool faster or make it more difficult to control the arc.
- **Fluid and Gas Flow:** The movement of gases and liquids in the welding environment is also important. For example, the way water or gas flows toward the weld can influence the movement of metal droplets and how the weld seam forms.
- **Work Environment and Waves:** The effects of waves, underwater currents, and other environmental factors are significant. Welding in an unstable environment makes the process harder, potentially jeopardizing both the welder's safety and the quality of the weld.

  Proper control of these parameters is essential to ensure the quality and safety of the welding process.

IV. EQUIPMENT USED IN UNDERWATER WELDING

Scuba divers/welders need the proper equipment to carry out their work correctly, efficiently, and safely. The following equipment is required for underwater welding to be done properly.

A. Power Supply

Underwater welding requires all welding equipment to be powered by direct current (DC), not alternating current (AC). Direct current provides a continuous flow of current in a fixed direction. Underwater, DC is a better option compared to AC. Diver welders use polarity that provides a longer lifespan for the electrode holder.. (İnternet, www.waterwelders.com)

Underwater cutting requires a power supply capable of providing a minimum of 300 A DC current. The power supply should be adjusted not only for proper arc formation but also with the diver/welder's safety in mind. It should be ensured that the welding machine is securely placed on the ground and that electrical connections and grounding lines are properly made. The power supply should be placed on dry wood, insulated metal, etc., and should not make direct contact with the ground. To prevent the power supply commutator from sparking, the machine and electrical equipment should be in good condition. It is important to remember that electrical current can pose a potential hazard during welding. The power supply should undergo periodic maintenance without delay.

B. Diver Helmet

Underwater welders need to use a reliable diving helmet while working. In standard welding, welding helmets protect the welder's eyes and face during operations. Similarly, underwater welding helmets serve this purpose while also allowing welders to breathe. Additionally, there are specially designed welding lenses for underwater welding. These lenses protect against the various effects of welding. They can also be adjusted to darken during welding and lighten after the task is completed.

C. Diving Suit

Most welders use waterproof diving suits. These suits are more practical in varying climate conditions. Depending on the diving environment, the suit can be made of rubber or have a tough outer shell. Additionally, some welders wear coveralls over the diving suit for extra protection.

If molten metal comes into direct contact with the diving suit, it can burn. Coveralls help prevent this burning. To protect their hands, divers/welders wear thick rubber gloves over latex gloves. To prevent water from entering the gloves, a rubber band is placed around the wrist area(see figure 13).

Figure 13: Underwater Welding Diving Suit

D. Diving Accessories

In addition to the diving helmet and diving suit, divers/welders also use the following accessories

- **Diving Knife:** Used for cutting in various situations and emergencies.
- **Umbilical:** This is the place where air is pumped to the divers from above the water's surface.
- **Harness:** This accessory is used to keep welders secured during work and to pull them to the surface after the job is finished.
- **Air Panel and Compressor:** The duty team monitors the gas gauge and ensures the welder receives air. Since it provides easy control and unlimited air supply, low gas pressure is typically used.
- **Knife-Type Switch:** It is not the same as a diving knife. The knife-type switch is an accessory designed to cut off the electricity with a single motion. It is located between the cable connected to the torch and the welding machine. The switch can be used by the telephone operator as per the diver's request

E. Electrodes

The electrode is the most crucial part of underwater welding equipment(figure 3), as it provides the material for the welding process. The most significant difference between a normal welding electrode and an underwater welding electrode is the coating. Underwater electrodes must be highly resistant to water. Some welders apply coatings to their electrodes themselves, but most coatings last for several hours. These coated electrodes can remain waterproof for up to 24 hours under water. They can work efficiently up to depths of 10.5 meters without degradation. However, higher pressures can compromise their structural integrity and cause pores to open, leading to failures in the coating.
The types of electrodes used are as follows:

- Cellulosic Electrode
- Acid Electrode
- Rutile Electrode
- Oxidation Electrode
- Iron Powder Electrode

F. Electrode Holder

Electrode holders used underwater are specially manufactured. These holders are equipped with a suspension strap that allows the diver to use both hands simultaneously when necessary and prevents the electrode holder from falling. A high-quality electrode holder has the following features:

- **Insulated:** Saltwater is a highly conductive material, and welders need to take all necessary safety precautions. If the electrode holder is well insulated, even a 200-amp current will not be felt by the welder.
- **Ergonomics and Lightness:** As the welding project grows, underwater welders need an electrode holder that is comfortable for long hours of work.
- **Correct fit:** Underwater welders need a flawless electrode holder hole and notch where the electrode can be placed.

G. 4.6 Welding Cable

The cable used in underwater cutting or welding should be extra flexible. In deep waters, large diameter cables should be used to prevent voltage loss, and the generator output amperage should be increased accordingly. The use of additional cables at connection points can also lead to current drops. Proper insulation of the cable and connections ensures minimal sparking at the power source commutator. Poor insulation can lead to electric shocks and rapid electrolysis. The underwater connection points of the cables must be well insulated. Care should be taken to ensure the welding cables do not break. Cables should be stored in dry environments and kept away from grease, oil, and similar substances.

H. 4.7 Arc Cable

It is the cable that completes the circuit with the part during cutting or welding processes with a welding machine. It must be at least as robust, flexible, and adequate as the welding cable. It should have a clamp that allows it to be easily attached to the part to be welded.

V. SAFETY RULES

In an underwater cutting and welding job, if the necessary safety rules are not followed while working as a dive supervisor, diver, or assistant, it means that your life, your diving partner's life, and of course the ship are at risk.

A. Major Hazards Present While Working Underwater

- Electric current
- Danger of falling parts being cut
- Accumulation of explosive gases
- Accumulation of explosive gases

The compartment must be ventilated by an authorized person to eliminate any possibility of explosion.
Holes should be made in appropriate locations to allow gases to escape

B. Safety Measures to Be Taken on the Diving Platform

- Ensure that the welding machine is not malfunctioning.
- Both connection terminals must be connected.
- Always stand on a wooden or rubber base.
- Always wear rubber or rubber-coated gloves when holding the electrode holder, torch, cable, or machine.
- The commutator of the welding machine must be clean.

C. Safety Rules for Underwater Electrode Holders and Cutting Torches

- Use electrode holders and torches specifically designed for underwater use
- The current-carrying parts of the holder and torch must be insulated with non-conductive material.
- Standard surface holders should only be used in emergencies.
- Always use a springless type of electrode holder.
- Inspect holders and torches for wear and cracks before starting work.
- Electrode replacement and tightening should only be performed when the current is OFF.
- The welder must never point the electrode or holder toward themselves.
- The welder must ensure that no uninsulated part of the holder touches themselves or the diving team.

D. Safety Rules for Electric Cables and Cable Connections

- All parts of the cable entering the water must be insulated.
- The cable and connections should be inspected before starting work.
- Only suitable and flexible welding cables should be used.
- Cable connections should be at least as strong as the cables' load capacity.
- All connection points should be tight and insulated with non-conductive material.
- Welding cables used underwater should not be used for surface work.
- Long cables should be suspended, if possible.

E. Safety Rules for the Safety Switch

- Always use a 300-400 amp single-pole safety switch
- The only suitable type is the knife-type safety switch.
- The electric current should always be OFF except during cutting or welding operations.
- The switch should not be operated in a flammable environment.
- The switch should have a parallel connection.

F. Safety Rules for Oxygen Use

Oxygen cylinders should not be rolled or dropped due to the high pressure inside. Oils, greases, and similar substances should be kept away from oxygen.

G. Safety Rules for Electric Igniters

- The igniter should be prepared before use
- The igniter circuit should only be turned off by an assistant when the diver requests it.

Before use, all cables should be inspected for wear and damage to the insulation.

H. Safety Rules for the Diver/Welder

- The diver should take even the smallest precautions to protect themselves from electric shocks.
- It should be ensured that the diving suit provides the best protection against electric shocks.
- A single-pole safety switch should always be used for underwater cutting and welding.
- No diver should have any contact with an open flame while wearing diving suits, with the air hose, or the pump hose, etc.
- A lit torch should never be neglected or left swinging in a way that it might get tangled in hoses.

(İnternet, www.actwelding.com)

VI. RECENT INNOVATIONS AND FUTURE PROSPECTS

Advancements in robotic and automated welding systems have significantly improved the efficiency and safety of underwater welding. Additionally, research into advanced materials and coatings is addressing issues like corrosion resistance and hydrogen embrittlement.

Future prospects include the integration of AI and remote-controlled welding technologies, which could revolutionize underwater welding by reducing human involvement and enhancing precision.

VII. CONCLUSION

Underwater welding is a critical process in the maintenance and construction of submerged structures, with primary applications in repairing offshore oil platforms, underwater pipelines, and ship hulls. Despite its indispensable role, it presents unique challenges such as the risk of hydrogen-induced cracking, the effect of water temperature and salinity on weld quality, and the technical difficulty of maintaining arc stability in submerged environments.

Advancements in technologies, such as hyperbaric welding chambers and robotic welding systems, have significantly improved the precision and safety of underwater welding. For instance, the integration of advanced sensor systems enables real-time monitoring of weld integrity, while robotic solutions reduce the physical risks to divers. However, the need for enhanced metallurgical understanding of weld behavior under varying pressure and temperature conditions remains a priority for future research.

Ultimately, the continued development of specialized welding techniques, such as friction stir welding for underwater applications, will help overcome these challenges. By addressing both technical and safety concerns, underwater welding will remain a cornerstone of marine engineering, ensuring the resilience and sustainability of critical infrastructure in submerged environments.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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