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Fundamental Difficulties Associated With Underwater Wet Welding

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ABSTRACT
The offshore industries carry out welding activities in the wet environment. It is evident that the wet environments possess difficulties in carrying out underwater welding. Therefore there is the need to improve the quality of weld achieved in underwater welding. This paper investigates the difficulties associated with underwater welding. The objective of this research paper is to identify and analyze the different difficulties in underwater welding so as to make a clear background for further research to identifying the processes of eliminating these difficulties. The major difficulties in underwater welding are the cooling rate of the weld metal and arc stability during underwater wet welding at a higher depth. Methods of decreasing the cooling rate of weld metal and how to achieve arc stability are the major methods of approach. The result of welds achieved in underwater welding will be much improved as compared to air welding if the effects of the difficulties associated with underwater welding are eliminated. This will lead to a more robust welding activities being carried out underwater.
Keywords **–** Arc stability, Cooling rate, Porosity, Underwater welding, Water depth

I. INTRODUCTION

The increasing demand for oil and gas has led the oil and gas companies to explore into the deep marine environment. The desire to repair damaged offshore structures as a result of corrosive defects, material fatigue, accident during assembly, construction errors, excessive operational loads, has brought about underwater welding [1]. The first underwater welding was done by British Admiralty – Dockyard for the repair of leaking ship rivets. Most recently, a lot of underwater activities have been going on, for example, platform installation, pipeline welding, watercraft welding, seashore components and offshore structures welding [1, 2]. Underwater wet welding is one of the most common repair measure because of its relative low cost and and high efficiency.

The desired qualities of a sound underwater weld are flexibility of operation in all positions, minimum electrical hazard, good visibility, good quality and reliable welds. However, the quality of underwater welding is impeded by loss of alloying elements from the weld metal, porosity of the welds, slag in the welds, increase in carbon and oxygen content in the welds, and increased tendency to cracking [1, 2]. The reduction in the mechanical properties in underwater wet welding is because of the water environment in which the welding arc is operating. The ease to remove heat from the welded area and the decomposition of water during the welding process are critical factors responsible for poor weld quality during underwater wet welding.

Underwater welding is classified according to their physical and mechanical requirements that load bearing welds must satisfy. These specifications are according to AWS D3.6M:2010 underwater welding code. The three underwater welding specifications are A, B, and O. Each type fulfils a set of criteria for weldment properties which have to be established during welding qualifications, and also a set of weld soundness requirements that should be verified during construction. Class A is comparable to air water welding in terms of toughness, strength, ductility, hardness, and bending. Class B is for less critical application with limited structural quality, where both the test applied for procedure qualification and acceptance criteria are less strict. While class O is to meet the requirements of another designated code or specification [3].

Nowadays. The commonly used underwater welding processes are shielded metal arc welding (SMAW), and flux cored arc welding (FCAW). Steels with low carbon content (CE < 0.4) are preferable for underwater welding process, this is because the fast quenching medium hardens the heat affected zone (HAZ) and thereby making it susceptible to hydrogen cracking. Most underwater welding are either in vertical or overhead positions, and therefore maintaining joint coverage in a moving water environment is difficult [4, 5]. The Fig. 1 below summarizes the effect of welding process carried out underwater on the welded joint. These effects will be fully examined in the next chapters of this paper.

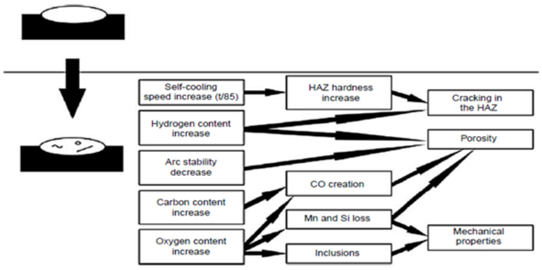

Fig. 1 The effect of moving the welding process to water environment [1].

II. COMPARING AIR WELD AND WATER WELDS

Underwater welding requires a higher current for the same arc voltage as compared to air welding so as to achieve a higher heat input. The weld bead size is quite similar for corresponding underwater and air welding. However, wet welding has a narrower weld bead and a higher reinforcement as compared to air welding. The general shape for air and wet welding does not appear to be significantly different. This means that the critical effect of the water only begins when the weld puddle starts forming and solidifies. The HAZ in underwater welds is reduced by 30 to 50% as compared to air welding, which suggest that heat dissipates rapidly from the weld bead into the base metal. Underwater welds bead shape are more spread out and less penetrating than air welds. The structure tends to change across the HAZ in underwater welding unlike the air welding which is more homogenous. The HAZ widths for air welding are 20 to 50% wider than the corresponding wet welding [6].

III. COOLING RATE AND SOURCES OF HEAT LOSSES IN UNDERWATER WELDING

The effect of rapid cooling for welds made underwater causes a change in the mechanical strength of the weld as a result of the fast cooling rate. The cooling rate is strongly affected by the welding procedure used as it relates to the heat input and weld joint design. Fast cooling can result in the formation of constituents such as martensite and bainite for welding conventional steels. These constituents are both high strength and brittle and are susceptible to hydrogen cracking. Cracking susceptibility is a function of weld metal microstructure, the weld metal microstructure is a function of hardenability and cooling rate. Fig. 2 shows the effect of welding heat input on the cooling time between 800 and 500 ^{0}C. The welding heat input for wet underwater welding is usually between 1.0 to 2.0 kJ/mm, and therefore having a short cooling time between 2 to 4 seconds. Fig. 3 shows that the cooling time decreases with increasing base metal thickness. However, there is a constant cooling time at 2 seconds for plate thickness above 15 mm [7]. Low welding speed is an effective way to reduce cooling rates in HAZ. Shielded metal arc welding (SMAW) for surface welding cools from 800 to 500 ^{0}C in the range of 8 to 16 seconds. Whereas typical wet welding for the same heat input range has a cooling range of 1 to 6 seconds depending on the heat input range of 0.8 to 3.6 kJ/mm and plate thickness [8]. One unique characteristics of cooling rate is that it is independent of the distance from the heat source especially in the HAZ [9]. The Fig. 4 shows the effect of cooling rate and distance to plate surface.

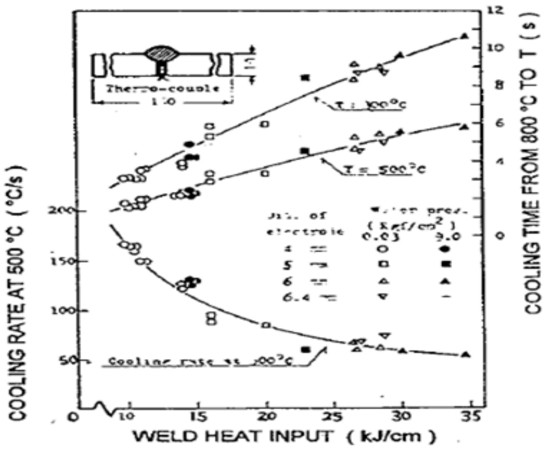

Fig. 2 Cooling rate vs heat input [12].

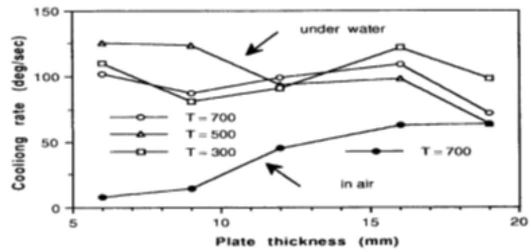

Fig. 3 Cooling rates for wet welding compared with welding in air [7].

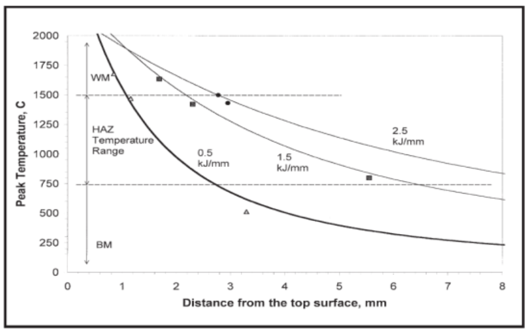

Fig. 4 Peak temperature profiles weighted and fitted for different weld samples; heat input values 0.5, 1.5, 2.5 kJ/mm [9].

Heat losses in air welding are from the molten surface outside the heat input circle which is basically due to radiation. The heat loss from the surface at some distance from the arc is due to natural convection. However, heat losses in underwater welding are mainly conduction heat losses from the plate surface into the moving water environment, the motion of the moving water is created by the rising bubble column in the arc area [10]. Formation of bubbles stirs up the water around the surface of the plate thereby increasing the heat transfer. The bubbles come together during the transition phase forming unstable film and thereby reducing the heat transfer. A stable film is finally formed which reduces the heat transfer to radiation [11]. Conduction and radiation account for the major heat losses in underwater welding.

The cooling rates of a wet SMAW welds are in inverse proportion to the thickness of the welded plate, up to a limiting thickness. The cooling rate increases at thickness above the limiting plate thickness level. This continues to a second limit above which cooling rates are approximately not affected by any increase in plate thickness as shown in Fig. 5. However, air welding demonstrates direct relationship to a limiting thickness value above which cooling rates are not a function of plate thickness [4]. The cooling rate increase with increase of plate thickness above the first limit because of higher conductive ability of the plate. Increasing the plate thickness beyond the first limit, makes the plate back side convection to decrease. Thermal insulation is a means of slowing the cooling rate in wet weld by slowing the rate of heat loss through convection to the surrounding water [4]. The difference in cooling rate between water welding and air welding is shown in Fig. 6A and 6B [6].

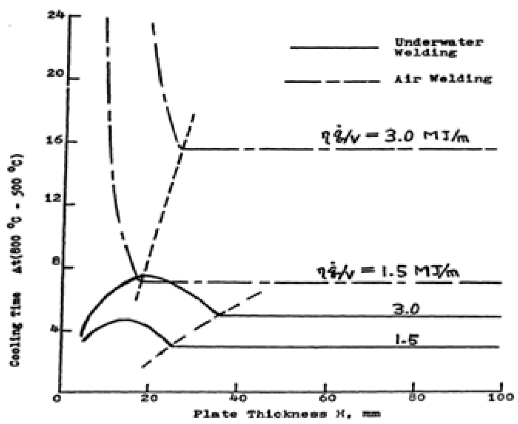

Fig. 5 Cooling time vs. plate thickness in wet and dry welds for two heat input values [4].

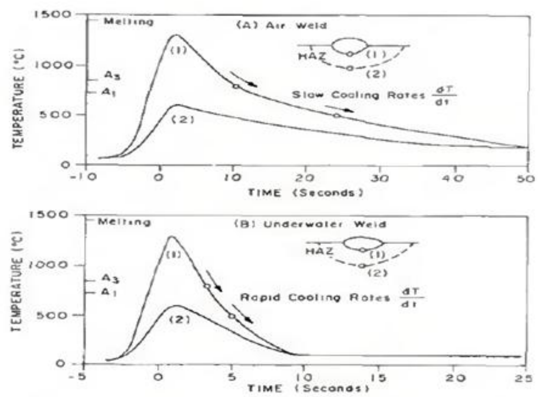

Fig. 6 Temperature histories of air welds compared to those of underwater welds [6].

IV. SOLIDIFICATION AND MICROSTRUCTURAL TRANSFORMATION

The mode and size of the solidification substructure affects the mechanical properties of weld joint. Achieving finer grains result in good weld joint properties and quality. This is achievable by controlling the welding parameters such as voltage, current, welding speed, and the welding environment which include air and water [13]. The molten weld pool in wet welding travels at a constant speed with the electrode. The weld puddle has tear drop geometry. The weld pool geometry is as a result of heat losses in the weld area behind the arc. The weld pool geometry affects the mode of solidification growth. This leads to the formation of coarse columnar grains which meet at the centerline. This grain type is susceptible to segregation and solidification cracking. The fast cooling rate during weld solidification leads to large amount of hydrogen in the weld pool to diffuse into the adjacent base metal and HAZ. Structural steel weld metal with microstructure such as martensite and upper bainite are more susceptible to hydrogen cracking. The formation of these phases in the HAZ is dependent on weld metal and base metal chemical composition, heat input and cooling rate, water temperature, and water pressure. The Fig. 7 shows continuous cooling transformation (CCT) diagram showing a bainite region with superimposed cooling curves. The obtained microstructure and corresponding temperature at which each microstructure will start and finish can be identified on the diagram.

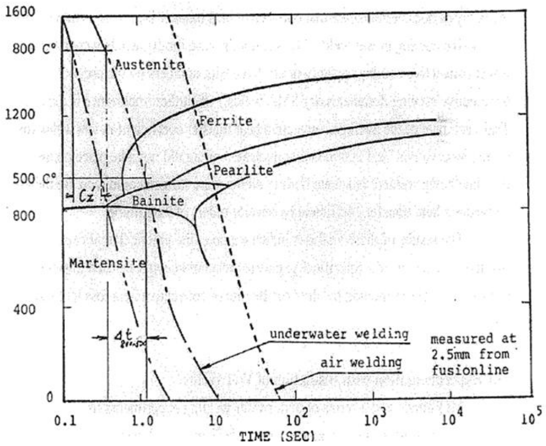

Fig. 7 CCT diagram showing a bainite region with superimposed cooling curves [14].

Acicular ferrite is a microstructural constituent that gives a high resistance to cleavage fracture and the formation of acicular ferrite is desirable in welded joint microstructure for improved toughness. It is possible to achieve acicular ferrite in underwater welds with the addition of alloying elements such as boron and titanium with the proper weld metal oxygen and manganes contents[8]. The Fig. 8 shows weld metal microstructure as a function of depth in underwater welding. The weld metal is basically grain boundary ferrite at shallow depth, with 10 to 20% aligned carbide. As the depth increases, the relative amount of grain boundary ferrite decreases to about 50%, and the amount of aligned carbide and sideplate ferrite increases. A drastic change in microstructure occurs in the first 50 m of depth. As the depth increases further from 50 m, the weld metal composition and microstructure remain fairly constant [8].

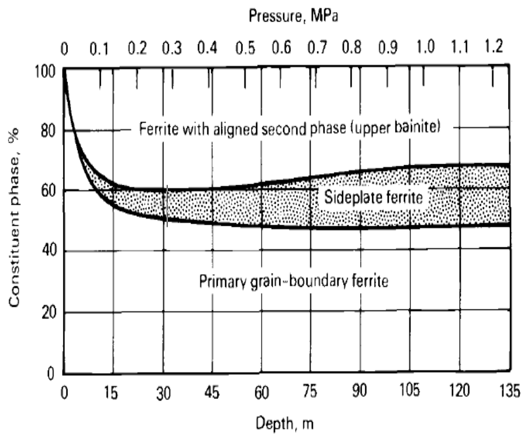

Fig. 8 Percentage of weld metal microstructural constituents for wet underwater welds as a function of water [8].

V. ARC STABILITY

The welding arc is constricted at increased water depth or pressure. However, welding in shallow depths is more critical than higher depth. But this is only to a certain depth of 1.5 to 6 m, where further increase in depth makes the arc unstable again. Unstable arc results in porosity. The electrical conductivity of the arc can be maintained with higher voltage. Although, this increase in voltage results in fluctuations in arc voltage, thereby porosity and slag are entrapped in the molten weld pool. It is evident that electrode diameter plays a role in arc stability with water depth and increase in current density. A smaller electrode diameter can increase the arc stability, an unstable arc affects the soundness of a weld done underwater [12].

VI. PRESSURE –INFLUENCE OF DEPTH IN UNDERWATER WELDING

The water environment affects the weld metal chemical composition. This is because of the decomposition of water which releases oxygen, hydrogen, and loss of alloying elements such as manganese and silicon. Manganese and silicon which are deoxidizers are increasingly lost at increasing depth or pressure as can be seen in Fig. 9. Increase in weld metal carbon content increases with depth due to carbon monoxide reaction when flux containing calcium carbonate is used. Welds carried out at greater water depth have lower densities. This is because of the formation of internal porosity. The shape of the pores changes from almost spherical to a more elongated one at depth between 20 to 30 m. the spherical pore is hydrogen concentration pore, while the elongated pore is bubble type pore [8].

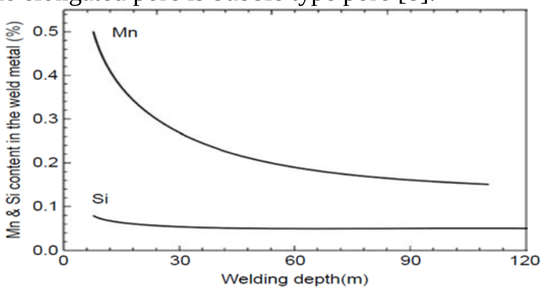

Fig. 9 Influence of depth of underwater welding on the content of elements in the weld deposit [1].

VII. DISCUSSION

The Fig. 10 below shows how hydrogen is diffused from the weld metal to the HAZ during welding. From the figure TF is the transformation of the weld metal from austenite into ferrite and pearlite while TB is the transformation from austenite to martensite. Hydrogen in the TF phase is rejected and moved to the TB phase because austenite cannot absorb hydrogen and hydrogen is soluble in ferrite. The base metal has higher carbon content than the weld metal because the filler metal usually has lower carbon content. And in that case, the HAZ is transformed from austenite into martensite after the weld metal has transformed from austenite into ferrite and pearlite [15]. For hydrogen induced cracking to occur, low temperature due to the fast cooling rate of the weld metal by the surrounding water helps in the formation of martensite and the presence of hydrogen from the decomposition of water.

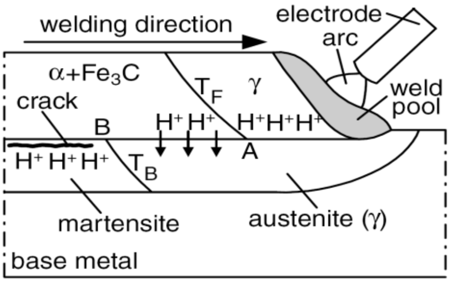

Fig. 10 Diffusion of hydrogen from weld metal to HAZ during welding [15].

Experimental evidence shows that underwater welds have increased strength and decreased ductility. Underwater welds show strength increase from 6.9% to 41%, while ductility decreases about 50% for most weld assemblies. This examination is in terms of the base steel material, weld orientation and corrosion of base steel material [16]. The effect of water environment on strength and ductility is shown in Fig. 11 which compares the strength and ductility for different base material welded underwater and in air. The shape of the base material whether the base plates are flat sheet pile or curved pipe do not have an influence on either the strength and ductility. However, the chemical composition differences have a significant influence on the strength and ductility.

A change in the orientation in the weld affects the mechanical properties of fillet welds. A change in the orientation for welds on SY295 indicates that changing the orientation from transverse to longitudinal direction, will increase the strength and decrease ductility from 24% to 41% and from 28% to 61% respectively. However, longitudinal fillet weld are more sensitive to wet welding environment with increase in strength of 29% and decrease in ductility of 65% on average, while transverse fillet weld with a strength increase of 20% and ductility decrease of 49%.

Underwater welds on corroded SY295 steel exhibit strength increase of 22%, and a huge decrease in ductility of 83%when compared with air welding [16].

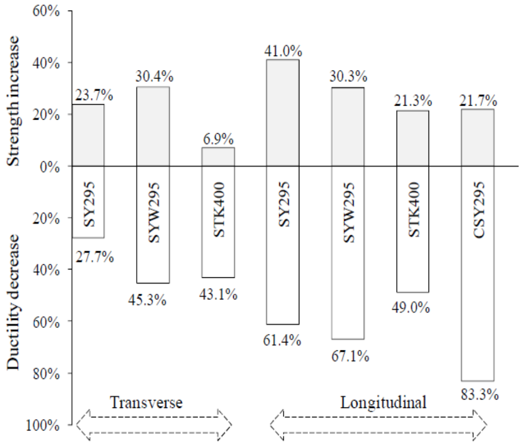

Fig. 11 Relative changes of strength and ductility from air welds to underwater welds [16]

VIII. CONCLUSION

Rapid quenching causes steep thermal gradient and high residual stresses which increases the weld susceptibility to crack initiation when loaded. Fast cooling also increases weld bead convexity reinforcement and thereby making welds more susceptible to toe cracking.

The influence of increased water depth on arc stability and loss of alloying elements, as well as fast cooling rates are important factors when considering an improvement strategy of welds done underwater.

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