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Research Paper

WELDING PROCESSES IN MARINE APPLICATIONS: A REVIEW

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This Research article is aimed at highlighting the importance of Welding Processes in marine applications. The recent developments in the manufacturing world have led to a revolutionary change in the design and development of various systems. Development in welding technology is one of such changes. Welding processes have been used extensively as a joining technique. This research article represents a review of underwater welding (UWW) technique which has found a significant role in the joining industry. The paper deals with review of various underwater welding (UWW) techniques from marine applications point of view. The paper was structured by taking into consideration the aspects, classification and, importance of UWW process. The paper also describes the characteristics, applications and the risk mitigation factors of underwater welding (UWW) techniques from marine applications point of view.

Keywords: Underwater welding, Marine applications, Processes

INTRODUCTION

The recent developments in the manufacturing world have led to a revolutionary change in the design and development of various systems. Developments in welding technology is one of such changes. Welding processes have been used extensively as a joining technique, used in design and fabrication of various structures like naval ships, airplanes, automobiles, bridges, pressure vessels, etc. Welding has emerged as a better option in contrast to other joining techniques in terms of joint efficiency, mechanical properties with a greater application impact.

In some intricate situations, the Robot based welding processes have replaced human welders. During the last few years, the automation of welding process for pipe structures have gained significant momentum with an objective to improve the productivity and accuracy in the areas involving marine applications, etc. Various research studies in

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the welding environment have shown that productivity improvement is a major thrust area of welding industry. The welders in today's world are under tremendous pressure to meet two major challenges. These are: the higher weld quality and; reduced manufacturing cost.

Another emerging area in marine application welding systems is the underwater welding technique. Underwater Welding (UW) has been significantly used for over five decades. However, its use has not reached to a significant level in a welding environment due to number of factors. The underwater welding process came into existence with the development of water-proof electrodes in 1940's (Keats, 2005). It is the process of welding at elevated pressures, normally underwater. It may be carried out in the water itself or dry inside a specially constructed positive pressure envelope, thereby providing a special environment. Under water is also known as "hyperbaric welding" when used in a dry environment, and "underwater welding" when in a wet environment. The application areas of this welding technique include a wide variety of structures, such as repair ships, offshore oil platforms, and pipelines. Steel is the most common material welded (Cary and Helzer, 2005). Various researchers have defined the concept of underwater welding in different ways (Haddad and Farmer, 1985; Oates, 1996; Schmidt, 1996; Khanna, 2004; and Cary and Helzer, 2005).

General Aspects of Underwater Welding

There are various ways in which underwater welding technique can be performed. In underwater welding technique, the main challenge is to create an environment for welding. These are discussed in the below in this article.

One of the main advantages of this welding technique is the savings in terms of time. For repair and maintenance jobs in marine applications, the equipment/vessel need not be taken out to carry out the welding operation. The main difficulties in underwater welding are the presence of a higher pressure due to the water head under which welding takes place, chilling action of the water on the weld metal (which might change the metallurgical structures and properties), the possibility of producing the arc mixtures of hydrogen and oxygen in pockets, which might set up an explosion, and the common danger sustained by divers, of having nitrogen diffused in the blood in dangerous proportions. Furthermore, complete insulation of the welding circuit is an essential requirement of underwater welding.

Importance of Underwater Welding in Marine Applications

In practice, the use of underwater wet welding for offshore repairs has been limited mainly because of porosity and low toughness in the resulting welds. With appropriate consumable design, however, it is possible to reduce porosity and to enhance weld metal toughness through microstructural refinement. Hence, welding in offshore and marine application is an important area of research and needs considerable attention and understanding where, many problems are still unsolved. In the present review, a brief understanding of the problems in underwater welding will be discussed in context to the existing welding techniques. Detailed description of a few advanced welding techniques has also been made. Finally, the scope of further research would be recommended.

CLASSIFICATION OF UNDERWATER WELDING

Underwater welding may be divided into two main types, wet and dry welding (Oates, 1996).

Wet Welding

This type of welding process is carried out at ambient water pressure in which, there exists a relationship between the welder and the diver in the water. This is carried out by means of a water-proof stick electrode, with no physical barrier between water and welding arc (Oates, 1996).

In wet welding technique, the complex structures may also be welded (Oates, 1996; Shida *et al.*, 1997; Khanna, 2004; and Kruusing, 2004). One of the most commonly used wet welding technique is the Shielded Metal Arc Welding (SMAW) process and the Flux Cored Arc Welding (FCAW) process. It also includes the self shielded flux cored arc welding. From economics point of view, the wet welding technique with coated electrodes is considered. The cooling rate in wet welds is much higher than in those obtained in dry welding. In the temperature range from 800 to 500 °C it can change from 415 to 56 °C/s (Steen, 1991). Underwater wet welds are also known to contain high amounts of porosity (Figure 2). Porosity may be formed by molecular hydrogen, carbon monoxide or water vapour (Irie *et al.*, 1997; Cavaliere *et al.*, 2006; and Cavaliere *et al.*, 2008). Pores are present to some extent in all wet welds. The main factors affecting this phenomenon are (Shida *et al.*, 1997; Irie *et al.*, 1997; Cavaliere *et al.*, 2006; and Cavaliere *et al.*, 2008): water depth, electrode covering and arc stability.

Special precaution should be taken to produce underwater arc to protect it from surrounding water. Wet welding does not need any complicated experiment set up, it's economical and can be immediately applied in case of emergency and accident as it does not need water to be evacuated. However, difficulties in welding operation due to lack of visibility in water, presence of sea current, ground swells in shallow water and inferior weld qualities (increased porosities, reduced ductility, greater hardness in the heat affected zone, hydrogen pick up from the environment) are the notable disadvantages of wet welding technique.

Dry Welding

Dry welding in underwater may be achieved by several ways (Oates, 1996):

Dry Habitat Welding

Welding at ambient water pressure in a large chamber from which water has been displaced, in an atmosphere such that the welder/diver does not work in diving gear. This technique may be addressed as dry habitat welding.

Dry Chamber Welding

Welding at ambient water pressure in a simple open-bottom dry chamber that accommodates the head and shoulders of the welder/diver in full diving gear.

Dry Spot Welding

Welding at ambient water pressure in a small transparent, gas filled enclosure with the welder/diver in the water and no more than the welder/diver's arm in the enclosure.

Dry Welding at One Atmosphere

Welding at a pressure vessel in which the pressure is maintained at approximately one atmosphere regardless of outside ambient water pressure.

Cofferdam Welding

Welding inside of a closed bottom, open top enclosure at one atmosphere.

Underwater welding in a dry environment is made possible by encompassing the area to be welded with a physical barrier (weld chamber) that excludes water. The weld chamber is designed and custom built to accommodate braces and other structural members whose centerlines may intersect at or near the area that is to be welded. The chamber is usually built of steel, but plywood, rubberized canvas, or any other suitable material can be used. Size and configuration of the chamber are determined by dimensions and geometry of the area that must be encompassed and the number of welders that will be working in the chamber at the same time. Dry welding requires a pressurized enclosure having controlled atmosphere. Weld metal is not in direct contact with water. Advantages of dry welding are improvement in stability of welding operation, reduced hydrogen problem, lower quench rate of the weld and base metal and restoration of weld strength and ductility. Dry welding may be carried out under high pressure, which consists of preparing an enclosure to be filled with gas (helium) under high pressure (hyperbaric) to push water back, and have the welder, fitted with breathing mask and other protective equipment (Oates, 1996). Limitations of hyperbaric welding are the practical difficulties in sealing the chamber and increase in pressure as weld depth increases leading to problem which affects both the weld chemistry and microstructures.

RISKS ASSOCIATED WITH UNDERWATER WELDING

There is a risk to the welder/diver of electric shock. Precautions include achieving adequate electrical insulation of the welding equipment, shutting off the electricity supply immediately the arc is extinguished, and limiting the open-circuit voltage of MMA (SMA) welding sets. Secondly, hydrogen and oxygen are produced by the arc in wet welding. Precautions must be taken to avoid the build-up of pockets of gas, which are potentially explosive. The other main area of risk is to the life or health of the welder/diver from nitrogen introduced into the blood steam during exposure to air at increased pressure. Precautions include the provision of an emergency air or gas supply, stand-by divers, and decompression chambers to avoid nitrogen narcosis following rapid surfacing after saturation diving. For the structures being welded by wet underwater welding, inspection following welding may be more difficult than for welds deposited in air. Assuring the integrity of such underwater welds may be more difficult, and there is a risk that defects may remain undetected.

CHARACTERISTICS OF A GOOD UNDERWATER WELDING

- Requirement of inexpensive welding equipment, low welding cost, easy to operate and flexibility of operation in all positions.

- Minimum electrical hazards, a minimum of 20 cm/min welding speed at least.
- Permit good visibility.
- Produce good quality and reliable welds.
- Operator should be capable in supporting himself.
- Easily automated.

APPLICATIONS OF UNDERWATER WELDING

- Offshore construction for tapping sea resources.
- Temporary repair work caused by ship's collisions or unexpected accidents.
- Salvaging vessels sunk in the sea.
- Repair and maintenance of ships.
- Construction of large ships beyond the capacity of existing docks.

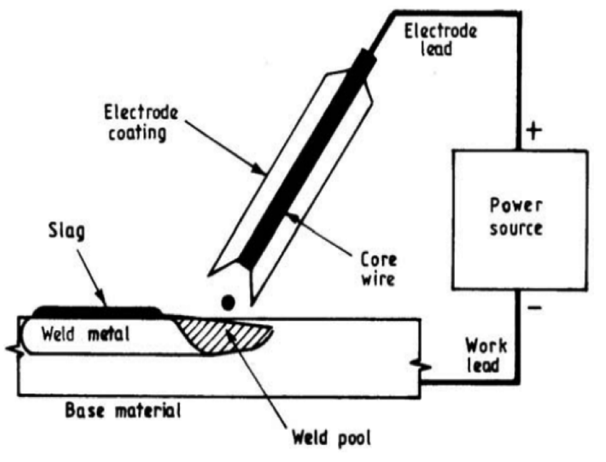
UNDERWATER WELDING TECHNIQUES

The fusion welding processes of greatest practical significance in underwater welding are manual shielded metal arc welding, tungsten inert gas welding, metal inert gas welding are used (Khanna, 2004). The principles of the above mentioned welding techniques are summarized below:

Shielded Metal Arc Welding

Shielded Metal Arc Welding (SMAW) is among the most widely used welding processes. During the process, the flux covering the electrode melts during welding. This forms the gas and slag to shield the arc and molten weld pool. Figure 1 shows the schematic of shielded metal arc welding process. The slag must be chipped off the weld bead after welding. The flux also provides a method of adding scavengers, deoxidizers, and alloying elements to the weld metal. For underwater wet welding with Shielded Metal Arc Welding (SMAW) technique, direct current is used and usually polarity is straight (Khanna, 2004). Electrodes are usually water proofed. Furthermore, it is flux coated which causes generation of bubble during welding and displaces water from the welding arc and weld pool area. Hence, the flux composition and depth of flux coating should be optimized to ensure adequate protection. Electrodes for shielded metal arc welding are classified by AWS as E6013 and E7014 (Khanna, 2004). Versatility, simple experiment set-up, economy in operation and finished product quality are notable advantages of the technique. However, during welding, all electrical leads, lighting gear, electrode holder, gloves, etc., must be fully insulated and in good condition. Ferrite electrodes with a coating based on iron oxide should be used as they resist hydrogen cracking. Flux cored arc welding is another technique which could not yet competed with

Figure 1: Schematic of Shielded Metal Arc Welding Process

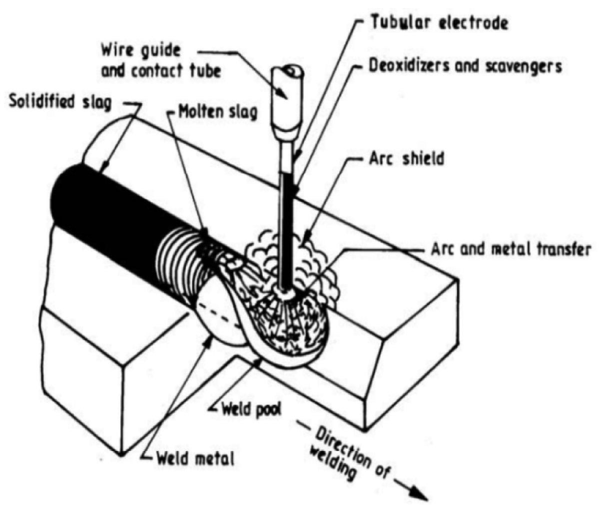


SMAW because of reported excessive porosities and problems with underwater wire feeding system (Oates, 1996).

Flux Cored Arc Welding

Flux Cored Arc Welding (FCAW) is a commonly used high deposition rate welding process that adds the benefits of flux to the welding simplicity of MIG welding (Khanna, 2004). As in MIG welding wire is continuously fed from a spool. Figure 2 shows the schematic of flux cored arc welding process. Flux cored welding is therefore referred to as a semiautomatic welding process. Self shielding flux cored arc welding wires are available or gas shielded welding wires may be used. Less pre-cleaning may be necessary than MIG welding. However, the condition of the base metal can affect weld quality. Excessive contamination must be eliminated. Flux cored welding produces a flux that must be removed. Flux cored welding has good weld appearance (smooth, uniform welds having good contour). Flexibility in operation, higher deposition rate, low operator skill and good quality of the weld deposits are the notable advantages of flux cored arc welding. However, presence of porosities and burnback are the problems associated with the process. Recent development of nickel based flux cored filler materials have provided improved wet weldability and halogen free flux formulation specifically designed for wet welding application (Oates, 1996).

Figure 2: Schematic of Flux Cored Arc Welding



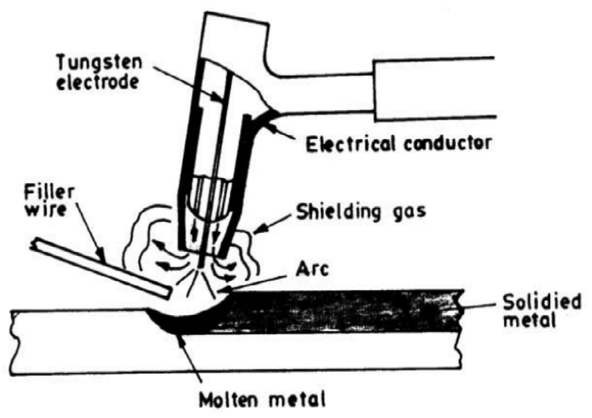
Similarly, improved underwater wet welding capabilities and halogen-free flux formulations have been developed with stainless steel flux-cored wires.

Tungsten Inert Gas Welding

TIG-welding (Tungsten Inert Gas) or GTAW-welding (Gas Tungsten Arc Welding) uses a permanent non-melting electrode made of tungsten (Khanna, 2004). Filler metal is added separately, which makes the process very flexible. It is also possible to weld without filler material. TIG welding has got the advantage that it gives a stable arc and less porous weld. Figure 3 shows the schematic of tungsten inert gas welding.

The most used power source for TIG-welding generates Alternating Current (AC).

Figure 3: Schematic of a Gas Tungsten Arc Welding Technique



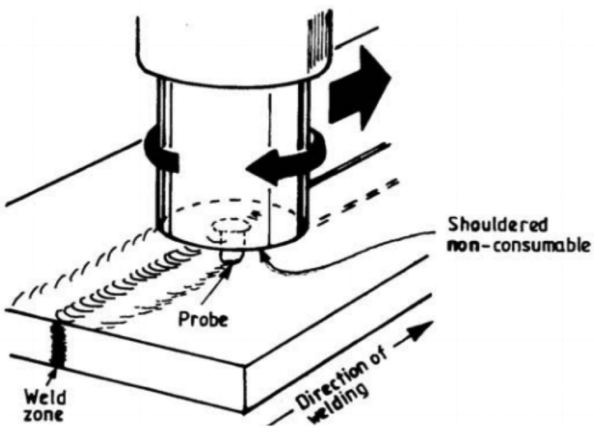
Direct current can be used. AC TIG-welding usually uses argon as a shielding gas. The process is a multi purpose process, which offers the user great flexibility. By changing the diameter of the tungsten electrode, welding may be performed with a wide range of heat input at different thicknesses. AC TIG-welding is possible with thicknesses down to about 0.5 mm. For larger thicknesses, > 5 mm, AC TIG-welding is less economical compared to MIG-welding due to lower welding speed. DC TIG-welding with electrode negative is used for welding thicknesses above 4 mm. The negative electrode gives a poor oxide cleaning compared to AC-TIG and MIG, and special cleaning of joint surfaces is necessary. The process usually uses helium shielding gas. This gives a better penetration in thicker sections. In deep see construction, free burning arc is used for fusion welding. The arc is then operated in a localized dry region created around the weldment at elevated pressures. Similar ambient conditions can be found in high pressure discharge lamps and in some plasma heaters and torches. The tungsten inert gas welding process at atmospheric pressures has been investigated extensively from the experimental and theoretical side (Haddad and Farmer, 1985; and Lancester, 1987). The properties of the free-burning arc column are studied for ambient pressures of 0.1 MPa (i.e., atmospheric) to 10 MPa for applications in underwater welding (Schmidt, 1996).

CURRENT UNDERWATER WELDING TECHNIQUES

Friction Welding (FRW)

Friction welding is a solid state welding process which produces coalescence of materials by the heat obtained from mechanically-induced sliding motion between rubbing surfaces (Khanna, 2004). The work parts are held together under pressure. This process usually involves rotating of one part against another to generate frictional heat at the junction. When a suitable high temperature has been reached, rotational motion ceases and additional pressure is applied and coalescence occurs. Figure 4 shows the schematic of friction welding process.

Figure 4: Schematic of Friction Welding Process



The start of the new millennium will see the introduction of friction welding for underwater repair of cracks to marine structures and pipelines. There are two variations of the friction welding process. In the original process one part is held stationary and the other part is rotated by a motor which maintains an essentially constant rotational speed. The two parts are brought in contact under pressure for a specified period of time with a specific pressure. Rotating power is disengaged from the rotating piece and the pressure is increased. When the rotating piece stops the weld is completed. This process can be accurately controlled when speed, pressure, and time are closely regulated. Cavaliere *et al.* (2006) investigated the effect of process parameters on fatigue behavior of AA6056 joints produced by friction stir welding. Cavaliere *et al.* (2008) carried out a research study on the effect of friction stir welding parameters to analyse the fatigue properties of AA6082 joints. Pessoa *et al.* (2006) carried out a study of Porosity variation for welding specimens. In this research study, the researchers have focussed on the multipass underwater wet welds and its influence on mechanical properties. There is a loss of ductility in the welded specimen and the Heat Affected Zone (HAZ). There is large amount of porosity in the underwater wet welds (Rowe *et al.*, 2002). Labanowski and Fydrych carried out a research study on some aspects of underwater welding processes. In this research study, the authors have observed that amount of hydrogen in weld metal is in the range from 5 to 21 ml/100 g Fe and depends on welding parameters, especially flow rate of shielding gas (Labanowski and Fydrych, 2008).

Friction welding requires relatively expensive apparatus similar to a machine tool. There are three important factors involved in making a friction weld:

1. The rotational speed which is related to the material to be welded and the diameter of the weld at the interface.
2. The pressure between the two parts to be welded. Pressure changes during the weld sequence. At the start it is very low, but it is increased to create the frictional heat. When the rotation is stopped pressure is rapidly increased so that forging takes place immediately before or after rotation is stopped.
3. The welding time. Time is related to the shape and the type of metal and the surface area. It is normally a matter of a few seconds. The actual operation of the machine is automatic and is controlled by a sequence controller which can be set according to the weld schedule established for the parts to be joined.

Laser Welding

Laser as a source of coherent and monochromatic radiation, has a wide scope of application in materials processing (Steen, 1991; and Dutta *et al.*, 2003). Laser assisted welding, because of the sheer volume/proportion of work and advancement over the years, constitutes the most important operations among the laser joining processes Figure 5 shows the front view of the schematic set up for laser underwater welding with a filler rod (Kruusing, 2004). The focused laser beam is made to irradiate the work piece or joint at the given level and speed. A shroud gas protects the weld pool from undue oxidation and provides with the required oxygen flow. Laser heating fuses the work piece or plate edges and joins once the beam is withdrawn. In case of welding with filler, melting is primarily confined to the feeding wire tip while a part of the substrate being irradiated melts to insure a smooth joint. In either case, the work piece rather than the beam travels at a rate conducive for welding and maintaining a minimum Heat Affected Zone (HAZ). There are two fundamental modes of laser welding depending on the beam power/configuration and its focus with respect to the work piece: (a) conduction welding, and (b) keyhole or

Figure 5: Schematic of Laser Welding with a Filler Rod. Argon Shroud Removes Heat and Prevents Undue Oxidation and Displaces Water. The Relative Position of the Laser Focus Determines the Quality and Configuration of the Weld

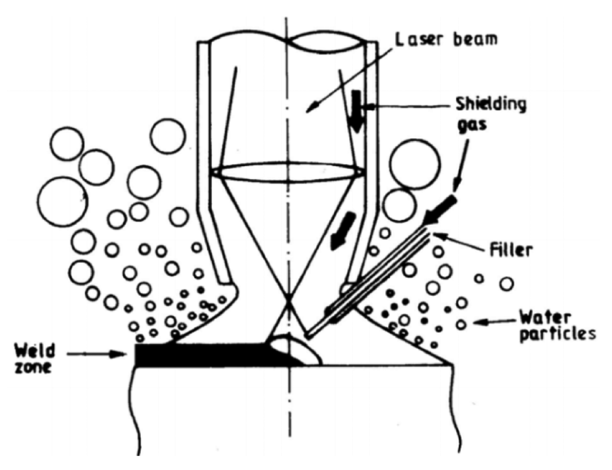
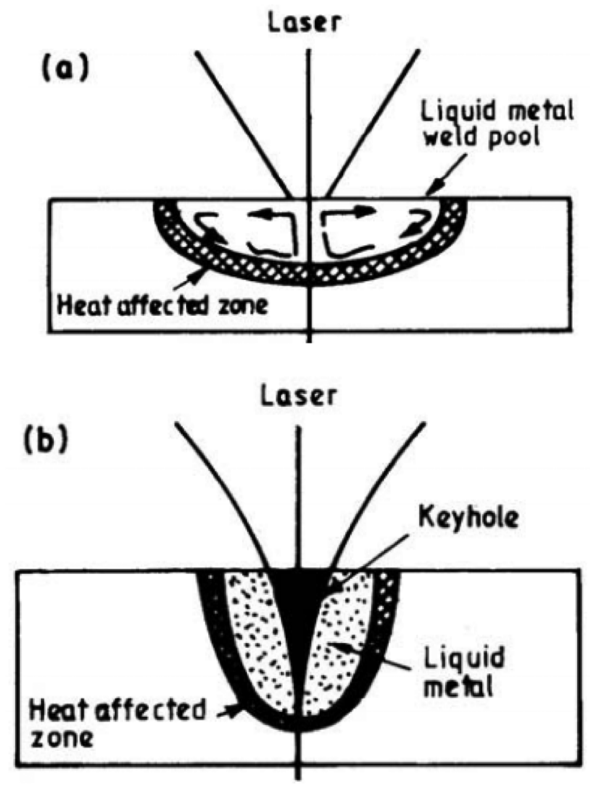


Figure 6: Schematic View of (a) Conduction Melt Pool, and (b) Deep Penetration Welding Mode. The Surface Boiling and Marangoni Effect are More in (a)



penetration welding (Figures 6a and 6b) (Dutta, 2003). Conduction limited welding occurs when the beam is out of focus and power density is low/insufficient to cause boiling at the given welding speed. In deep penetration or keyhole welding, there is sufficient energy/unit length to cause evaporation and hence, a hole forms in the melt pool. The ‘keyhole’ behaves like an optical black body in that the radiation enters the hole and is Underwater laser assisted welding compared to the other underwater welding methods (Irie *et al.*, 1997; Ogawa, 1998; and Ogawa *et al.*, 1998;) has the advantages of low heat input, easy to transfer energy and control adaptability. The low heat input is of significance for reducing of the sensitivity of stainless steels to Stress Corrosion Cracking (SCC). Underwater LBW has not been used in application, however, because a series of problems have not been solved yet. The plasma induced by the interaction of the laser beam and the metal vapor or the shielding gas in CO_2 laser assisted welding has shielding effect on the laser beam, but the plume induced in Nd:YAG laser assisted welding has not such shielding effect on laser energy transferring. No matter CO_2 or Nd:YAG laser assisted welding, the optical emissions induced in the welding process indicate the basic characteristics of the keyhole and the variation of welding parameters.

ULBW COMPARED TO GTAW

The filler metal used for Underwater Laser Beam Welding (ULBW) is the same as that for Gas Tungsten Arc Welding (GTAW), and is selected for suitability for the application and base material being joined. It is introduced into the pool created by the laser beam in a manner very similar to that seen in during welding with a gas metal arc welding machine (Figure 5). however, ULBW is a completely automatic welding process. In this respect, ULBW differs from GTAW performed with a machine, where the operator makes adjustments during welding (www.westinghousenuclear.com).

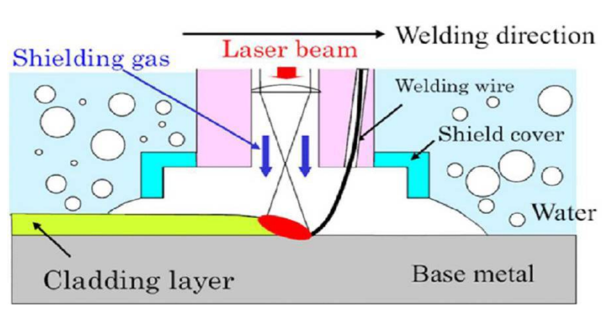
Reliable Weld Characteristics

The laser beam's precise heat input and dilution controls result in consistent weld quality. Weld chemistry testing shows high deposit purity as a result of the low heat input.

Various Application Uses

The optical fiber delivery of the laser light minimizes weld system complexity and allows weld heads to be developed for tight and remote applications. Being an automatic process also makes it ideal for use in locations such as the high-radiation areas found in nuclear power plants.

Figure 7: A Schematic View of Underwater Laser Beam Welding



A Schematic view of Underwater laser beam welding (www.westinghousenuclear.com).

FUTURE SCOPE

- Automation of the underwater joining and inspection of the welded structures.
- Mechanized underwater welding for actual usage of a very large floating structures.
- Investigation of the potential of using a robot manipulator for underwater ultrasonic testing of welds in joints of complex geometry.
- Application of advanced welding technique, like friction, laser welding and understand the behavior of materials after the welding and process optimization.
- Invention of new welding techniques and explore the possibility of its application in underwater welding.
- Generation of research data book on weld ability of materials during underwater welding.

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