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Welding processes of metals for offshore environment: Underwater welding

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ABSTRACT

Offshore welding is important in the fabrication process of sophisticated offshore structures with a wide range of materials such as steels and alloyed steels to withstand the harsh and corrosive environment during the exploitation of oil and gas offshore. In this literature study, offshore welding was investigated in three perspectives such as welding process environment, applicable materials for offshore environment and suitable modern welding technologies for underwater welding of offshore structures. The first finding shows that on-board welding, dry dock welding and underwater welding are the main forms of welding process environment offshore. The second finding also shows that thermo-mechanical control process (TMCP) steels could be used for constructing pipelines and offshore structure. Moreover, materials such as 22 Cr and 25 Cr duplex and 6 Mo stainless steels, nickel base austenitic alloys and titanium alloys could also be used for offshore structures since they possess excellent weldable properties, high fracture toughness, high strength, and can also fight against the corrosive environment offshore. However, the third finding which pertains to suitable modern welding technologies for underwater welding of offshore structures was justified by examining the defects conventional welding processes such as shielded metal arc welding (SMAW), flux-cored arc welding (FCAW), gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) have posed on offshore structures and the defects modern welding technologies such as friction stir welding (FSW), laser beam welding (LBW) and Hammerhead "wet-spot" welding could pose on offshore structures. It was therefore evident that underwater welding with conventional welding processes produces more weld joint defects as compared to modern welding technologies. The afore-mentioned finding was further justified by examining the weld joints produced by the said modern welding technologies through tensile test, hardness test and fracture toughness test. It was shown that the strength values of the weld joints in FSW, LBW and Hammerhead "wet-spot" welding were similar to the base materials employed as samples in the experimental welding process. This implies that friction stir welding (FSW), laser beam welding (LBW) and Hammerhead "wet-spot" welding produces fewer or defect-free weld joints and exhibit excellent quality welds as compared to conventional welding processes, hence could serve as suitable modern welding technologies for underwater welding of offshore structures.

Keywords: Offshore Welding, Underwater Welding, Modern Welding Technologies, Offshore Structures, and Offshore Materials.

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1. INTRODUCTION

In recent times, the demand to fabricate sophisticated offshore structures with a wide range of materials such as steels and alloyed steels to withstand the harsh and corrosive environment offshore and the need to carry out repair and maintenance work on offshore structures installed underwater is increasing. This is as a result of the tremendous increase in demand of energy sources from resources in the offshore environment which have been under-exploited in certain regions and those that are depleting. Vast amount of oil and gas resources are found offshore, and Russia for example, being one of the world's leading oil and gas producers, has offshore resources constituting about 85 trillion cubic meters of natural gas and 15.5 billion tons of oil reserves [1]. It has also been observed that the Far Eastern, Eastern Siberia and the Arctic regions such as the Barents Sea and the Kara Seas which were once out of reach of human activities as a result of the severe climatic factors now prove to be potential locations for large-scale offshore developmental projects [2]. As offshore environments are known to be remote, hostile and characterized by extreme temperatures, seasonal darkness, windy and icy surroundings [3], tapping resources from such environment for global energy market stability requires stringent implementation of effective and safety measures, as well as the selection of suitable modern welding technologies and offshore structural materials for the entire fabrication process.

Actually, selecting materials for the construction of offshore structures such as pipelines, jacket platforms seem very challenging. Operating condition is therefore an essential factor to consider and also the compatibility of the mechanical and electrochemical processes amongst the different offshore materials [4]. A typical example can be sited on the Arctic region where the operating temperature ranges from -40 ^{0}C to -60 ^{0}C [5]. These fluctuations in temperatures have an extreme influence on the materials. In addition, material selection takes into account the entire cost of the offshore structural members. Nevertheless, choosing cost effective materials for economic viability requires the consideration of factors such as strength level, fracture toughness, availability, weldability and machinability. Structural steels such as API 2H, 2Y, 2W and others which fall under industrial standard such as ASTM, BSI, and ISO have been used for a long time for the construction of offshore structures due to its low cost and ability to satisfy the requirements at operating temperatures as a result of its toughness and fracture resistance [4,5].

Generally, as most offshore structures are built and conveyed from onshore sites for installation in the offshore environment [6], conventional welding processes seem to be the main joining process. On the other hand, bolted and flange mechanical connections have been used as joining techniques for offshore structures especially for subsea installation. These joining techniques yielded a number of uncertainties in the range of 10 to 30% and had adverse effects on the Norwegian oil and gas industry. Technical reports documented by the Norwegian Oil Industry Association (OLF) [7] shows that, the Norwegian Continental Shelf has suffered immensely from gas and oil leakages to a significant number of about 25% between the periods of 1994 to 1998 due to problems related to mechanical connections. The need for improvement and development brought about the use of standardized integrated bolted flange joints and flange connections such as API RP 14E, ASME/ANSI B16.5a and ANSI-flanges and SPO-flanges/compact flanges respectively [7]. Further limitations in the use of these joining techniques brought about the commercialization of conventional welding processes owing to reliability and versatility factors. Conventional welding processes are therefore employed for onshore and offshore welding of offshore structures especially in girth (circumferential) welding of offshore pipelines. Huge amount of offshore projects have been implemented successfully by utilizing these conventional welding processes since high percentage of the offshore platform structures are made of weldable steels [5, 7]. It is therefore factual that, the contribution of some conventional welding processes in the construction of offshore structures has been satisfactory to some extent.

In addition, it has been observed that conventional welding processes such as submerged arc welding (SAW), gas metal arc welding (GMAW), shielded metal arc welding (SMAW), and flux cored arc welding (FCAW) have been used for underwater welding of offshore structures. These processes in a way have not benefited the oil and gas industry to the fullest due to problems and associated defects experienced in the underwater environment. Although to some extent all welds have imperfections and can be improved through corrective measures, the weld joints made from conventional welding processes on offshore structures undergo some defects since the imperfection in such welds exceeds a given set of dimension as a result of unfavorable factors such as operating conditions, normal usage and unpredictable natural occurrences including vibrations, collisions and storms. These defects, resulting from imperfections, such as hydrogen cracking (cold cracks), hot cracks, porosity, lack of fusion, slag and slag-lines, crater cracks (end cracks), lack of penetration, burn through, undercut, etc. have led to some catastrophic failures of offshore structures globally [7, 8].

However, to help combat failures in offshore structures installed underwater, it is therefore salient to employ modern welding technologies suitable for underwater welding of offshore structures and also suitable for repair work, maintenance as well as replacement works since most offshore structures are ageing. Current research papers have brought to the lime light a number of modern welding technologies which are of higher preference to conventional welding processes for underwater welding of offshore structures. The use of friction stir welding, stud welding and explosive welding have been noted as options for underwater welding [9]. Other researches propose the use of laser welding and friction stir welding [10] as well as the use of hammer head "wet spot" welding for underwater works [11].

This paper therefore investigates and suggests suitable modern welding technologies which could be applicable for underwater welding of offshore structures. This research work consists of six sections. The first chapter introduces the objectives and research questions aimed for this work and present the concepts of offshore welding in general. The second chapter highlights the most common and new offshore structures and the materials suitable for constructing these structures. In the third chapter, conventional welding processes and its associated defects are presented. The fourth chapter delves into modern welding technologies applicable for underwater welding of offshore structures. The findings obtained from the said chapters are discussed in the fifth chapter. Conclusions with regards to the contents of this paper are finally drawn in the sixth chapter.

1.1 Research Objectives and Research Questions

The first objective of this paper is to clarify the different forms of welding process environments being employed offshore. To reach this objective, this paper seeks answers to the first research question:

1. What differences exist between on-board offshore welding, dry dock welding and underwater welding, and what are the classifications under these welding process environments?

The second objective is to present materials applicable to the offshore environment and also the types of structures installed in the offshore environment. This objective gives rise to the second research question:

2. What are the classifications of materials applicable to offshore, and what are the various types of structures installed in the offshore environment?

The third objective is to investigate suitable modern welding technologies applicable for underwater welding of offshore structures. This objective could be reached by considering these research questions as follows:

3. Which common welding processes have been used for underwater welding of offshore structures, what are the observed defects, and why are they still in use in the offshore environment?

4. Which modern welding technologies could be used for underwater welding of offshore structures and why?

1.2 Research Methodology

The research questions presented above address new solutions to existing challenges in the oil and gas industry operating in the offshore environment. In order to achieve the said objectives and answer the research questions constructed for this academic research paper, a literature review approach was used to serve as a foundation and support for the new suggestions and proposals. In this sense, highly ranked journals, articles, conference papers, and handbooks were studied, evaluated, discussed and presented in this paper.

1.3 Motivation for the Research Project

The motivation for this project work is as a result of the current challenges confronting the oil and gas industry operating in the offshore environment. The aggravated demand of oil and gas on the world market poses a lot of pressure on the oil and gas industry and as it can be observed, most oil and gas reserves are drying out of resources and newly discovered sites for oil and gas exploitation happen to be offshore with severe climatic conditions.

Tapping resources from these locations is very challenging. The arctic region can be sited as a typical example. Offshore companies are also going far into deepwater exploitation of oil and gas. Research has shown that some welding processes have been used in the offshore environment which has led to defects and serious failures. This simply implies that not all the welding technologies are applicable in the offshore environment. In addition, it has been observed that, offshore structures installed years ago needs repairs, maintenance and replacement since these structures have been susceptible to defects.

To achieve the aim of meeting the world's oil and gas demand as well as combating failures leading to catastrophe offshore due to environmental conditions, there is the need for sophisticated offshore structures to be constructed for oil and gas exploitations and also withstanding the environmental challenges. Furthermore, there is also the need to investigate into modern welding technologies suitable for materials for offshore structures and especially underwater welding technologies.

1.4 Scope

This project work focuses on modern welding technologies employed in the offshore environment. As stated early, offshore welding process environments can be categorize in three forms. These are on-board offshore welding, dry dock welding and underwater welding. In this report, much emphasis would be laid on underwater welding technologies since in the authors view, less research work has been carried out in this field and this calls for critical attention and consideration.

1.5 Offshore Welding

The completion of the first historical offshore well in the Gulf of Mexico at 4.6m depth of water in Louisiana in 1947 by Kerr-McGee marks the origin of the offshore industry [8]. Offshore projects have thereafter been carried out at water depth ranging from 20 – 500m [12]. Exploiting oil and gas resources from such water depths and distances off the sea-shore therefore requires the installation of structures which can withstand the operating conditions and the environmental factors. These attributes have brought the necessity for the construction of sophisticated offshore structures, some of which are platforms and pipelines to facilitate the exploitation processes offshore. As mentioned earlier, most offshore structures are fabricated and transported from the shores of the sea and installed offshore by means of joining processes of which welding processes are considered paramount.

However, in the history of the offshore industry, metals have been the most valuable materials for offshore structural and production applications. Welding processes carried out on these metals away from the sea shore can be termed as offshore welding. It has been estimated that the geotechnical depth ranges of water offshore as shown in figure 1 are: shallow water/near shore (< 20 m), offshore (20 – 500 m), deepwater (500 – 1500 m), and ultra-deepwater (> 1500 m) [12]. However, owing to the extreme harsh conditions offshore, there have been a lot of technological developments to bridge the gap between challenges existing between offshore materials, operation conditions and welding processes. Offshore welding therefore consists of three welding environments such as on-board welding, dry dock welding and underwater welding.

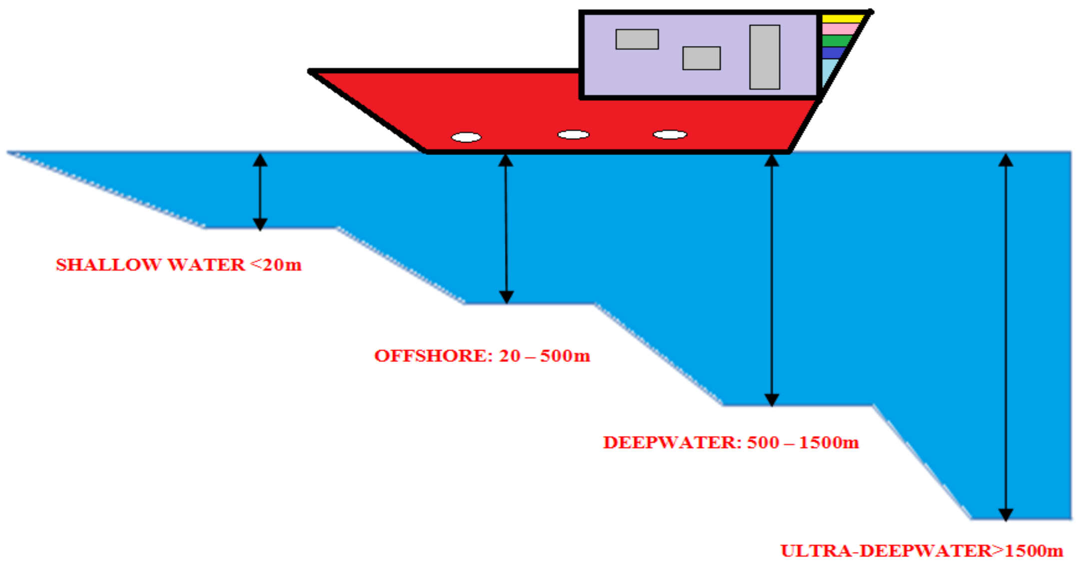

Figure 1: Geotechnical depth ranges in the offshore environment.

On-board welding describes an offshore welding process in an environment whereby offshore structures are welded in specially enclosed workstation. Welding is often done on a lay-vessel [13]. Materials to be fabricated such as pipelines are transferred from storage areas to the workstations by the help of special conveyer systems. Pipelines are beveled to the right dimensions and aligned face-to-face for a particular welding process to commence. Mostly, these welding processes are automated. In this respect, five welding passes are performed on the pipelines. The sequence is as follows: root welding, hot pass welding, fill one welding, fill two welding and capping [14].

The concept of **dry docking** has been opted as one of the expensive ways of welding defective structures such as pipelines offshore since it provides a dry out-door welding environment. Dry docking explains the process of pulling defective components under water above sea level for inspection, maintenance and repair works to be done [15-17]. Before welding is carried out on a defective pipeline, protective covers and anti-corrosion coatings are chipped off and the surfaces cleaned [18, 19]. A particular welding process is initiated and after welding, the protective materials are applied on the pipeline and finally submerged onto the seabed [20]. Figure 2 depicts how dry dock welding is carried out offshore. Pipelines are lifted above the water level by means of strings and cranes and are made to dry before the commencement of the welding process. This process is time consuming but on the other hand helps to ensure proper protection to the weldments made as compared to underwater welding.

Figure 2: Dry Dock welding process [14].

Underwater welding describes the process of welding offshore structures in an environment surrounded by water. Underwater welding is therefore used synonymously with the term hyperbaric welding. In the mid-1970, wet hyperbaric welding was launched in Norway [21]. Welders were housed in an enclosed chamber to perform welding tasks underwater in the wet environment. However, due to technological shift and the increase in depth of water as to exploit oil and gas, dry hyperbaric welding was introduced to serve as a remote welding practice. Welders are housed in habitats and welding tasks are performed in dry environment. Underwater welding has been applied diversely in the offshore industry. These include: construction of offshore structures for harnessing sea resources, salvaging vessels sunk in the sea, repair works due to collisions or unpredicted accident of ships, oil rigs, and barges [22]. However, as most offshore structures are installed in water, the salinity nature of the water (sea water) and other factors reacts with these structures [23]. Corrosion is one of the common defects which attack offshore structures by eating away some part of the materials which creates pores and rust which in a long term could have an adverse effect on the structures. Offshore structures installed underwater decades ago are therefore susceptible to these attacks. Underwater welding stands in this way to terminate these defects from getting worse. Research has shown that, underwater welding is one of the frequently used techniques for repair and maintenance works of offshore structures underwater [22].

However, due to the corrosive nature of this environment, it is a major concern of the offshore industry as to which underwater welding classification and welding technology could be used optimally to eschew detrimental defects in future. The following sub-chapter presents the various classifications of underwater welding employed in the offshore industry.

1.6 Classification of Underwater Welding

Underwater welding, as the name implies is the process of welding offshore structures where the presence of water is prominent. Underwater welding processes are often carried out in either the splash zone or the deep water zone. The splash zone is a shallow depth level covered intermittently by water as a result of movement of tidal waves of the water. It has been observed that, most offshore repairs and maintenance work are carried out in the splash zone due to the frequent occurrence of collision between ship, barges, vessels and platforms [10]. On the other hand, deep water zone describes the region about 1000m below the surface of the water [24]. Current research has shown that arc welding processes have been used at water depth of 2,500m [16]. Collision rate in this region is very rare since pipelines installed in this region are far from the water surface. A defect such as rusting is rather usual in this region since the environment is severely corrosive. Even though repairs and maintenance works in deep water region seem tedious, underwater welding happens to be of extensive economical merits, because welding in this region surpasses the need to pull out defective structures underwater to the water surface for dry docking or on-board welding, hence it is cost effective and time saving [10].

On the other hand, underwater welding involves a lot of risk and challenges. The operation conditions are very tough and severe [4] resulting in higher pressures [10] of about 0.1MPa or 1bar for each 10m increase in depth [25]. Structures in this region are therefore prone to metallurgical changes due to the cold temperature of the water. Research has shown that, the difficulties in underwater welding is as the result of the presence of hydrogen in the weld, higher cooling rates and higher water ambient pressure [26, 27]. The tendency of explosion could occur since arcs produced could evolve as a mixture of hydrogen and oxygen pockets. Additionally, the health of divers is of high risk since nitrogen could be diffused into the blood stream [10].

However, owing to the merits and demerits of underwater welding both in the splash zone and in deep water zones, classifying underwater welding is of a great necessity. It provides the means to select suitable welding processes for the right class of underwater welding. In this regard, it is very relevant to note that, not all underwater welding classes are suitable for a particular welding process. Thus, the suitability of the welding process is also of a concern in relation to the underwater welding environment and the class. Moreover, underwater welding classification serves as a guide to welders as to which consumables are appropriate for a particular task. A successful weldment can be made underwater when the best welding processes and the right classification of underwater welding is chosen.

Even though there is still room for developments and investigations to be done in underwater welding of offshore structures, there have been a number of researches under this respect. Research conducted in this field has shown that underwater welding may be classified into two main types. These are wet welding and dry welding [9, 28]. Figure 3 shows the different types of underwater welding employed offshore. It can be seen that in wet welding there is direct contact with water during the welding process whiles in dry welding water has been evacuated or shielded from the welding process.

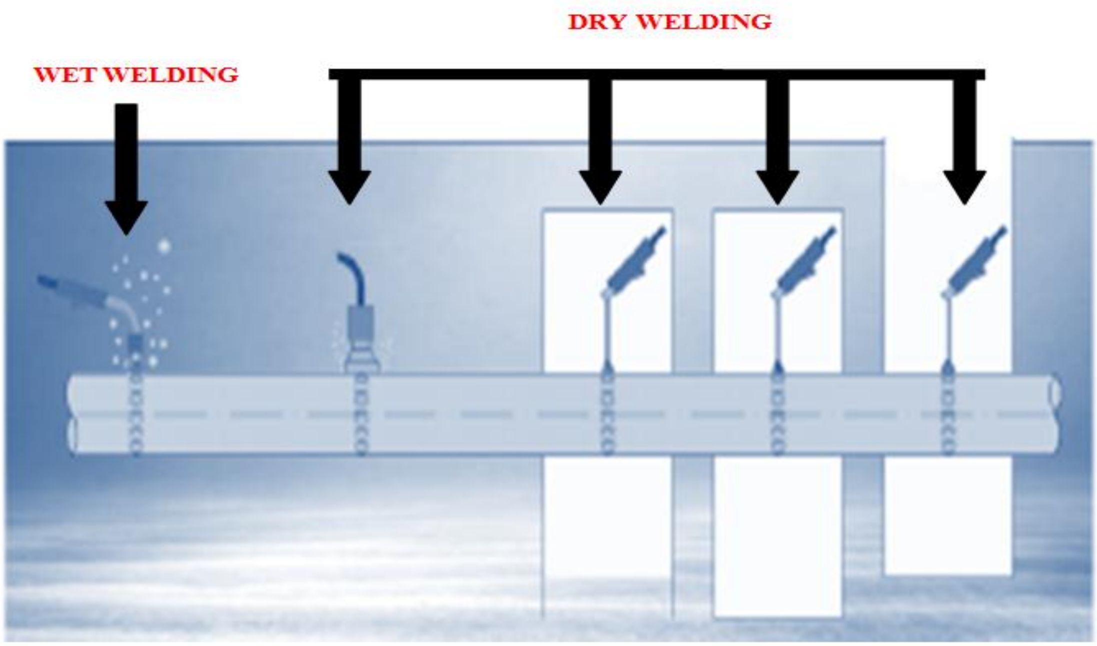

Figure 3: Underwater welding techniques [24].

1.6.1 Wet Welding

Offshore structures such as pipelines have been fabricated by means of wet welding techniques. Wet welding is a phenomenon where by welding is performed at ambient water pressure usually with water-proof stick electrode [28]. Welding is carried out manually by divers/welding at shallow depths. Because there is no obstacle between the welding arc and the water, it is easy to weld sophisticated geometrical structures [28, 29].Wet welding has been considered to be economically viable due to its versatility in comparison with dry docking and dry welding [29]

[30]. Initial setting of complicated equipment is not needed, hence applicable to emergency situations such as performing welding patches on leaking pipelines [10].

However, the notable downsides of wet welding have raised a lot of concern and the need for development and improvement. The quality of welds made through wet welding technique has not been efficient enough due to the increase in porosity, reduced ductility, and hydrogen cracks. Porosity in underwater wet welding is achieved as a result of increase in depth of water where molecular hydrogen, carbon monoxide or water vapor is the primary cause [31, 32]. Ductility of weldment is also reduced since the cooling rate in wet welding is rapid as compared to that in dry welding. A cooling rate of 415 ^{0}C to 56 ^{0}C may be achieved instead of 800 ^{0}C to 500 ^{0}C [27]. The presence of hydrogen also causes hydrogen pores and cracks in the welds as well as contributing to embrittlement in the heat affected zones [33].

1.6.2 Dry Welding

Dry welding, also termed as dry hyperbaric welding, is an underwater welding technique where welding is performed at elevated water pressure in dry environment. Welding with this technique is mostly done when the water depth is very high. It has been found that, dry welding may be achieved through five different forms [28]:

1. Dry habitat welding

   This describes the technique of welding offshore structures in a large chamber at ambient water pressure. In this process, water is forced out of a chamber so as to obtain a dry atmosphere where welders/diver needs not to be in diving gears.

2. Dry chamber welding

   The process of dry chamber welding is also done at ambient water pressures utilizing a simple open-bottom dry chamber. The chamber is made in a way to house the head and shoulder of the welder/diver. However, full diving gear is worn during the welding process.

3. Dry spot welding

   This welding technique is done in a small transparent gas filled enclosure at ambient water pressure. The welder/diver in full diving gear has direct contact with the water except the arm performing the welding process is housed in the enclosure.

4. Dry welding at one atmosphere

   This describes the technique of welding underwater where by welding is done at one atmosphere. External ambient water pressure has no effect on the welding process. Other research paper defines this welding technique as a local cavity welding [26].

5. Cofferdam welding

   This welding technique is performed at one atmosphere inside a closed bottom, open top enclosure.

Weldment made under the technique of dry welding has no direct contact with water during the welding process. The dry atmosphere ensures stability in the welding process, eliminates or minimizes the occurrence of hydrogen and oxygen in the weld, ensures an appreciable cooling rate of the weld and base material restores weld strength and ductility considerably. The quality of weld obtained from dry welding is much better as compared to wet welding. In addition, the weldment made under dry welding can be protected much better as compared to wet welding, because in dry welding the welding environment is much similar to air welding (onshore welding, on-board welding, and dry docking). On the other hand, sealing and maintaining of pressure in the hyperbaric chamber has been a major challenge [10].

2. OFFSHORE STRUCTURES AND MATERIALS

The entire fabrication and installation process of offshore structures involve numerous joining processes. Selecting materials for such construction of offshore structures is very vital and demanding due to the fact that, these sophisticated structure should be weldable, withstand the harsh environmental conditions, as well as the effects from pressure and forces from wind and ocean waves offshore. This chapter highlights the common structures which are installed offshore and the materials which are fabricated into offshore structures.

2.1 Offshore Structures

The predominance of metals in the manufacturing industry has facilitated the easy construction of sophisticated and demanding components, of which offshore structures are beneficiaries. Offshore structures have been explained by researches as structures installed in water either on the seabed or floating on the seabed without anchorage to dry land and, to withstand harsh environmental conditions [34, 35], as well as static and dynamic loads [34]. The static and dynamic load arises from hydrostatic loads, current loads, gravity loads, deck loads and wind and tidal waves respectively. Other environment effect causes offshore structures to fluctuate in response to motion of the structure and waves exerting on it [34].

However, in the quest of harsh environmental conditions, offshore structures have also been installed in the Arctic region even though the susceptibility of weldments made from metals at low temperatures in the Arctic region (-40 ^{0}C to -60 ^{0}C) yields in brittle fracture [5]. As most offshore structures are composed of welded tubular joints with sophisticated design with respect to shape and size [36], factors such as high load carrying capacity, impact strength, fatigue property, low temperature toughness, and corrosion resistance should be satisfied [37].

Due to the sophisticated design of offshore structures in terms of joint geometry and shell behavior, non-uniform distribution of local stresses and response to load occurs in the welded tubular joints surface and through the joint thickness. This phenomenon results into stress gradient and sites of stress concentration normally along the chord and brace weld toes. Structural failure is bound to occur when these stress concentrations yield fatigue cracking [36].

It has also been noted that, the sources of stress in tubular welded joints originate from normal stresses, geometric stresses and notch stresses. When tubes of welded joints behave as beams and columns, a normal stress is said to occur. Geometric stresses originate from the differences in response to load of braces and chords under the loading configuration, hence causing the tubes to bend. Notch stresses occur at the weld toe due to notch effects or discontinuity in geometry of the tube walls [36].

In order to avoid or minimize these effects, the selection of materials for the construction of offshore structures should be considered carefully and critically. Also welding processes and techniques should be chosen through efficient evaluation.

Additionally, offshore structures are categorized either by function or configuration. Exploratory Drilling structures (A Mobile Offshore Drilling Unit [MODU]), Production structures (processing, drilling, workload, accommodation, oil storage, and riser support) and Storage Structures are the notable functions of an offshore structure. A structure could serve multi-functions depending on operation needs. Offshore structural configurations are fixed structures, either piled or gravity, a compliant or articulated structure, or a floating structure [35]. In the interest of this paper, only fixed and floating offshore structures will be described.

2.1.1 Fixed Offshore Structures

Fixed offshore structures are mainly constructed from welded steel tubular members and serve as a platform to facilitate oil and gas production. Fixed offshore structures can be classified under bottom-founded (piled) structures or gravity base structures (GBS). The construction of bottom-founded (piled) structures are such that, the cross members behave as a truss so as to support the weight of the entire structure, processing equipment, and the environmental effects which may arise from dynamic and static loads from wind and tidal waves [8, 35]. This constructional design helps in achieving the "lowest natural frequency of flexural motion which surpasses the highest frequency of significant wave excitation" [8]. On the other hand, the construction of gravity based structures is based on the weight of the structure, hence needs no additional piles to stay in position.

Jacket platform is one of the common fixed offshore structures. It is constructed of welded steel tubular members of small diameter to form a space frame for drilling and production purposes. The fabrication process is done onshore and afterwards transported on barges to installation sites. Positioning the jacket platform could be assisted by grouted piles if it is bottom-founded. Some jacket platforms have been constructed as gravity based. Figure 4 illustrates a gravity based fixed offshore jacket platform. It can be seen that, the base of the jacket structure consists of huge storage cells made of either steel or concrete cement to carry the weight of the whole jacket platform. A typical example of a gravity based jacket platform structure is the one located in the UK Maureen field made of steel [8]. In addition, figure 5 depicts a bottom-founded fixed offshore jacket held in place by grouted piles. Considering the two types of fixed offshore structures, it can be said that the choice of a particular fixed offshore structure is dependent on load carrying capacity in relation to operational factors such drilling, and pipeline laying.

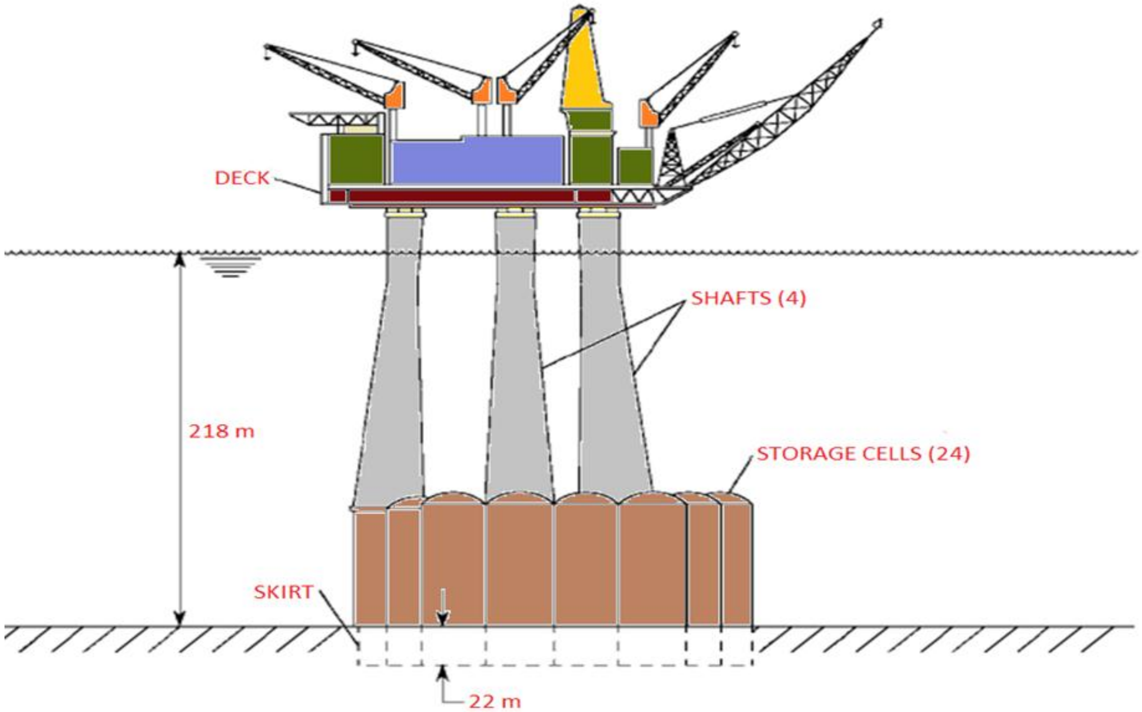

Figure 4: Gravity based fixed offshore jacket platform [13].

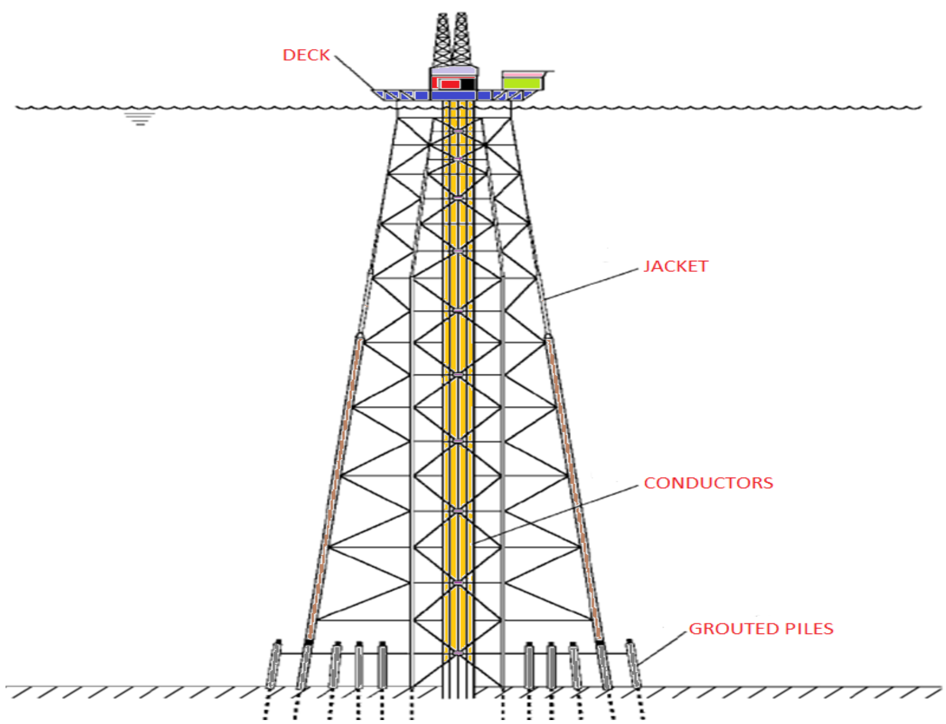

Figure 5: Bottom-founded fixed offshore jacket platform [13].

However, the use of fixed offshore structures has not been economically and technically feasible recently in the offshore industry. This is as a result of the depleting shallow depth oil and gas reserves. Exploitation has therefore shifted from shallow water depth to deep water depth. Offshore structures such as complaint or floating structures have been developed to meet this challenge [8]. Figure 6 illustrates the technological shift from fixed offshore structures to complaint or floating offshore structures. It can be seen that, the depth of water keeps increasing with respect to time. Owing to this factor, the lengths of the jacket platforms have to be increased to reach the seabed which seems un-attractive in terms of cost.

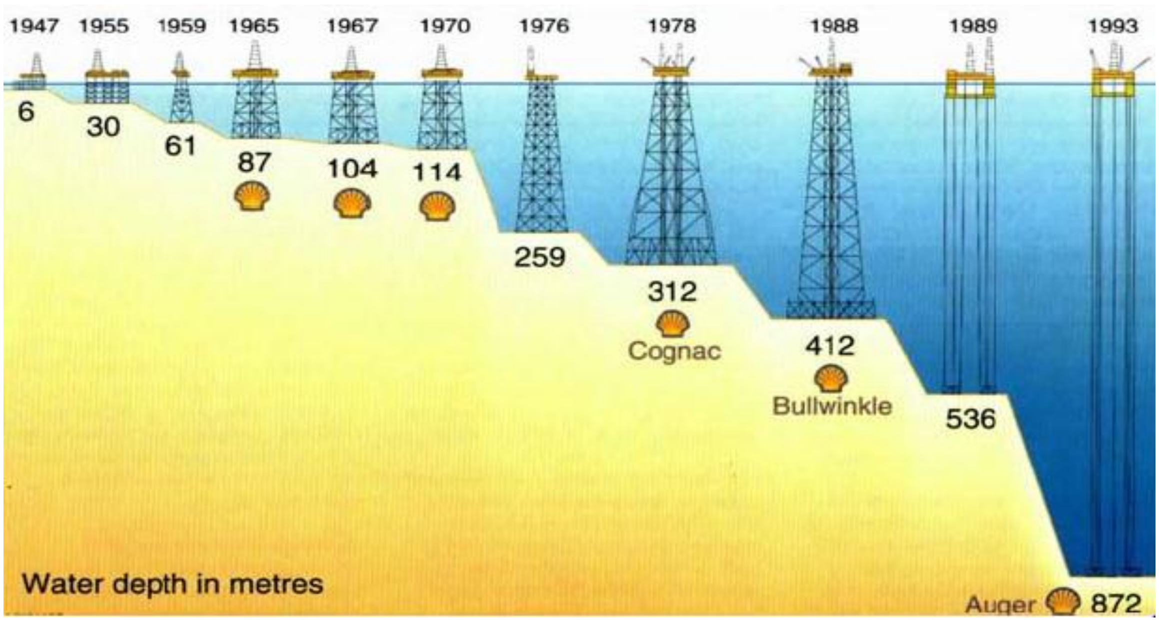

Figure 6: Historical development of fixed offshore structures [35].

2.1.2 Floating Offshore Structures

Floating offshore structures have been developed extensively in recent times to bridge the gap which existed between the exploitation of oil and gas from shallow water depths to deep water depths. These structures are categorically noted as floating production and storage offloading (FPSO), semi-submersible, tension leg platform (TLP) and Spar [38].

- FPSO – serves as a huge waterplane area for process and storage facilities.
- Semi-submersible – serves as a small waterplane area for drilling and to workover wet tree wells.
- TLP – serves as a waterplane area for drilling and workover with dry tree wells.

- Spar – Consists of a very deep draft and a small to moderate waterplane for drilling and workover dry tree wells.

Figure 7 shows the various types of floating offshore structures employed offshore. It can be see that there is higher flexibility during operation because oil and gas beneath the seabed can be exploited irrespective of the depth. Also transporting these structures to different exploration site can be done with ease since external vessels are less required in this process.

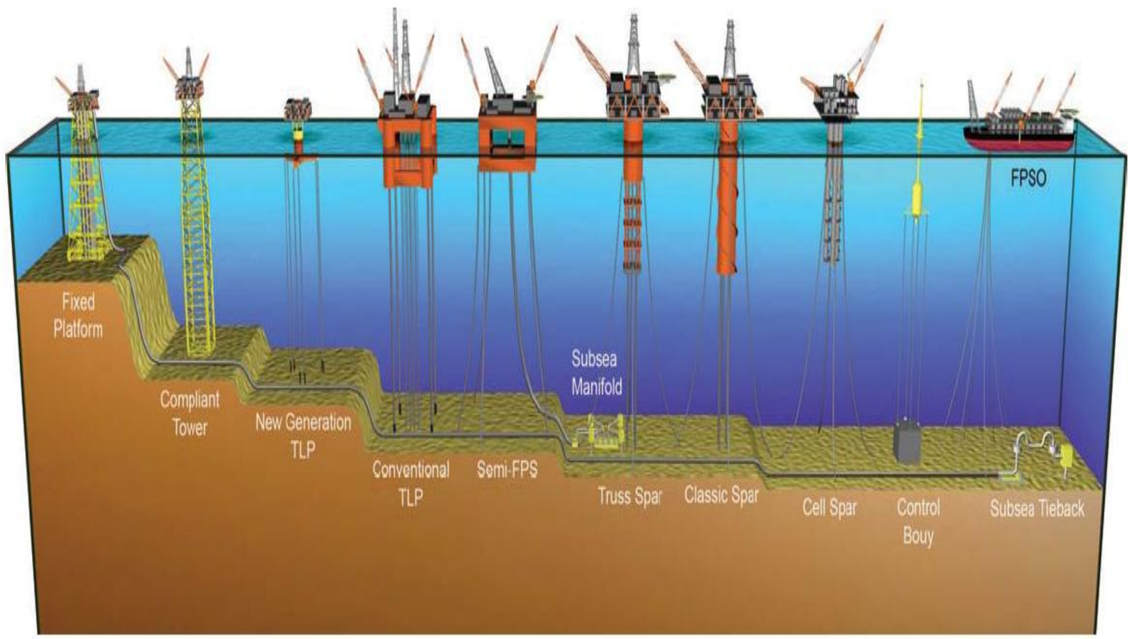

Figure 7: Offshore platform major structural concepts [13].

Moreover, the system of operation of a floating offshore structure is governed by three main structural components namely; Floating hull, mooring system and riser system. The core function of the floating hull is to provide space for operation works such as production and storage to be carried out. The mooring system provides the means of anchorage between the structure and the seabed, thus keeping the structure in station from environmental forces. The riser system facilitates in drilling operations as well as the transportation of offshore products such as oil and gas [35]. Table 1 shows major differences between fixed and floating offshore structures.

However, pipelines can also be considered as either fixed or floating offshore structure since they can be made to rest on the seafloor or float. They are mostly used for offshore products transportation from production platforms to storage centers. The entire installation process of pipelines involves the fabrication of the pipeline on-board on a lay-vessel or on a lay-barge, welding, inspection and launching [14]. There are several methods of installing a pipeline to the seabed. These include: J-lay, S-lay, Reeling, Piggyback, and Multiple lay [8].

Table 1: Bottom-founded verse Floating structures [8].

FUNCTION	BOTTOM-SUPPORTED	FLOATING
Payload support	Foundation-bearing capacity	Buoyancy
Well access	"rigid conduits (conductors) surface wellheads and controls	"dynamic" risers subsea, wellheads subsea or surface controls
Environmental loads	Resisted by strength of structure and foundation, compliant structure inertia	Resisted by vessel inertia and stability, mooring strength
Construction	Tubular space frame: fabrication yards	Plate and frame displacement hull: ship yards
Installation	Barge (dry) transport and launch, upend, piled foundations	Wet or dry transport, towing to site and attachment to pre-installed moorings
Regulatory and design practices	Oil industry practices and government petroleum regulations	Oil industry practices, government petroleum regulations and Coast Guard & International Maritime Regulations

Pipelines installed through the S-lay method, as shown in figure 8, tend to obtain a characteristic S-shape from an inclined horizontal position. A long boom-like curved structure, called a stinger is used in launching the pipeline onto the seabed. Rubber pads along the stringer presses on the pipeline surface to bend, thus acquiring the S-shape. Excessive bending at the stinger could lead to bucking, fracture and flooding of the pipeline. Once the pipeline is successfully launched onto the seabed, it regains its shape and form. The pipeline tends to behave like a cable rather than a beam. S-lay is used up to water depths of 1000m [13].

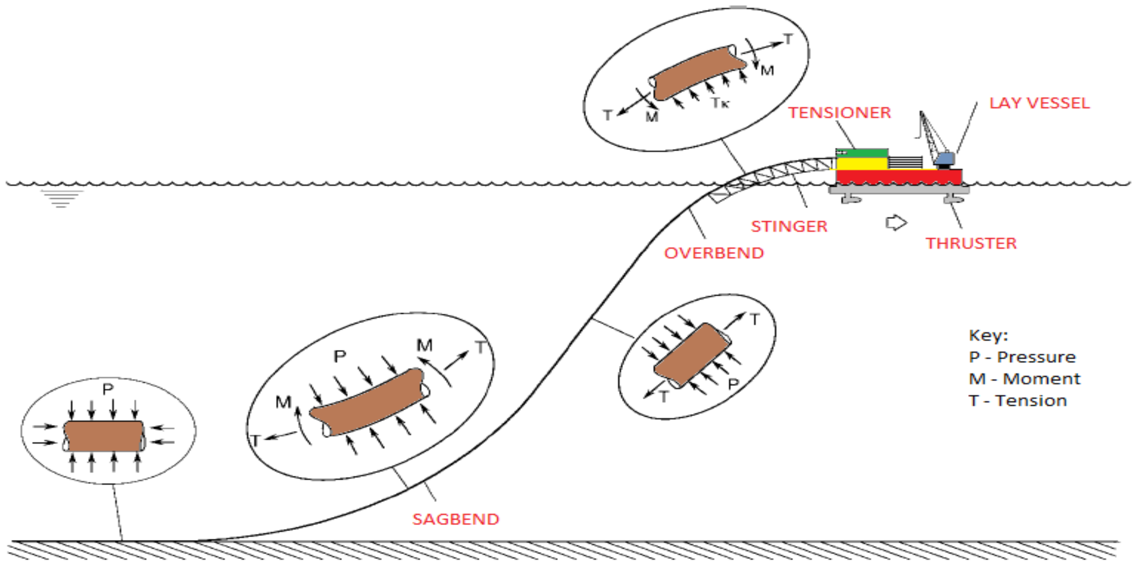

Figure 8: Schematic representation of S-lay pipeline installation and associated pipeline loadings [13].

The J-lay, as depicted in figure 9, is an alternative installation method to S-lay. Pipelines obtain a characteristic J-shape while been launched onto the seabed through an inclined vertical position. Like the S-lay method, excessive bending at the stinger of the J-lay vessel/barge could also lead to bucking, fracture and flooding of the pipeline. However, J-lay is more suitable when installing pipelines to very deep water depths of about 3350m.

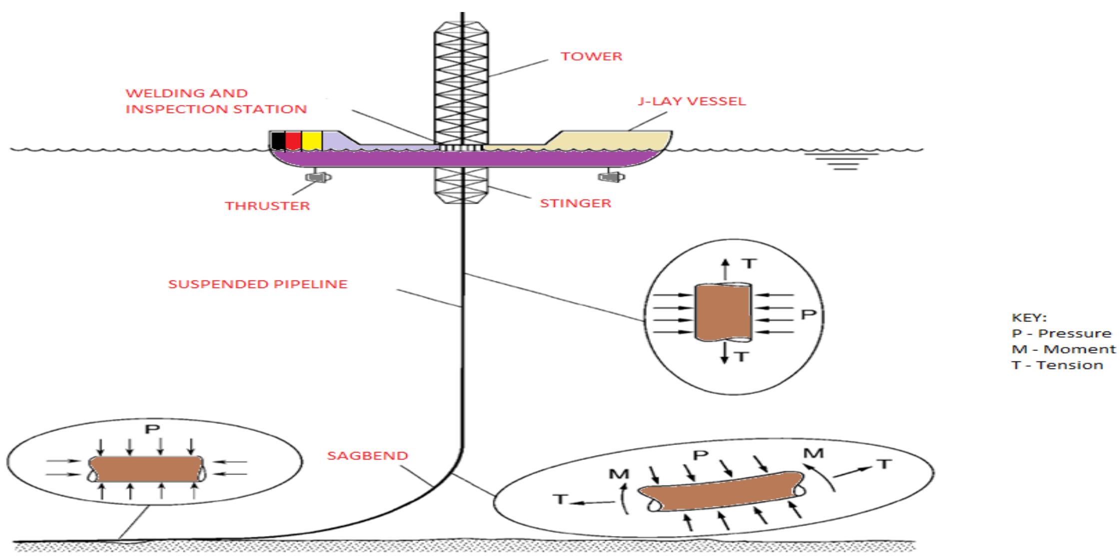

Figure 9: Schematic representation of J-lay pipeline installation and associated pipeline loading [13].

Pipelines are therefore prone to defects during the fabrication process. These defects could be aggravated during the laying process as a result of excessive pressure exerted on them. Repairing and maintaining pipelines is therefore inevitable in the offshore industry [13]. Figure 10 illustrates the various pipeline defects which could arise in the offshore environment. This includes part wall defect and through-wall defect. A through-wall defect is considered as a severe phenomenal pipeline defect since it could lead to pipeline leaks and pipeline rupture.

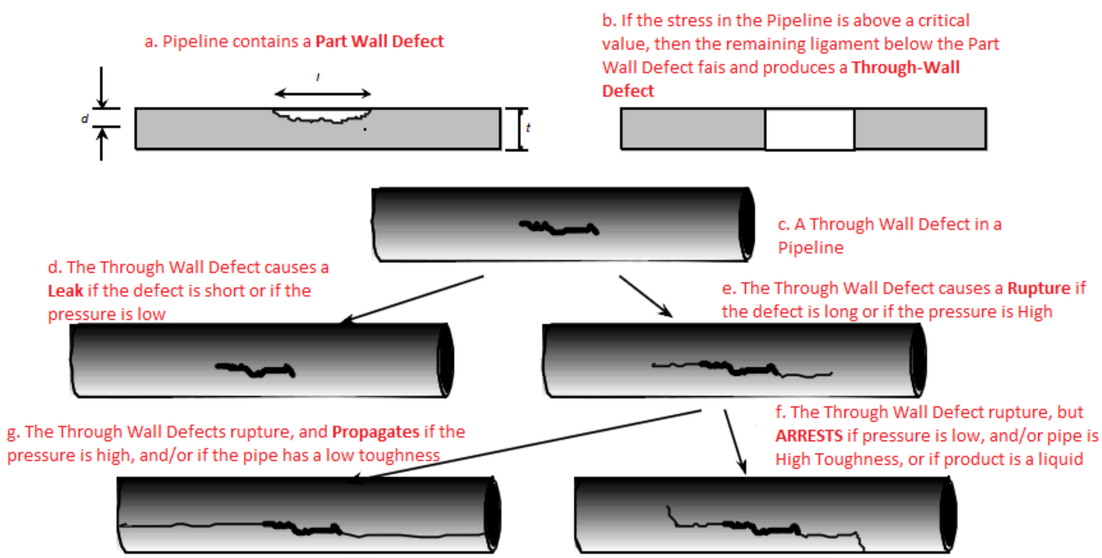

Figure 10: Pipeline defects corresponding to pressure difference [39].

2.2 Offshore Materials

Selecting materials for offshore structures seems challenging due to the severe climatic conditions and external forces prominent in the offshore environment. Characteristic factors that need consideration in the material selection process include strength of the material, fracture toughness, corrosion resistance properties, chemical composition of the material and the microstructural properties of the material. However, weldability property of the materials is highly a dictating factor since these materials needs to be joined together to form sophisticated structures such as welded tubular structures. The various types of material application for offshore structures and production are namely; structural steel, production equipment steel, corrosion resistance alloys and non-metals [4]. Structural steels and corrosion resistance alloys would be the main focus in this sub-chapter.

2.2.1 Structural Steel

Carbon and low alloy steels have been used as structural steels for the construction of offshore structures and pipelines way back in the mid-1960s according to standards such as ASTM (A7, A36), API (5L B), BSI, and ISO. Catastrophic failures such as lamellar tearing and poor weldability have been observed as the main drawbacks in using these standards. These and other factors make the said standards less attractive to the offshore industry in terms of cost, safety and reliability [4].

Alternatively, high strength low alloy steels (HSLA) have been used for offshore structures due to its high strength properties, ease of fabrication, low cost and toughness properties [5]. In addition, thermo-mechanical control process (TMCP) steels, which are of fine ferrite grain steel (ASTM 10-12) are now used for applications such as pipelines, and offshore structures. These type of steels possess high strength, high fracture toughness and highly weldable.

Table 2: Specification and typical chemical composition of thermo-mechanical control process (TMCP) Grade 60 Pipe [4].

ELEMENT	SPECIFICATIONS	COMPOSITION
Carbon	0.10 max.	0.065
Manganese	1.15 – 1.40	1.35
Silicon	0.15 – 0.30	0.18
Sulphur	0.005 max.	0.0025
Phosphorus	0.018 max.	0.007
Aluminum, total	0.02 – 0.05	0.03
Titanium	0.003 – 0.020	0.015
Niobium	0.01 – 0.03	0.02
Nickel	0.25 max.	0.21
Copper	0.25 max.	0.21
Chromium	0.10 max.	0.035

However, TMCP steels have been noted to have higher residual stresses due to sensitivity to heat affected zone softening when welded with high heat input [4]. This phenomenon makes TMCP steels with yield strength between 290 and 414 MPa low in toughness, hence resulting in local brittle zones (LBZ) [4, 40].

The advent of alloys used in modifying LBZ free steels have resulted in achieving high-quality offshore structural steels with excellent weldability, higher fracture toughness, and higher strength [4].

2.2.2 Corrosion Resistance Alloys

Offshore structures installed underwater are prone to corrosion and rust due to the offshore corrosive environment. Corrosive resistance alloys such as stainless steel, nickel base alloys, cobalt base alloys, nickel-copper alloys and titanium alloys have been used as materials to resist CO_2 effects in corrosive environment and H_2S effects in stress corrosion environment [4].

Stainless steel and nickel-copper alloys have been used to fabricate offshore structures but these alloys have suffered external corrosion attacks and erosion corrosion respectively. However, the advent of 22 Cr and 25 Cr duplex and 6 Mo stainless steels, nickel base austenitic alloys and titanium alloys with excellent weldable properties have proven to be the best choice for such environments [4].

Figure 11 shows a bar chart of different alloys. The allowable stresses of the alloys are plotted against their corresponding cost. It can be seen that the cost of each alloy is not directly proportional to its allowable stress. The UNS S34565 alloy has the highest allowable stress with less cost when compared to that of 6 Mo SS and Ti Gr 2 alloys. Hence, considering the allowable stresses of alloys for the construction of offshore structures is very essential, thus minimizing cost when necessary.

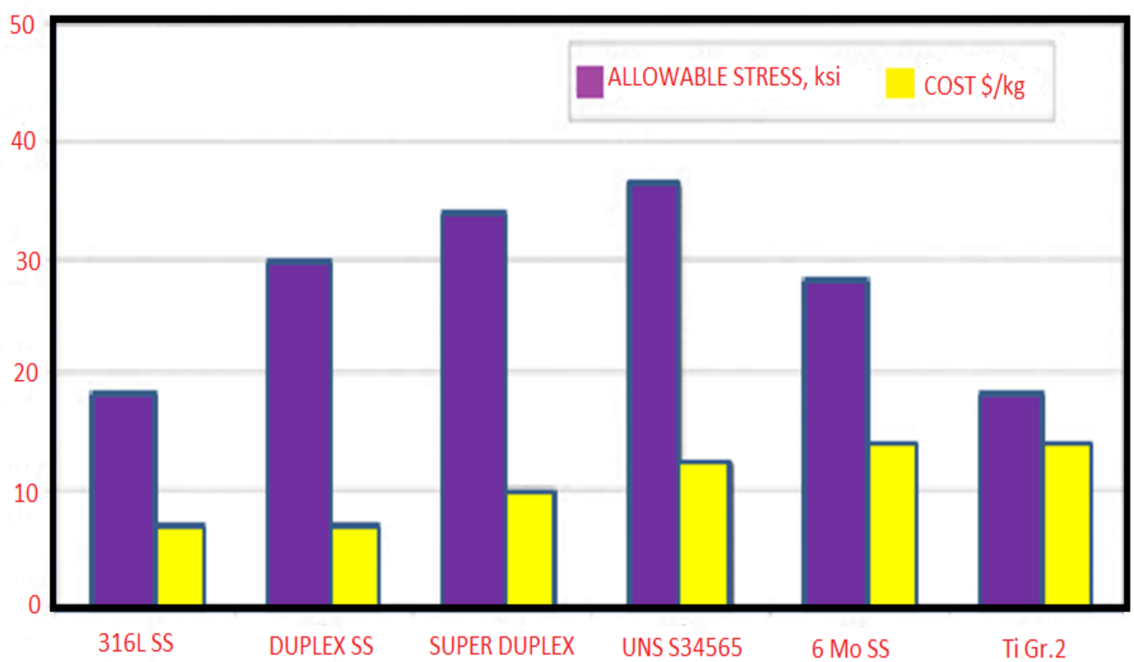

Figure 11: Cost and allowable stress for different alloys [4].

3. CONVENTIONAL WELDING PROCESSES AND THEIR ASSOCIATED DEFECTS IN UNDERWATER WELDING

Arc welding processes, also known as conventional welding processes have been used offshore to weld offshore structures underwater, especially for repair and maintenance works. However, there have been a number of defects in the use of some of the arc welding processes employed offshore. This chapter presents the notable conventional welding processes which have been applied in offshore underwater welding and their associated defects.

3.1 Manual Metal Arc Welding

The technique of welding underwater with manual metal arc welding (MMAW) serves as a means for repairing and maintaining offshore structures. Manual metal arc welding (MMAW) similarly known as shielded metal arc welding (SMAW), has been used to join pipelines together [41] and also has been commercialized to wet welding [10, 11, 24, 25] of offshore structures. As it has earlier on been said, the depth of water is an influential factor and thus has extreme effect on the welding process as well as to the operator [10]. The process of MMAW has been performed at water depth of 100m and even further to 200m depth. Nevertheless, a dry hyperbaric MMAW has been done at a water depth of 300m [25]. Figure 12 shows a generalized shielded metal arc welding process. It can be seen that, the process of SMAW involves the use of consumable metallic coated electrode which serves as the filler material.

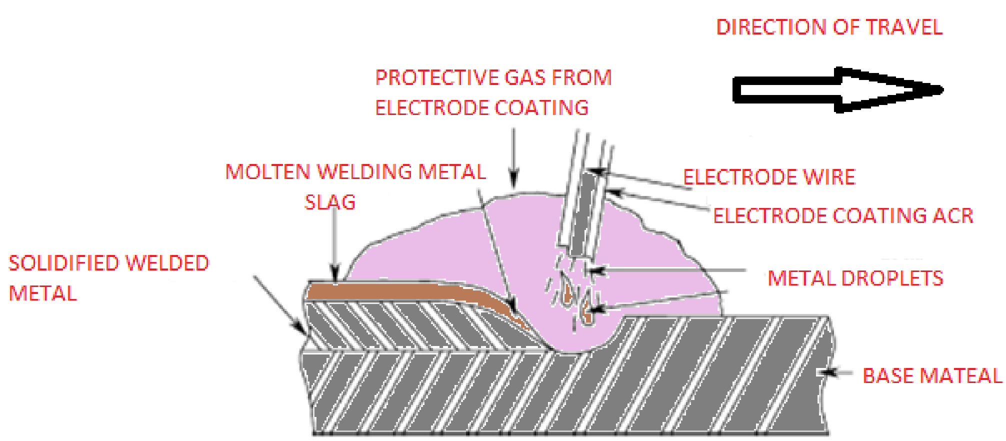

Figure 12: Shielded metal arc welding process [42].

A direct current or alternating current is used as the power source. Before the commencement of the process, an electric arc is initiated by striking the tip of the electrode to the base material. This process produces an intense heat which melts both the base material surface and the electrode together.

The surface of the base material forms a molten weld pool while the melted electrode drops to fill the pool created. However, the coating on the metallic electrode provides a shielding effect to the arc and the molted weld pool from environment gases. A slag is afterwards produced on top of the weldment [43]. The entire welding process requires a high electrical insulation [10] since any exposed wire could lead to electrical shock and death of the welder/diver.

Performing SMAW process in wet underwater welding (DC power source) [9] contributes to a lot of defects even though it serves as a repair technique. The quality of welds made by SMAW wet welding technique yields in porosity, reduced ductility, and hydrogen cracks. Porosity in this sense occurs as a result of increase in depth of water where molecular hydrogen, carbon monoxide or water vapor is the primary cause [31, 32]. Ductility of weldment is also reduced since the cooling rate is very rapid. A cooling rate of 415 ^{0}C to 56^{0}C may be achieved instead of 800 ^{0}C to 500 ^{0}C [27]. Also, hydrogen and oxygen are produce from the MMAW arc [10] which contributes to embrittlement in the heat affected zones [33]. A detrimental effect such as cold cracking or hot cracking is prone to materialize especially in high strength steels from these occurrences [44, 45].

3.2 Flux Core Arc Welding

The technique of flux core arc welding (FCAW) process has been used to weld offshore structures in wet underwater welding [24, 25] as well as in dry underwater welding [21]. The FCAW process is similar to that of SMAW but the main difference is that, FCAW utilizes a continuously fed flux-cored electrode containing alloying elements, arc stabilizers, and deoxidizers which provides a self-shielding effect to the electric arc from surrounding gases during the welding process. In some instances, an external gas is used for shielding the electric arc form atmospheric gases such as oxygen and nitrogen [46]. Figure 13 depicts a flux-core arc welding process with shielding gas incorporated. It has been observed that FCAW process is mostly used to weld HSLA steels, thus a preferable alternative to SMAW due to its productivity level as well as weld quality [47].

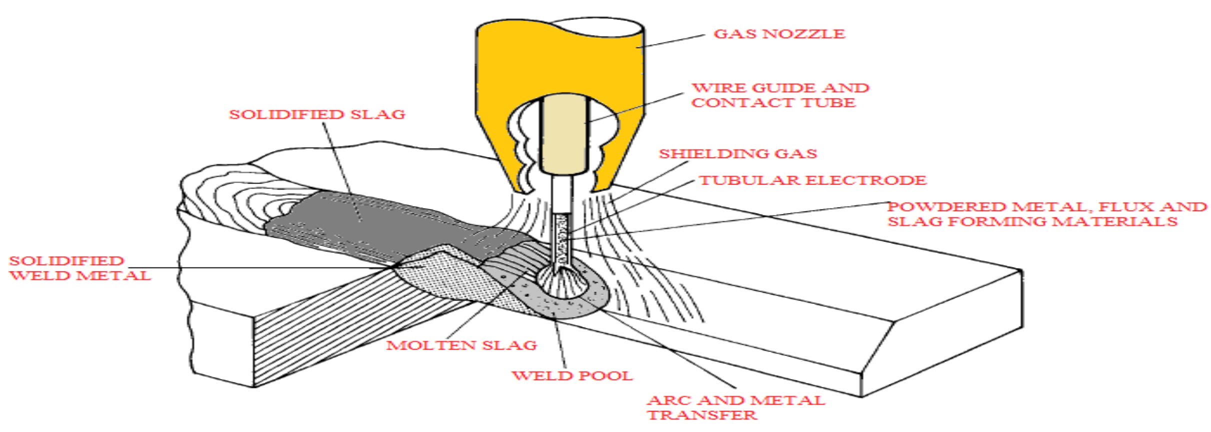

Figure 13: Gas-shielded flux- cored arc welding [46].

However, in underwater welding, the main defects associated to FCAW process include porosity and burnback. Halogen free flux formulation and nickel-based flux cored filler materials have been used as electrode in underwater wet welding and weldability has been improved [28]. Also stainless steel flux-cored wire has been used in wet welding since it provides a halogen free flux formulation [10].

3.3 Gas Metal Arc Welding

The GMAW process is normally performed in dry hyperbaric welding due to the welding process set-up (complex equipment). The mode of operation is a bit similar to that of FCAW, but in GMAW the continuously fed electrodes are not flux-coated and the metal transfer mechanism from the electrode to the workpiece is characterized by short-circuiting transfer mode, spray transfer mode, or globular transfer mode. Also shielding the electric arc and the molten weld pool from atmospheric contamination requires an external gas or mixture of gases supplied through external cylinders. A broader spectrum of materials such as carbon steels, high strength low alloy steel, stainless steel, aluminum, copper, and nickel alloys have been welded effectively by GMAW process due to its versatility to accommodate inert and reactive gases (carbon dioxide) to be used as shielding gases [48].

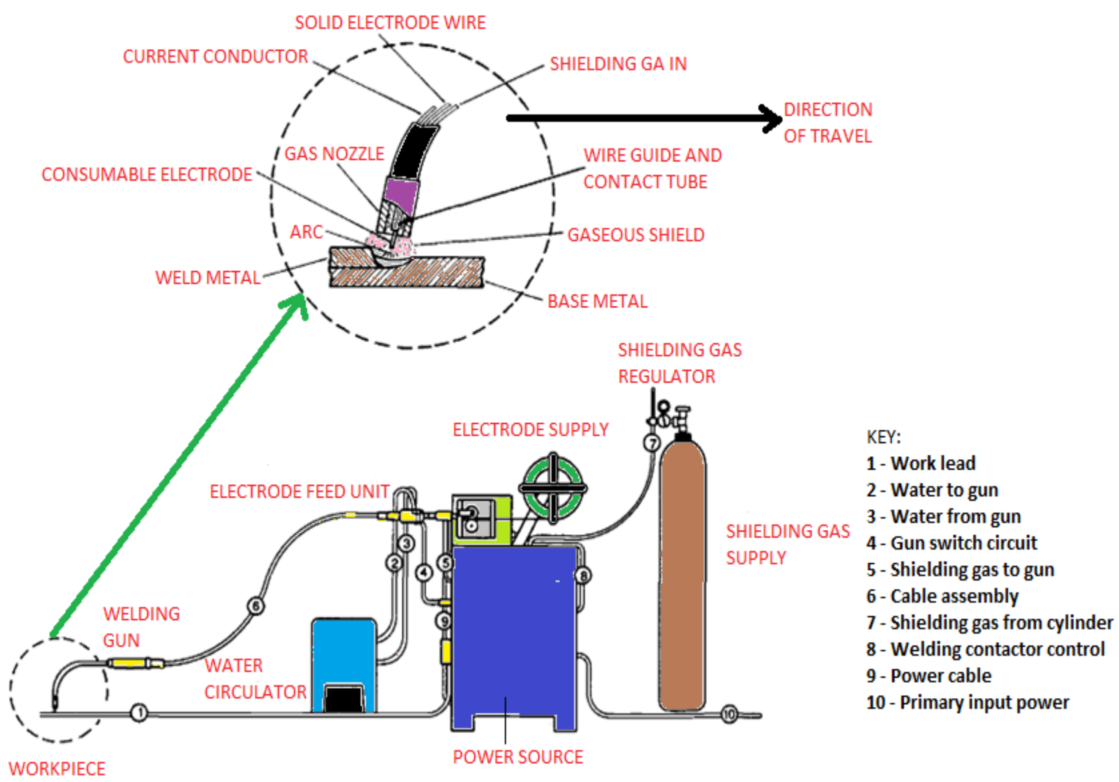

Figure 14: Schematic diagram of gas metal arc welding process (GMAW) [48].

Defects which originate from underwater welding are not limited to only wet underwater welding with welding processes such as SMAW and or FCAW, but also to dry underwater welding processes including GMAW. A current machined implant experimental research performed on a high strength low alloy steel grade S355J2G3 with GMAW process with suitable consumables has shown defects using the dry underwater welding technique, specifically the local cavity method (dry welding at one atmosphere) [49].Table 3 shows the chemical composition of the steel grade S355J2G3 used as the specimen for the machined implant experiment.

Table 3: Chemical composition of tested steel (S355J2G3), wt.pct [49].

STEEL GRADE	C	Mn	Si	P	S	Cr	Ni	Cu	Al
S355J2G3	0.17	1.44	0.35	0.014	0.014	0.04	0.077	0.30	0.027

It was therefore observed that due to the high contents of Mn, Cr, Mo and Ni in the base material and rapid cooling cycles introducing higher diffusible hydrogen contents in the welding process resulted in a hard bainitic or martensitic microstructures in the heat affect zone (HAZ), hence causing cold crack joints in the base material as illustrated in figure 15 and 16 [49].

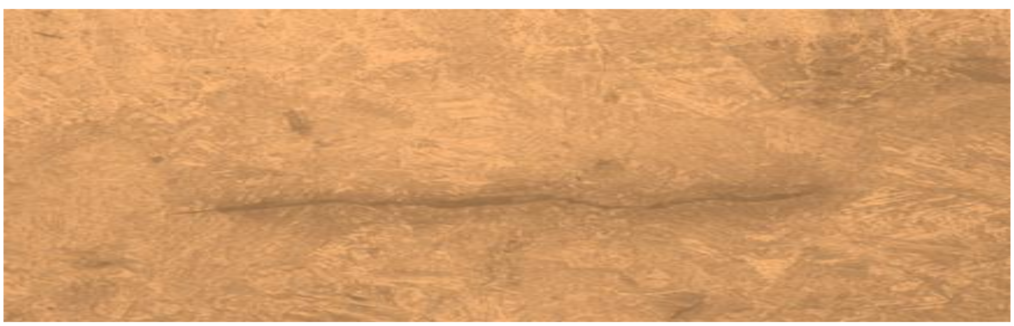

Figure 15: Microphotograph of cold crack in the bainite structure of the heat affected zone [49].

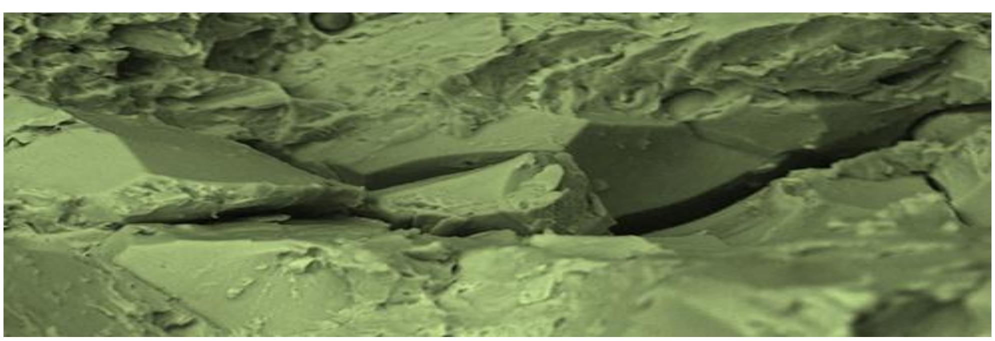

Figure 16: A part of crack path in the implant specimen: W_g=50l/min, e_L=10 KJ/cm, σ_i=400MPa [49].

3.4 Gas Tungsten Arc Welding

Among the previously mentioned conventional welding processes employed in the aquatic environment, gas tungsten arc welding (GTAW) process happens to produce the best weld quality when performed in dry hyperbaric welding. The GTAW process is also known as tungsten inert gas (TIG) welding because a non-consumable tungsten electrode [50, 51] is used in the welding process and also the shielding gas is either argon [10] or helium or a mixture of both [51]. The shielding gas protects the electric arc created between the non-consumable tungsten electrode and the base metal from atmospheric contamination, hence sustaining a weld pool temperature of about 2500 ^{0}C. Metals and metal alloys such as stainless steel, aluminum, magnesium, copper, reactive materials as well as dissimilar materials have been welded excellently with the GTAW process [51].

Figure 17 shows a schematic diagram of a gas tungsten arc welding process incorporating a filler rod. The importance of the filler rod is to facilitate high deposition rate during the welding process. An experimental research conducted under the auspices of SINTEF on steel grade X70, utilizing GTAW with two filler materials with different chemical composition in the welding process have been examined. It was observed that, increasing sea water depth decreases the toughness of the Ni-Mo containing weld in the GTAW process, thus resulting in a crack growth in a partially transformed brittle region [21].

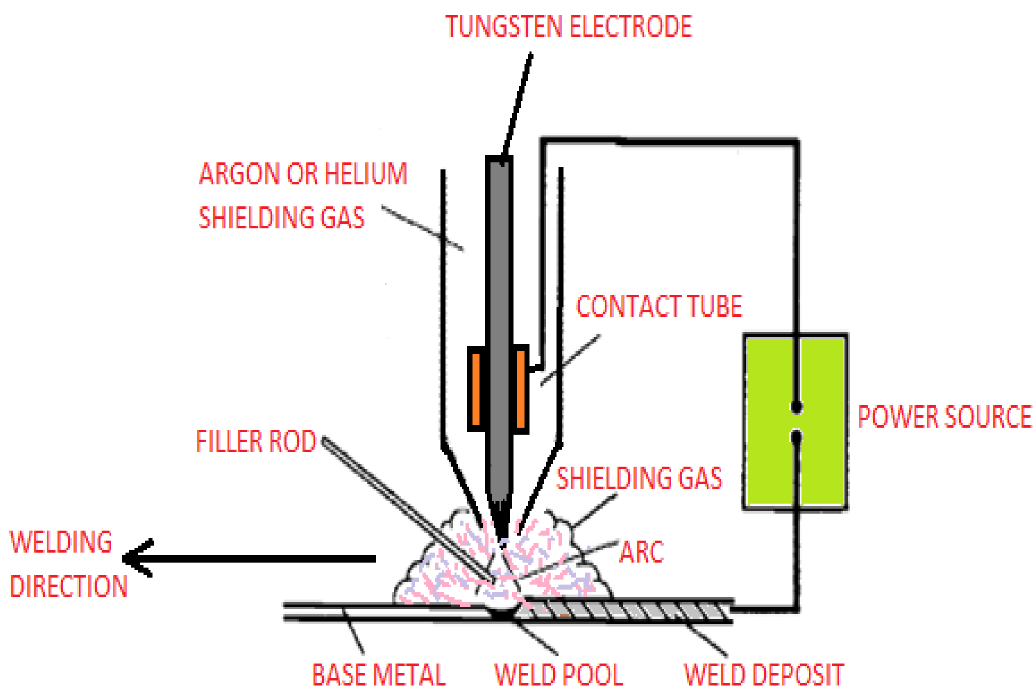

Figure 17: Schematic view of gas tungsten arc welding process (GTAW) incorporating a filler rod [51].

Other associated defect observed in the GTAW process is tungsten inclusion. This occurs when the tip of the tungsten electrode comes into contact with the weld pool [51]. Hydrogen and oxygen contamination are on extensive assessment since they have been a major effect in the GTAW process when performed on higher alloyed steels such as duplex stainless steels [18] and supermartensitic 13% Cr stainless steels [52].

Owing to these effects, a limited amount of duplex and supermartensitic 13% Cr stainless steels have been used for constructing pipelines. However, technological improvements in the performance of GTAW on these steels in pipeline tie-ins and repair offshore have been met. A pipeline repair system (PRS) spool constructed under the Norwegian oil and gas industry have shown that over 70 pipeline tie-ins have been performed with a diver-assisted remotely controlled welding under a GTAW process [53]. Out of the number of pipeline tie-ins mentioned herein, quite a large number of weldments were made with the GTAW process on X65 steel grade. Steel grades such as X60 and X70, as well as duplex and supermartensitic 13% Cr stainless steel were the least in the entire installation process [21].

4. MODERN WELDING PROCESSES FOR UNDERWATER WELDING

Underwater welding has been carried out on offshore structures with conventional welding processes, but the degree of defects in some of the processes is seen to be alarming. These defects have resulted in low productivity levels, poor weld quality as well as environmental safety related issues of the entire welding processes. As these conventional welding processes receive developmental improvement in underwater welding of offshore structures, a remedy to these challenging problems is the use of modern welding technologies. Researchers have found that, friction stir welding (FSW), laser beam welding (LBW) , and Hammerhead “wet spot” welding could serve as modern welding technologies applicable to offshore structures to alleviate or eschew underwater welding problems offshore [9, 10, 11].

4.1 Friction Stir Welding

The advent of friction stir welding (FSW) in 1991 by Wayne Thomas at The Welding Institute (TWI) has contributed immensely in the joining process of materials such as aluminum alloys, magnesium, and copper for wider industrial applications. The FSW process is described as a solid state keyhole joining process [54-56], which means the base material does not melt in the form of molten pool [57, 58] but rather softens when heat is generated through frictional force between a rotating tool and the base material. In addition, aluminum alloys grades from 2xxx and 7xxx series, which have conventionally been non-weldable, can now be fabricated with FSW with speed and quality [54]. Figure 18 shows a schematic diagram of friction stir welding process. The friction stir welding equipment consists of a rotating tool with a pin profile and a shoulder.

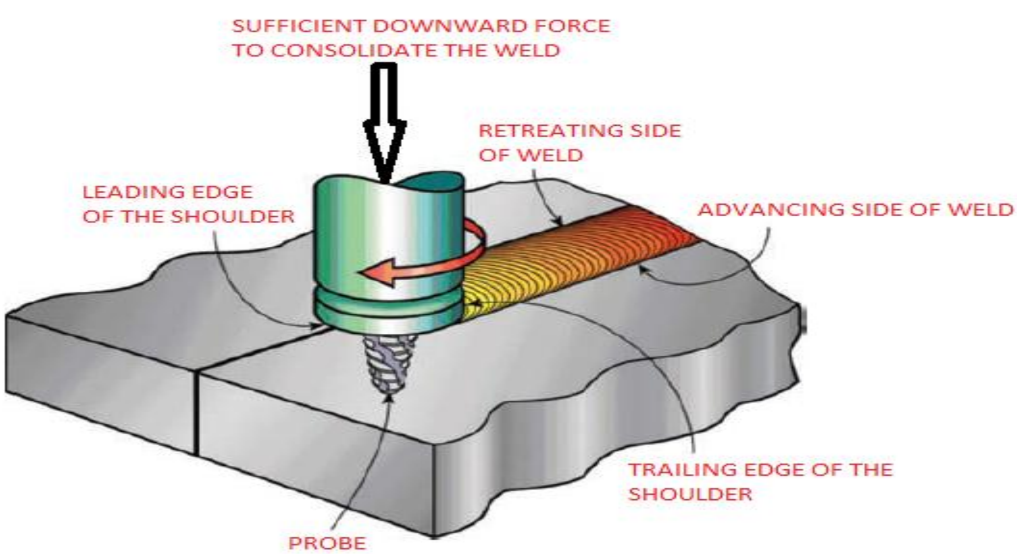

Figure 18: Schematic diagram of friction stir welding (FSW) [59].

The pin, also termed as probe of the rotating tool is inserted into a firmly clamped base material so that the shoulder part also comes into contact with the base material. The pin is non-consumable and influences the material flow at the joint, process loads, process-zone temperature, and weld quality [60]. A circulating action of the rotating tool produces heat through friction which causes the joint between the base materials to soften. The join is stirred to form a perfect weld as the tool moves along to the end [54].

Advantages of Friction Stir Welding (FSW)

A list of advantages is highlighted below [54].

- Highest quality of mechanical properties of joints as testified by tensile, bend and fatigue tests
- Fumes-free welding process
- Porosity-free welding process
- Spatter-free welding process
- Low shrinkage of the workpiece
- Possibility to achieve long welds with low distortion
- Efficiency in energy consumption
- Possibility to weld in all positions.

Disadvantages of Friction Stir Welding (FSW)

A list of disadvantages is highlighted below [54]

- Slow welding speeds (up to 750mm/min for welding 5mm thick 6000 series aluminum alloy)
- The need for a backing bar
- Keyhole at the end of each weld.

The utilization of friction stir welding process in offshore underwater welding seems to be an effective welding technique since steels and alloy steels could be welded with very less or no defects. It has been observed that, the weldment made from underwater friction stir welding of 6061 aluminum alloy yielded higher fatigue strength than weldment made in air [61]. Other research attested to the facts that, weldment made from underwater friction stir welding can achieve substantial ultimate strength. This improvement in the mechanical property of the weld joint is characterized by the level of heat in-put in relation with the welding parameters [62].

For a clearer justification, an experimental research has been carried out to examine the defects, tensile strength and fracture toughness of joints made from underwater friction stir welding of a 2219 aluminum alloy. The samples for the underwater friction stir welding were cleaned with acetone and after clamped to a backing plate in a vessel of water at room temperature. In the welding process, an FSW machine (FSW-3LM-003) was used to perform a longitudinal weldment along the joint of the samples [63].

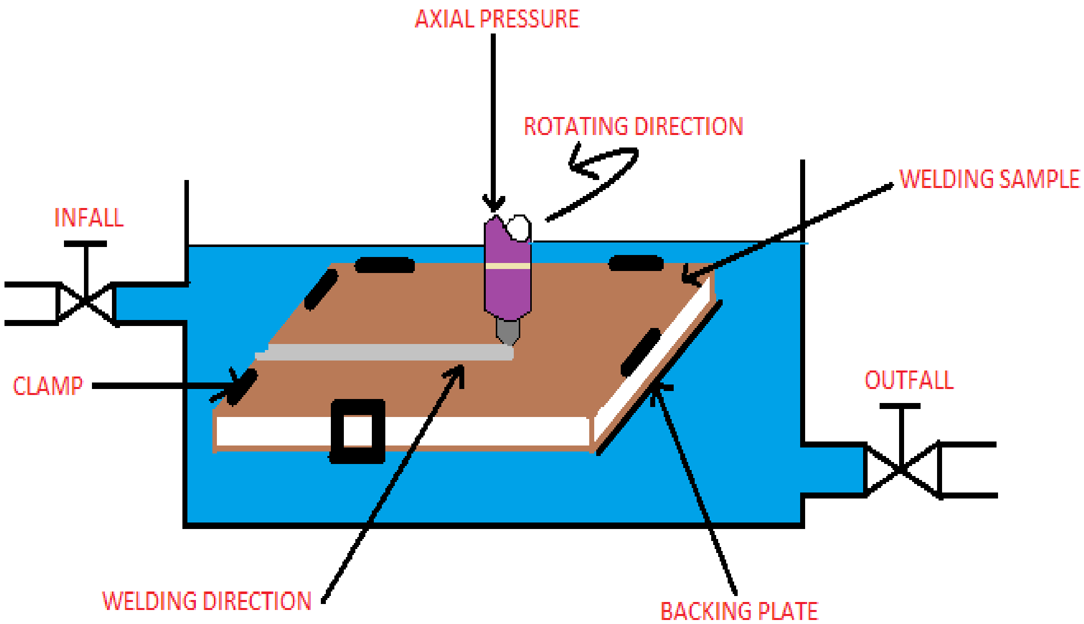

Figure 19: Underwater friction stir welding (FSW) schematic diagram (adapted from [63]).

The figure above depicts the set up for the friction stir welding experiment conducted underwater. In addition, table 4, 5, 6 and 7 below shows the chemical composition and mechanical properties of the 2219 aluminum alloy as well as the tool size and welding parameters used in the experiment.

Table 4: Chemical composition of 2219 aluminum alloy (mass fraction, %) [63].

Cu	Mn	Fe	Ti	V	Zn	Si	Zr	Al
6.48	0.32	0.23	0.06	0.08	0.04	0.49	0.20	Bal.

Table 5: Mechanical properties of 2210 aluminum alloy [63].

Ultimate Strength/MPa	0.2% proof Strength/ MPa	Elongation/ %
432	315	11

Table 6: Tool size used in FSW [63].

Shoulder diameter/ mm	Pin diameter/ mm	Pin length/ mm	Tool tilt/ (^{0})
22.5	7.5	7.4	2.5

Table 7: Welding parameters used in FSW [63].

Rotation speed/ (r.min $^{-1}$)	Welding speed/ (mm.min $^{-1}$)	Axial pressure/ kN
800	100	4.6

After the completion of the FSW process, the joints were perpendicularly cross-sectioned in the welding direction by an electrical-discharge machine and analyzed through a metallographic and tensile test. The test results, as represented in figure 20 below, showed a tensile strength of 341 MPa, which is approximately 79% of that of the base material, was obtained through underwater FSW whiles a tensile strength of 324 MPa, which is equivalent to 75% of that of the base material, was achieved through FSW in air (normal joint). It can therefore be said that underwater FSW produces a higher tensile strength than that performed in air.

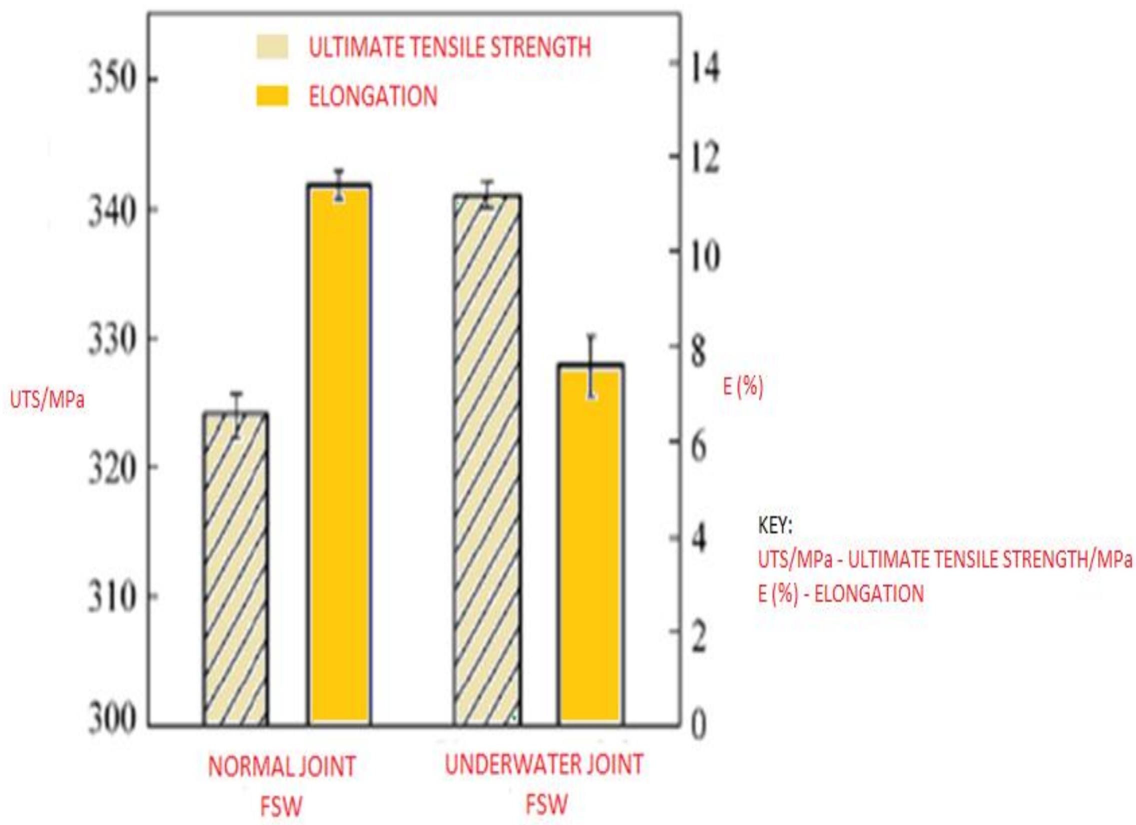

Figure 20: A graph showing the ultimate tensile strength and elongation properties of normal joints and underwater joints of friction stir welding process [63].

Moreover, it was observed that joint elongation produced from underwater FSW process yielded a lower value of 7.6% as compared to approximately 11% joint elongation value obtained from air FSW. The difference in the joint elongation values was therefore noted as a significant cause of joint fracture features, whether on the retreating side (RS) of the weld or the advancing side (AS) of the weld produced from the FSW process. Figure 21 depicts locations of fracture in both normal friction stir welding and underwater friction stir welding. It can be said that, fracture is bond to occur on the AS between the thermal mechanical affected zone (TMAZ) and the heat affected zone (HAZ) in the case of normal FSW while the occurrence of fracture in underwater FSW lies between the weld nugget zone (WNZ) and the TMAZ on the AS. Hence, underwater FSW process improves the strength in the HAZ, thus avoiding any catastrophic failure in the base material.

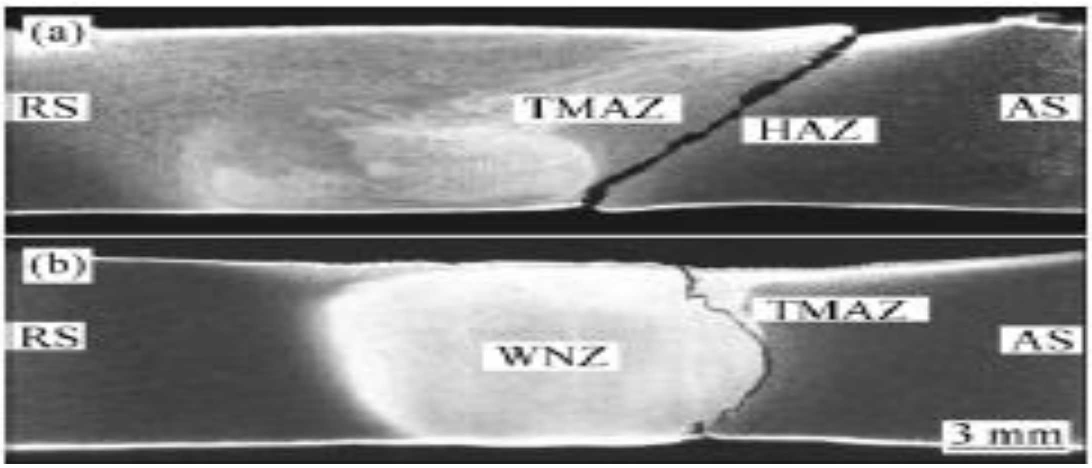

Figure 21: Locations of fracture of different joints: (a) Normal FSW; (b) Underwater FWS [63].

However, another experimental research [64] has also showed that the mechanical properties of a 2219 aluminum alloy base material is greatly affected by welding speed when welded underwater by friction stir welding. In the experiment, welding speeds were varied between 50 to 200 mm/min at a constant rotation speed of 800rpm. It was observed that a maximum tensile strength of 347 MPa, approximately 80% of that of the base material, was obtained with less joint elongation (8.8%) at welding speeds between 50 to 150 mm/min as illustrated in figure 22. It can also be seen from the graph that, tensile strength increased at welding speeds between 50 to 150 mm/min. On the other hand, a drastic fall in tensile strength, approximately 185 MPa was achieved during welding speeds of 200 mm/min. It can be said that the tensile strength of a weld joint is influenced by welding speeds in the underwater FSW process.

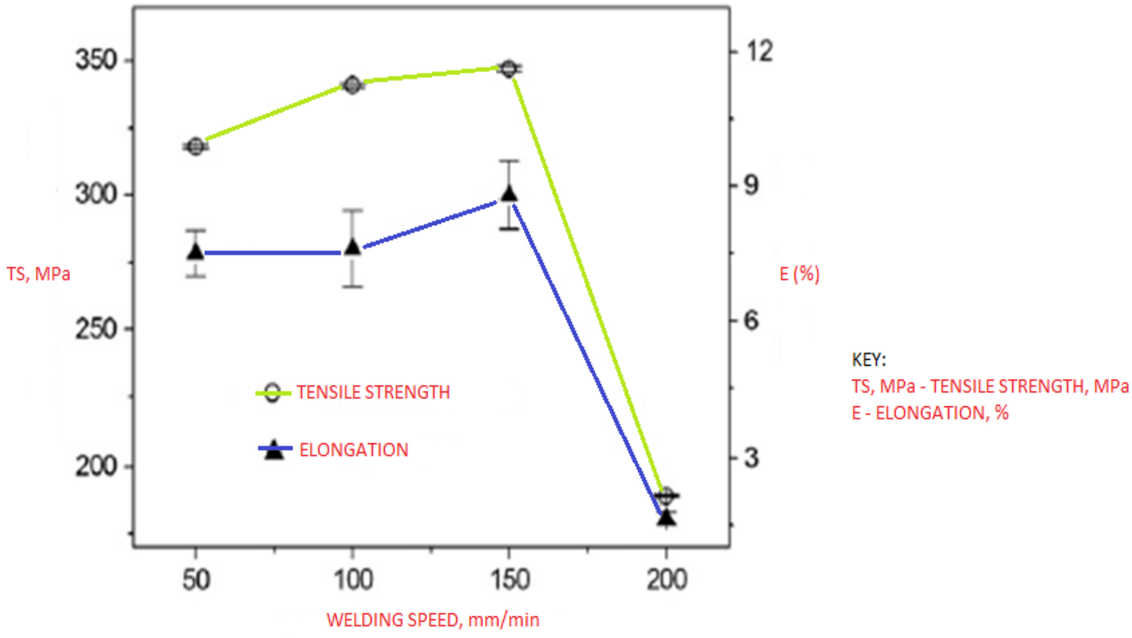

Figure 22: A graph of tensile properties of the welded joints verse different welding speeds in underwater FSW. Error bars are based on the standard deviation [64].

The welded joints at different welding speeds were analyzed and cross sectioned after the tensile test process. Figure 22 therefore shows the cross sectional view of the welded joints at different welding speeds. It was observed that at welding speeds of 50 mm/min (a), 100 mm/min (b) and 150 mm/min (c), excellent quality welds with no defects were obtained. However at welding speed of 200 mm/min (d), a groove defect was achieved. This defect is a result of decreased tensile strength in relation to the fast welding process. Thus, tensile strength of weld joints obtained underwater FSW is greatly affected by the welding speed.

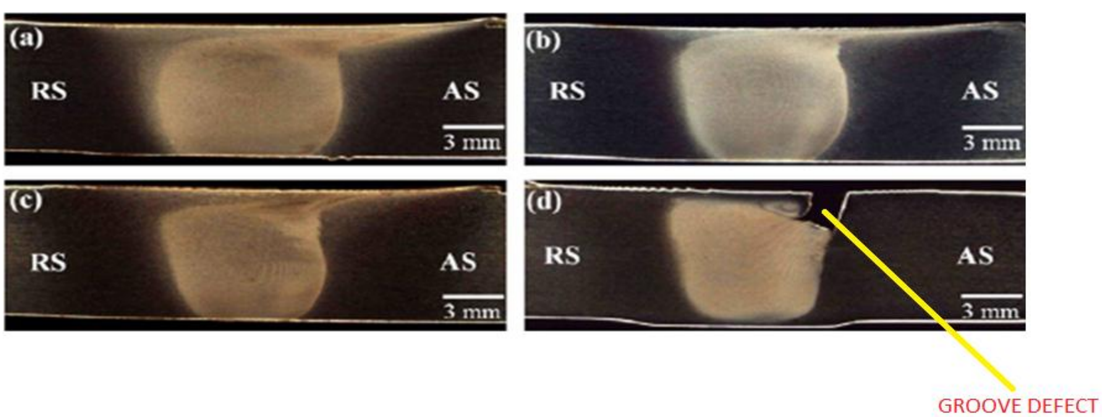

Figure 23: Cross sections of the welded joints at different welding speeds: (a) 50 mm/min (b) 100 mm/min (c) 150 mm/min and (d) 200 mm/min [64].

In addition, the various welding speeds were observed as influential factors to fracture features of the weld join as illustrated in figure 24 below. At welding speed of 50mm/min (a), a fracture was found in the HAZ adjacent to the TMAZ on the RS. This occurrence was due to the lowest hardness property which exhibited in the retracting side of the weld joint. Also other fracture features were observed at welding speeds between 100 to 150 mm/min in the TMAZ adjacent to the WNZ on the AS. This occurrence is as a result of weaker and shaper WNZ/TMAW interface prominent in the AS region. This implies that for a high-quality weld joint to be obtained from underwater FSW, an appropriate welding speed range should be chosen since lower welding speeds increases heat input in the base metal, hence leading to low tensile properties in the HAZ while a rather high welding weld could lead to a groove defect as a result of deteriorated joint properties [64].

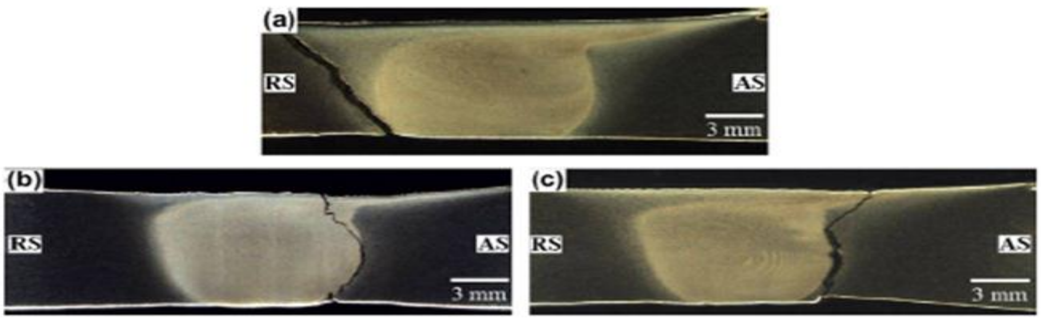

Figure 24: Fracture locations of the joints welded at different welding speeds (a) 50 mm/min (b) 100 mm/min and (c) 150mm/min [64].

The weldability of steels and titanium has been claimed to be a challenging process with FSW as a result of the unavailability of extremely higher thermal resistance and wear resistance tool material to weld at temperatures of 1000 ^{0}C [65]. The unavailability of suitable material is as a result of the high cost [60].

In contrast to the above statements, recent investigations have shown that FSW of high melting materials such as carbon steels, low-alloy steel, nickel alloy, copper and copper alloys, high strength steel, titanium alloy, stainless steel , and magnesium alloy is possible just that the tool life could be shortened. An FSW process performed on carbon steel as the base material yielded recrystalization of grain in the stir zone as similar to that achieved in FSW of an aluminum alloy [66-69].

Additionally, a martensitic transformation is bound to occur after a FSW process is performed on a high-carbon steel (C>0.5 wt %, 0.7 wt % C, and 1.02 wt % C). The martensitic transformation in this case is attributed to the occurrence of rapid cooling after a complete tool pass [65]. Rapid cooling remediation can be achieved by introducing or incorporating an external heat source in the FSW process.

4.2 Hammerhead “wet spot” Welding

Wet underwater welding in recent times has received a lot of concern owing to the challenges encountered as a result of the welding processes or techniques employed offshore. The reason to this concern is because of the major influential defects the conventional welding process, SMAW process to be precise, has on offshore structures. Quite a number of researches have shown that rapid cooling rate is the cause of mechanical/ metallurgical quality problems [77-74], hence limiting the use of SWAW process in wet underwater welding. Also the skill and ability of the welder/diver to perform underwater welding task is an influential factor [11].

However, the need to combat these defects in underwater welding offshore has brought into the metal industry an innovative manual metal arc welding process called the hammerhead “wet-spot” welding [11]. Even though less publication have been made on this underwater welding process, it has been claimed in few papers [11] that the hammerhead “wet-spot” welding is in to stay due to the advantages it has over the conventional SMAW process as proven by experimental results.

The hammerhead “wet-spot” welding equipment, as shown in figure 25, utilizes an electronic control device which consists of key welding functions and features to control a consumable Fe-Cr-Ni-Mo electrode during the welding process to produce a spot/plug weld. The control device is housed in a Piranha II safety switch and has functions and features including [11]:

- Main on/off switch
- First peak (high) current control
- Second background (low) current control
- Timer (up to 20s)
- High, low and auto current selector
- Amp and volt meter
- 400-amp dual pole isolation switch
- 110v power supply and remote control function cables.

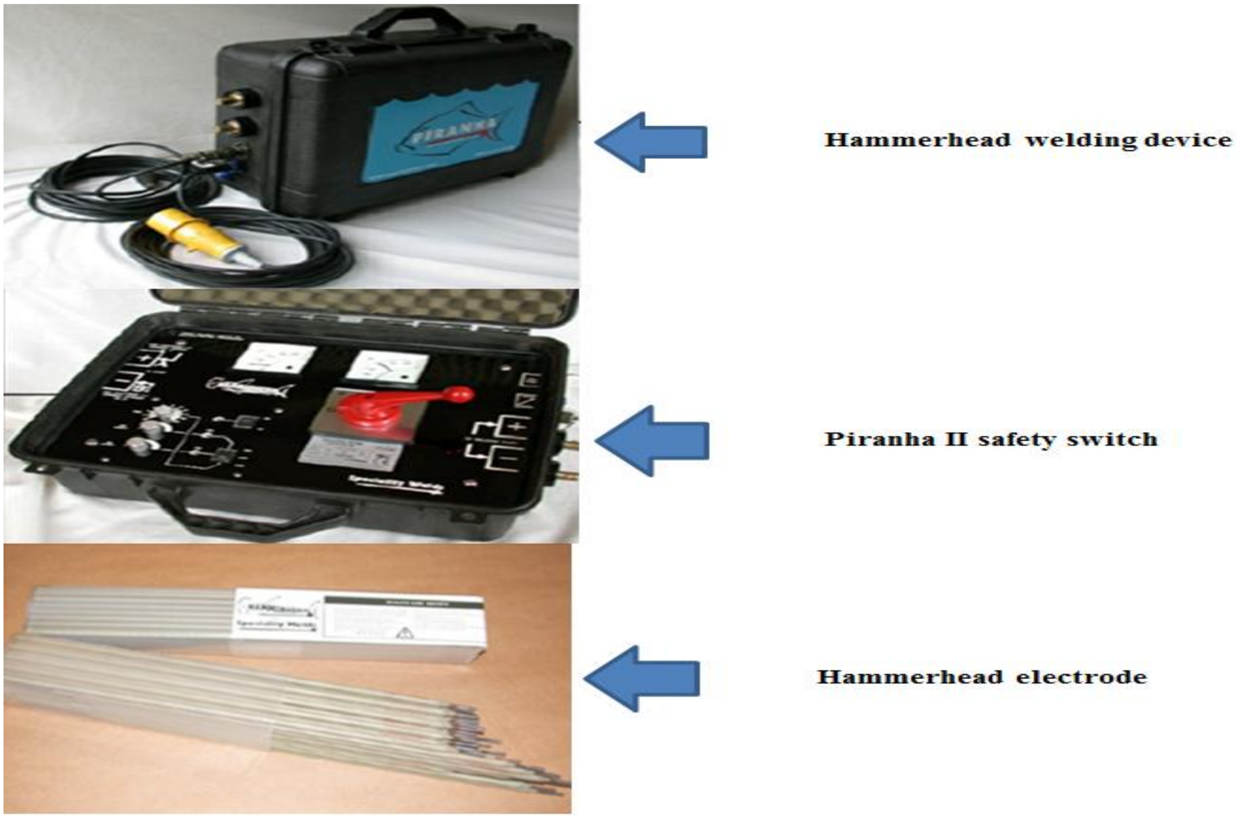

Figure 25: Hammerhead “wet-spot” welding device and electrodes. [70].

Before the start of the welding process, pre-settings are made on the control unit to retrieve 9 volts from the 110 volts transformer which is further rectified into a direct current. A relay is triggered by pressing a reed switch, also known as knife switch to start a timer when the first arc is initiated on the workpiece. The device is switched to “auto” mode after the pre-settings are made. A suitable current needed in the welding process is controlled by the two independent potentiometers: first peak (high) current control and second background (low) current control. It is also possible to set the device to manual mode. In this case, the welder requests for additional “high or low” current values to the initially selected “pre-set” values [11].

Prior to an arc initiated on the workpiece, the first peak (high) current control produces a preset current which allows the electrode to pierce and penetrate through the workpiece, thus creating a hole via the workpiece to aid the joining process. It is therefore required of the diver to apply adequate pressure to the electrode to pierce it through the workpieces during the welding process. A reed switch “relay- trigger”, therefore times the depth of the penetration to eschew bursting via the base (back) workpiece. The second background (low) current control initiates automatically after the penetration process, thus fills the hole created in the first phase of the welding process.

A spot/plug weld which runs through both workpiece is created as a weld nugget until the welding arc is broken. Figure 26 shows a weld sample of the hammerhead “wet-spot” welding process. Moreover, for a second weld to be made, the control device resets automatically after a break in the second phase or after a 5-seconds delay in the welding process. The formation of weldment with this welding process somehow appears to be similar to the principles of riveting [11].

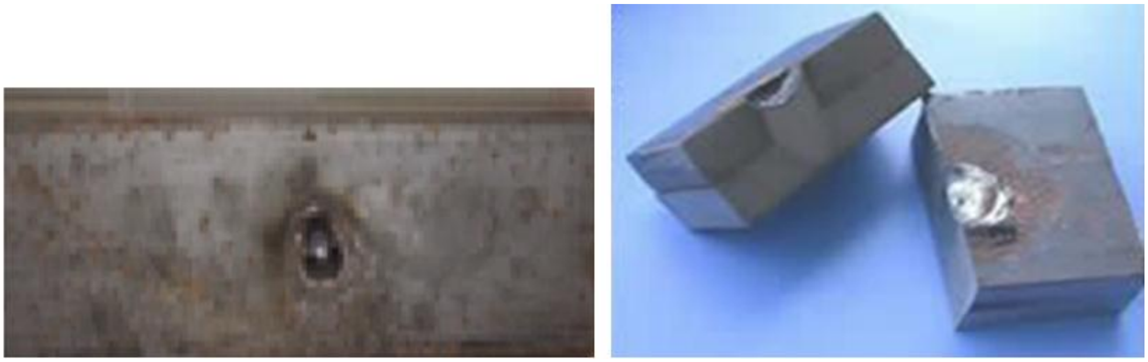

Figure 26: Hammerhead “wet-spot” welding samples [70].

In wet underwater welding, hammerhead “wet-spot” welding method also serves as a remotely controlled process. The control device is automatically operated above water level there by controlling the welding speed, welding time, and deposition rate suitable for a particular electrode and thickness of the workpieces to ensure quality welds.

An experimental research conducted on low carbon steel with hammerhead “wet-spot” welding process has shown a number of excellent prospects with fewer defects [11]. The composition of the base metal and the hammerhead electrode used are represented in table 8 and table 9 respectively. The welding process was carried out both in the wet environment (W) and dry environment (D).   Four persons were employed to carry out the welding process and out of this number, two were skilled welders. The welding parameters were the same but the visibility to weld was different. A lap joint about 50% overlapping between the steel plates was to be welded. Plates were clamped to prevent relative movement. A 150x150x1, 1.0 millimeter steel plate of carbon equivalent value CEV 0.35, was used as the sample for this experimental work. The core wire and outer flux coating of the hammerhead electrode was 3.2 mm and 6.0 mm respectively. The applied force used during the welding process was about 5-10Kg, hence producing a pressure at the tip of the electrode approximately 1.73 – 3.49N/mm^2 (MPa) [11].

Table 8: Composition of the steel plate sample [11].

Element	C	Si	Mn	P	P
% (max.)	0.2	0.55	1.6	0.035	0.035

Table 9: Composition of Hammerhead electrodes [11].

Element	Cr	Ni	C	Mo	Mn	Si	Nb
Min.	21	11	0.020	3	0.60	0.70	-
Max.	24	14	0.10	5	2	2	-

It was observed that, the quality of the weldments made were somewhat similar in both dry (D) and wet (W) situations, even though the weldments were performed in nil visibility. Also, there were no significant differences between the weldments made by the skilled welders to that of the un-skilled welders. Adequate fusion between the plates was observed. Minor defects such as slag inclusions were observed in the wet spot welds. Defects from the dry spot weld were not visible to the naked eye. A convex circular pattern appeared on all the welds but that of the wet spot welds were more pronounced. There were excess “flash” on the wet welds due to excess material which came off the molten nugget as a result of continuous pressure on the electrode. The flash material can be removed by a hammer blow. Good penetration was achieved in both welds as a result of a blister showing at the back-face of the very base material. However, the depth of penetration was not accurate enough in both cases and also welds produce in air were larger than those produce underwater (about 50% difference). Figure 27-30 shows the macro-photographs of the weldments made in both dry (D) and wet (W) environment by the respective welders noted as Welder A-D.

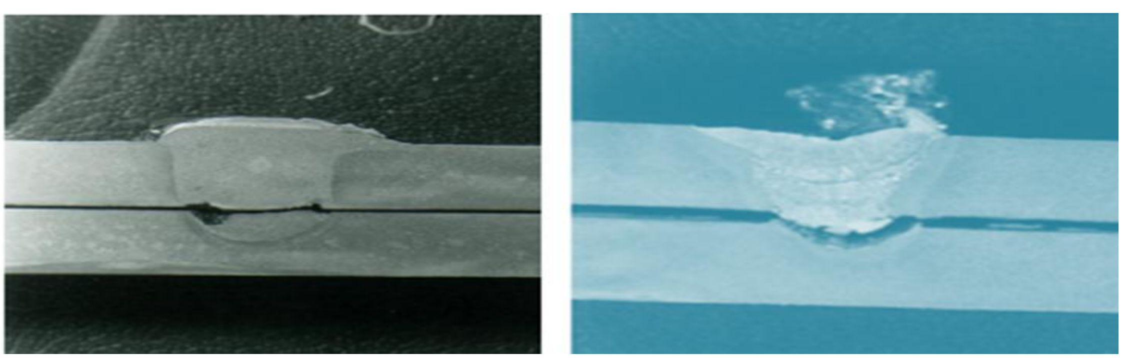

Figure 27: Macro-photograph for welds D1 (left) and W1 (right) conducted by Welder A [11].

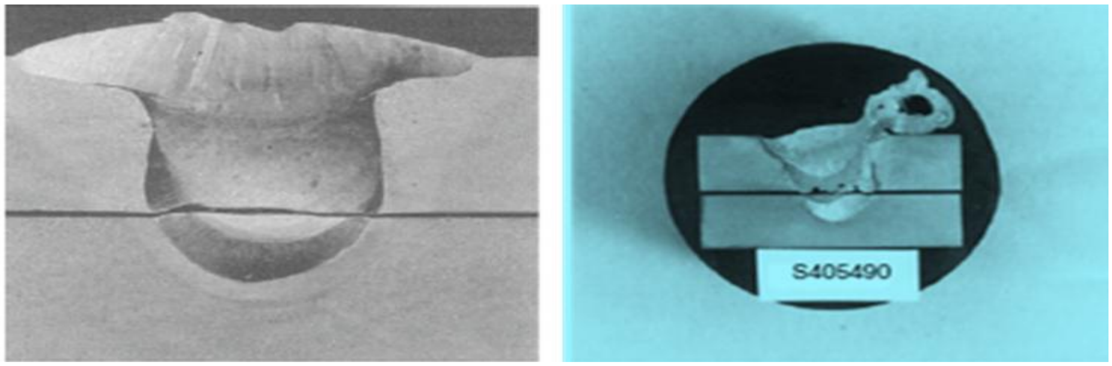

Figure 28: Macro-photograph for welds D1 (left) and W1 (right) conducted by Welder B [11].

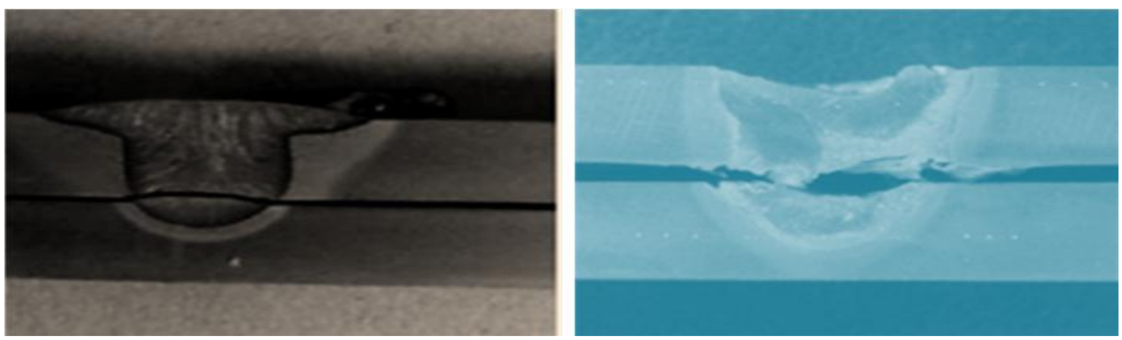

Figure 29: Macro-photograph for welds D1 (left) and W1 (right) conducted by Welder C [11].

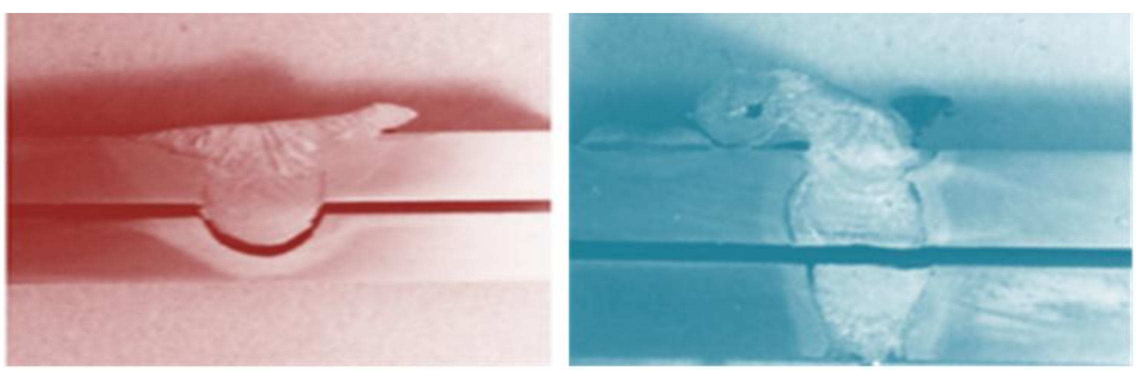

Figure 30: Macro-photograph for welds D1 (left) and W1 (right) conducted by Welder D [11].

A transverse tension shear test performed for both the wet and dry welds showed a less tensile strength properties of the wet welds as compared to the dry welds. This result is linked to rapid cooling rates observed during the wet welding process, hence affecting the mechanical strength of the welds. Also a hardness survey performed on the two welds showed lower hardness values in the wet welds as compared to that of the dry welds. The heat affected zone in the wet welding process did not yield into a martensitic structure. However, a macro/microscopic survey, as illustrated from figure 35 - 38 above, showed that the increase in hardness in the dry welds is as a result of increased dilution during the "high" current stetting operation, thus diluting more carbon from the base material into the molten weld pool. A martensitic formation was therefore observed.

A graph of Hammerhead single wet and dry spot welds was plotted to determine the failure load values of actual wet welds, theoretical average of the wet welds, actual dry welds and the theoretical average of the dry welds, as illustrated in figure 31 below. . From the graph, it can be seen that the failure load values obtained in the dry welds were higher than those obtained in the wet welds. This implies that the hardness of the welds created in the dry environment were higher than those created in the wet environment. This result however contradicts the expected results. This is because it is a known fact that underwater welding is affected by rapid cooling rate which leads to harder welds and also embrittlement in the heat affected zone as observed in most conventional welding processes [70, 73].Hence, the wet welds happens to be more ductile than those made in the dry environment as depicted by the theoretical average values of both the wet and dry welds.

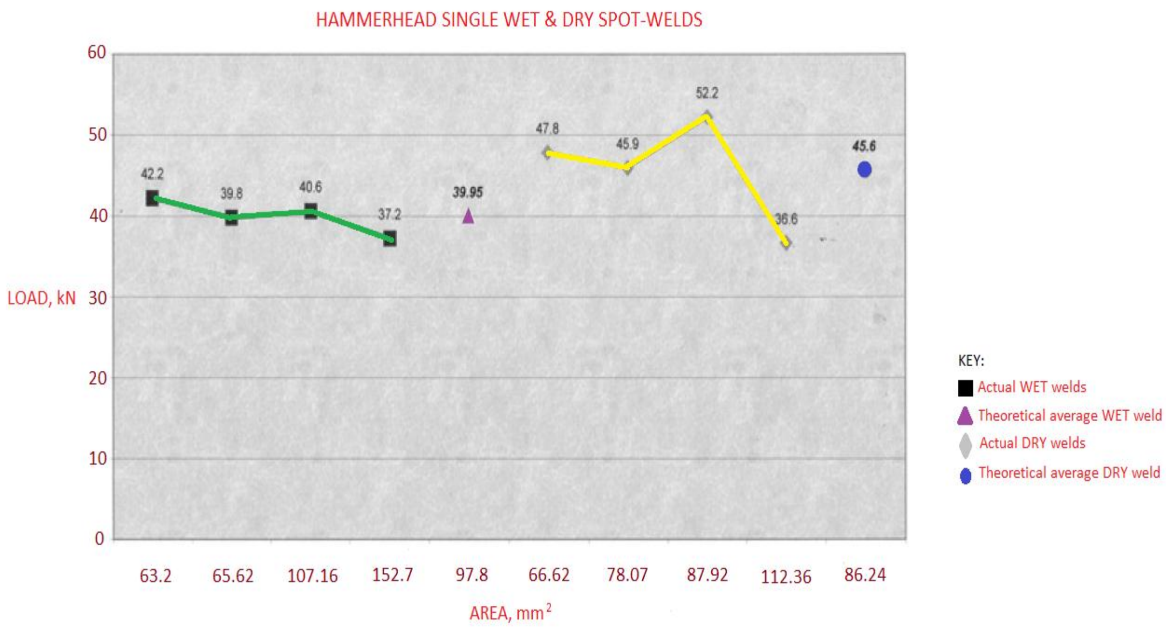

Figure 31: A graph of Hammerhead single wet and dry spot welds [11].

Advantages of Hammerhead "wet-spot" welding

A list of advantages is presented below [11].

- The ability to produce consistent quality spot welds in nil visibility
- High versatility since there is no need to control welding parameters such as travel speed, electrode angles, arc length.

- High productivity in terms of deposition rate since there is no need for groove or material preparation/cleaning
- Does not require any welding skills, hence saves time and money incurred for training welders
- There is no need for multiple pass as observed in fillet and butt welds
- Suitable for welding stainless steels and/ or high strength carbon steels
- The electrodes offer high strength and high toughness properties and it’s capable of resisting hydrogen cracking.

Disadvantages of Hammerhead “wet-spot” welding

A list of disadvantages is presented below [11].

- Deep penetration is rarely achieved due to lack of preparation of the materials to be joined together.
- Slag inclusions are possible to occur in weldments made in wet underwater welding.
- The process is limited when workpieces to be joined together are thicker.
- There is a possibility of martensitic formation in the HAZ during dry welding, hence tensile strength is reduced.

Interesting enough, it has been presented in several papers [10, 31, 32, 33] that wet underwater welding with conventional SMAW process produces a lot of defects such as porosity, hydrogen and oxygen cracking, slag inclusion, as well as martensitic structure in the heat affected zone as a result of rapid cooling rates. However, examining and evaluating the performance of Hammerhead “wet-spot” welding in wet underwater welding, it can be said that Hammerhead “wet-spot” welding could be used as an alternative welding process to SMAW process in wet underwater welding.

4.3 Laser Beam Welding

Laser beam welding in recent times has been opted as one of the effective underwater welding processes offshore. This is because laser beam welding exhibits better weldability on offshore steel grades than conventional welding processes, of which ferritic stainless steel is a typical example [75].

The acronym “laser” stands for light amplification by stimulated emission of radiation, and by this definition lasers used for material processing are of high energy density, intense heat and produces narrow width at both the heat affected zone and the fusion zone [75]. Laser beam welding can therefore be described as the use of a focus light beam which possesses high heat energy to join materials without any external pressure applied and with or without the aid of shielding gases [76]. The different types of lasers which have received recommendations for welding applications are CO_2 lasers and Nd: YAG solid state lasers [77], and these lasers have been noted for their distinct welding processes such conductive limited welding and keyhole welding [78-80].

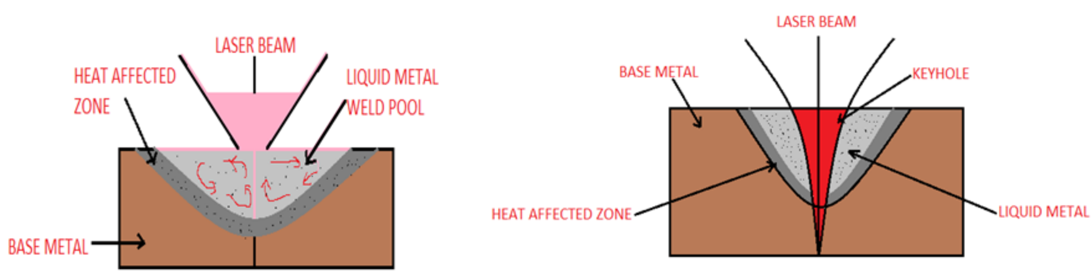

Figure 32: Schematic view of conduction melt pool (left), and deep penetration welding mode (right). The surface boiling and marangoni effect are more in conduction laser welding (adapted from [10]).

An experimental research conducted on a 304 stainless steel with underwater Nd: YAG lasers (HL4006D) welding process has shown satisfactory results. The experiment was performed in both wet and dry (local cavity method) environments. A laser power of 3 kW, welding speed of 1 m/min and a focal position of 1,0mm was used in the set-up [81]. Semi-reflecting mirrors and infrared optical sensor were used in the welding process monitoring. Also, nitrogen was employed as a shielding gas so as to decrease porosity for the keyhole welding process [81-83].

The first experiment was performed as a wet underwater welding process, where the laser beam was irradiated directly onto the workpiece at a water depth from 0mm (in air) to 10mm. Figure 33 shows the experimental set up [81].

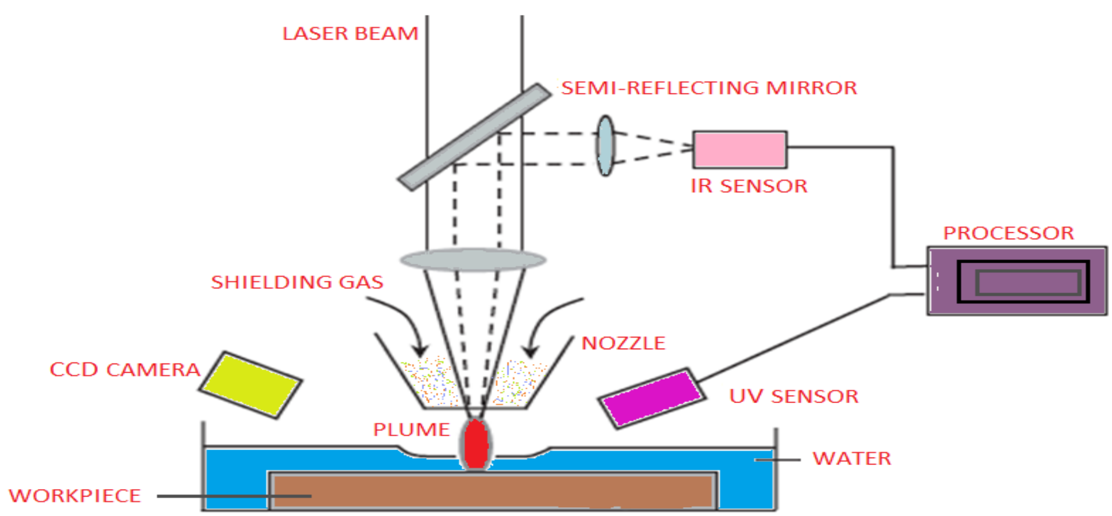

Figure 33: Schematic diagram of a monitored underwater laser beam welding [81].

The result of the first experiment, as depicted in figure 34-36, shows that at a water depth of 1.0 mm, the laser beam penetrated deeply through the film of water. A metal plume formation evolved on the workpiece resulting in a keyhole weld. Hence a good quality weld was obtained on the steel sample. However as the depth of water was increased from 3.0 mm to 10.0 mm, the penetration of the laser beam was observed to be shallow, thus creating a blue plasma on the surface of the workpiece. This occurrence therefore resulted in a poor weld [84].

Figure 34: Plume and plasma induced in underwater LBW (3kW, 1.0m/min) at 1.0mm water depth [81].

Figure 35: Plume and plasma induced in underwater LBW (3kW, 1.0m/min) at 3.0 mm water depth [81].

Figure 36: Plume and plasma induced in underwater LBW (3kW, 1.0m/min) at 10mm water depth [81].

However, the second experiment as illustrated in figure 37 below, utilized a local cavity method by means of a water curtain gas-shielding nozzle which expelled water to achieve a dry welding environment. The shielding effects of the local cavity method and detected signals where studied by means of varying the flow speed of the gas for different nozzles [81].

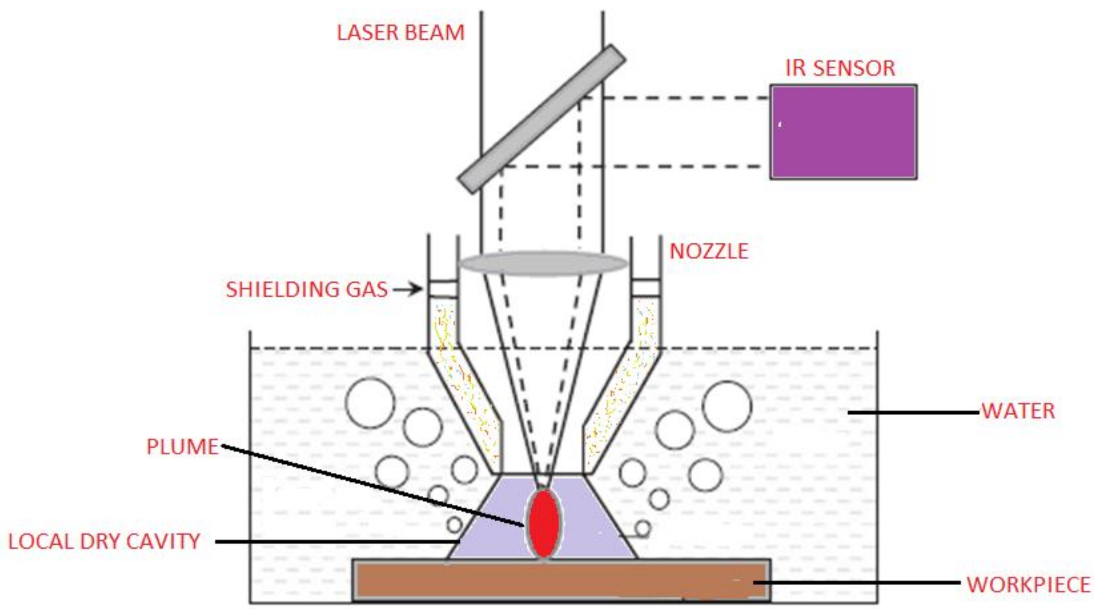

Figure 37: Schematic diagram of local dry cavity underwater laser beam welding process. [81].

The results of the second experiment showed three different weld qualities in relation to shielding conditions as presented in figure 38 below. A good quality weld was obtained in the first condition when a stable dry cavity was formed by the water curtain. In the second condition, a fairly good quality weld was obtained. This was due to the entry of water droplets into the dry cavity which obstructed the laser beam, thus resulted in weld pool oxidization. The quality of weld obtained in the third condition was somewhat of bad quality due to the presence of water in the cavity which interfered strongly with the laser beam [84].

Figure 38: Local dry cavity observations formed by water curtain nozzle in underwater LBW [84].

On this note, it can be said that wet underwater laser beam welding is affected by depth of water, thus offering a shielding effect to the laser beam. Depth of water is therefore a detrimental factor to wet underwater laser beam welding since deep penetration cannot be achieved when water depth is high. Also, sound welds are bound to occur in underwater local cavity method but with few defects. However, it can be said that the local cavity method is therefore dependent on the flow of the shielding gas and stability of the water curtain [84].

Advantages of LBW

A list of advantages is illustrated below [76, 78, 79]:

a) Deep weld penetration with narrow HAZ is achievable
b) Toughness properties of welded joints are better as compared to conventional welding processes
c) Distortion of welded structures is very minimal
d) Productivity is high since thick material sections can be welded at high speeds without multiple pass.

Disadvantages of LBW

A list of disadvantages is illustrated below [76, 78, 79]:

a) Initial cost of acquiring welding equipment is very high
b) The welding process is limited to space, and environmental conditions due to the extreme protection needed
c) Cracking defects are bound to occur due to the rapid cooling effect of the welding process.

5. DISCUSSION AND CONCLUSIONS

This chapter presents the findings of the literature study conducted under the theme of this project work. Also the findings are discussed with regards to the research questions constructed for this project work.

5.1 Findings and Discussions

After thorough study of highly ranked research papers, the first research question of this project work resulted in a number of findings. Actually, it was in the interest of this paper to investigate the different types of offshore welding environments since previous studies in this field have not explicitly clarified the differences between these offshore welding environments. It was found that offshore welding environments consist of three types and they are; on-board offshore welding, dry dock welding and underwater welding. The approach used in welding offshore structures in these three welding environments is very distinct and diverse. On-board offshore welding was observed as the technique used for welding offshore structures in work centers mounted on ships, lay barges or lay vessels. Also, dry dock welding technique is performed when defective offshore structures such as pipelines are pulled to the water surface for welding. This welding process is normally carried out in air, hence achieving a dry welding environment. It was further observed that underwater welding technique is the process of welding offshore structures beneath water.

With reference to the finding obtained from the first phase of the literature study, it can be deduced that on-board welding environment happens to give the best weld joint quality and protection among the three welding environments. However, it was somewhat surprising that dry underwater welding has to some degree the same weld qualities as on-board welding despite the operating environmental conditions prevailing. Another important finding was that, in terms of cost effectiveness with respect to time, underwater welding (wet) is seen to be a much better welding technique as compared to dry dock welding even though the whole process is affected by the depth of water. This finding corroborates the ideas of [29, 30] who suggested that wet underwater welding is the cheapest and fastest way to weld underwater offshore structures. Moreover, weldments made underwater, especially wet underwater welding are prone to severe defects as compared to on-board and dry dock welding. It can thus be suggested that dry dock welding could be preferred if the depth of water is shallow. This is because the weldments made in dry docking can be protected in a better way than when performed in wet underwater welding.

Additionally, the second research question also brought useful results to the classifications of materials applicable to offshore as well as the various types of structures installed in the offshore environment. The results indicate that offshore structures could be grouped in two categories and these are fixed offshore structures and floating offshore structures. A typical example of fixed offshore structure is a jacket platform which facilitates drilling and production purposes. Surprisingly, it was found that jacket platforms are falling out of use from offshore structural system as a result of the depleting shallow depth oil and gas reserves. Constructing jacket platforms is therefore not economically and technically feasible in deep to deeper waters oil and gas exploitation. In view of this, floating offshore structures such as FPSO, semi-submersible structures, TLP, and spar are much preferred in recent times. The most interesting finding was that pipelines are considered either as fixed or floating offshore structure, depending on whether it is made to rest on the seabed or floating on the seabed. Another important finding was the process of laying pipelines to obtain characteristic shapes such as J-shape or S-shape. It was observed that the laying process could lead to bucking, fracture, and flooding of the pipeline. This finding is in agreement with [39] findings which showed a number of defects which erupts doing the normal usage of pipelines after being laid.

Also results obtained from the research question relating to offshore materials shows that materials to be selected for constructing offshore structures should possess high strength properties, fracture toughness, corrosion resistance properties and excellent weldability properties. Surprisingly, carbon and low alloy steels were found to be non-attractive materials since they possess poor weldability properties. A new class of HSLA called thermo-mechanical control process (TMCP) steels has demonstrated the said properties said herein and are used for constructing pipelines and offshore structure. This finding is consistent with that of [4] findings which showed specifications and typical chemical composition of a TMCP Grade 60 pipe. In contrast, [40] findings have shown that TMCP steels with yield strength of 355 MPa exhibit low toughness, hence resulting in LBZ. Nevertheless, [4] findings has shown that alloys could be used to modify LBZ free steels to achieve high-quality offshore structural steels with excellent weldability, higher fracture toughness, and higher strength. Another important finding was that materials such as 22 Cr and 25 Cr duplex and 6 Mo stainless steels, nickel base austenitic alloys and titanium alloys could be used for offshore structures since they possess excellent weldability properties and can also fight against the corrosive environment offshore. In general, therefore, it seems that selecting a material for a specific offshore structure is a challenging task and also requires that a number of factors should be consideration.

The third research question serves as the main task of this project work. The question was constructed in a way to help find why modern welding technologies should be preferred for underwater welding of offshore structures to conventional welding processes. It was also of interest to find which conventional welding technologies have been used for underwater welding of offshore structures, their associated defects and why they are still in use. The findings obtained indicates that conventional welding technologies such as SMAW, FCAW, GMAW, and GTAW have been used for underwater welding of offshore structures. Wet underwater welding has been carried out mostly with the SMAW process and the reasons is that, wet SMAW process is versatile and the cost of welding is economically feasible. However, with the inception of hyperbaric chambers, it seems possible to performed wet hyperbaric welds with SMAW process. The FCAW process has also been used for wet underwater welding but has not received much recommendation as SMAW due to the nature of equipment employed for the FCAW process. However, in terms of weld quality, the FCAW process was noted to surpass that of SMAW since it produces fewer defects. Moreover, the FCAW process demonstrates very good quality welds in the dry environment, hence suitable for dry underwater welding tasks. It can be suggested that the FCAW process can also be performed as a wet hyperbaric welding process. In addition, the GMAW and GTAW processes have receive high recommendations for dry hyperbaric welding due to the complexity of equipment utilized. The GMAW and GTAW processes were noted to produce very good quality welds when applied on weldable materials such as carbon steels, high strength low alloy steels, stainless steels, aluminum, copper, and nickel alloys. Few defects were noticed and these are hydrogen and oxygen contaminations as well as embrittlement in the HAZ. The reason why conventional welding processes are still in use is because there is less knowledge about the impact of modern welding processes in the offshore industry and in view of this; they have not been utilized fully for welding offshore structures. Instead, most of the conventional welding processes have been automated. This finding is consistent with findings of [85] which show that, GMAW process is now automated as an orbital GMAW welding process, likewise GTAW process as a tungsten inert gas hyperbaric orbit robot welding. However, even though some conventional welding processes have been automated to serve as remote welding processes there is still gaps which arise in the issues of weld quality, safety and productivity.

To bridge this gap, the current study found that modern welding technologies such as friction stir welding (FSW), laser beam welding (LBW), and Hammerhead "wet-spot" welding could be preferred to conventional welding processes to weld offshore structures underwater. Firstly, the FSW process provides the possibility to weld wider range of materials such as aluminum alloys, titanium alloy, magnesium, copper, steels and alloy steels which are mostly used as offshore structures. Also, the FSW process produces fewer defects with excellent weld quality in terms of fatigue strength, and tensile strength. The likelihood of a martensitic structure to occur in the HAZ is negligible. This is because the process itself does not involve the melting of the base metals into molten pool but rather softens them to enhance easy stirring for perfect quality weld. In contrast, there is a high possibility of a keyhole at the end of each weld. Also welding speeds are slow and there is the need to provide backings for the materials to be welded. One unanticipated finding was that, material thickness and hardness is not at all a challenge with FSW since both ends of the workpieces could be welded to ensure deep penetration.

Also, the Hammerhead "wet-spot" welding technique is a special wet welding process which utilizes a consumable Fe-Cr-Ni-Mo coated electrode to produce spot/plug welds one at a time even in nil visibility. It is a manual metal arc welding process and basically similar to the principles of riveting. Weldments are made through high and low currents from an electrical control device. Weld joint defects such as porosity, hydrogen and oxygen cracking are minimal in Hammerhead "wet-spot" welding process. However, although it is a general fact that rapid cooling rates produces defects in weld joints, the Hammerhead "wet-spot" welding process rather produces joints with high strength and high fracture properties, thus it is not affected by rapid cooling rate in wet underwater welding. The probability for a martensitic structure to be born in the HAZ is none. Also, the most interesting finding was that, with Hammerhead "wet-spot" welding process there is no need for skilled welders/divers to perform the welding task, no need for material preparation or cleaning. However, the welding process is limited if thick metal sections are to be welded together, hence lack of penetration is prominent. Nevertheless, there is no need for multiple passes as observed in SMAW fillet and but welds. Offshore structural materials such as stainless steels, and high strength carbon steels can be easily welded with Hammerhead "wet-spot" welding process.

Another important finding was that laser beam welding (LBW), which exhibits excellent weldability on offshore steel grades than conventional welding processes stands to be one of the effective underwater welding processes offshore. The CO_2 laser and Nd: YAG laser types are the common types used for welding applications due to their distinct welding processes such as conductive limited welding and keyhole welding. Interestingly, it was found that the depth of water is a detrimental factor to wet underwater laser beam welding since deep penetration cannot be achieved. It may be the case that the film of water turns to obstruct the rays of the laser beam even when the laser beam is accurately focused on the workpiece underwater. It is therefore a challenge to obtain the maximum heat density needed to produce a perfect weld. Utilizing a local cavity method for dry underwater LBW produced sound welds with less stability. The HAZ produced by LBW is very narrow, thus leads to less distortion of the welded structure. Thick material sections can be welded at a faster rate as a result of keyhole welding. Generally, the equipment employed for LBW is very expensive and also setting up the welding equipment demands space and time. It can thus be suggested that the mounting of such equipment in hyperbaric chambers could be a bit challenging.

Some of the issues emerging from the findings imply that choosing a specific environment for offshore welding demands a lot of consideration in terms of the influence the environment has on the welding process. There is also an implication that underwater welding cannot be ruled out of offshore welding since it serves as repair and maintenance technique. Hence, there is also the need to consider between wet underwater welding and dry underwater welding for a particular underwater welding task. For cost effectiveness, wet underwater welding could be opted. However for optimum quality welds with few defects, dry underwater welding could be the best choice. Conventional welding processes still have a position in offshore underwater welding since such processes cannot be eliminated swiftly and to some extend are undergoing developmental changes to lessen the defects they eventually contribute on offshore structures. In addition, modern welding processes such as FSW, LBW and, the Hammerhead “wet-spot” welding could be utilized in welding offshore structures both in wet and dry underwater welding. However, although the results obtained from welding offshore structures with modern welding processes seems satisfactory, there is still a gap to fill because the weldments made in wet underwater welding processes from the various modern welding technologies reviewed were made in fresh water but not sea or lake water. However, since the findings obtained from the literature study did not explicitly explain the different situations between welding in fresh water and welding in sea or lake water, a question still stands whether the salinity of the sea or lake water could have had an influence on the welding processes.

5.2 Suggestions for Further Studies

In order to commercialize the use of modern welding technologies, as presented in this study for underwater welding of offshore structures, the following suggestions for further research should be considered. Additionally, to fully harness the benefits of conventional welding processes in underwater welding, the latter suggested topic below should also be a target for researching.

a) Performing an experiment in wet underwater welding in sea or lake water with modern welding technologies such as FSW, LBW and the Hammerhead “wet-spot” welding since fresh water was used in the afore-mentioned experiments. This would help to investigate micro-structural effects the salty nature of the sea or lake water would have on offshore structural materials and the entire welding process.

b) Performing underwater hybrid welding either as friction stir laser hybrid welding or some conventional welding processes with laser welding on offshore structural materials.

c) Maximizing the performance of conventional welding processes for underwater welding tasks through effective automation or mechanization systems.

6. CONCLUSIONS

This research work has investigated welding processes of metals for offshore environment, specifically modern welding technologies for underwater welding. The objectives of this work were constructed in three phases, of which four concrete research questions were formulated. The first objective was to clarify the different forms of welding process environments being employed offshore. It was found that offshore welding process environments consist of three forms and these are on-board welding, dry dock welding and underwater welding. Additionally, it was found that underwater welding could be categorized under two main classes such as wet underwater welding and dry underwater welding.

The second objective was to examine and present materials (metals) applicable to offshore and also the various types of structures installed in the offshore environment. It was found that a new class of HSLA called thermo-mechanical control process (TMCP) steels could be used for constructing pipelines and offshore structure. A second major finding was that materials such as 22 Cr and 25 Cr duplex and 6 Mo stainless steels, nickel base austenitic alloys and titanium alloys could also be used for offshore structures since they possess excellent weldable properties, high fracture toughness, high strength, and can also fight against the corrosive environment offshore. Furthermore, offshore structures were found to be fixed offshore structures and floating offshore structures and are mainly constructed from steels. It was also shown that floating offshore structures are become more popular due to deep to deeper water oil and gas exploitations as a remedy to the depleting shallow water oil and gas reserves.

The third objective was to investigate suitable modern welding technologies applicable for underwater welding of offshore structures. It was evident that modern welding technologies such as friction stir welding (FSW), laser beam welding (LBW), and Hammerhead “wet-spot” welding could be suitable for underwater welding of offshore structures. This finding was hypothesized after reviewing, examining and evaluating the micro-structural properties of the weld joints after been subjected to tensile testing, hardness testing and fracture testing. The performance of conventional welding processes on offshore structures in underwater welding were also examined and it was found that a lot of defects such as cold and hot cracking, porosity, slag inclusion, undercutting, and hydrogen pores are bound to occur in the weld joint. Conclusions can be drawn that, modern welding technologies such as friction stir welding, laser beam welding and Hammerhead “wet-spot” welding could be used for underwater welding of offshore structures since they provide excellent quality welds both at wet and dry environments. Also these modern welding technologies could be suitable to weld a wider range of constructional materials during the fabrication process since nowadays offshore structural materials are of different steel grades and alloying materials.

This research work makes several noteworthy observations to the general understanding of offshore underwater welding in terms of offshore welding environments, materials used for constructing offshore structures and the welding process which could be employed to achieve cost minimization, high productivity, and safety. However, despite the contributions highlighted, the most important limitations lie in the fact that wet underwater welding was performed in fresh water but not sea or lake water. Also the availability of research papers in this particular field was limited, hence multiple reviews, examinations and evaluations were impossible to fully achieve. Owing to this reasons, this research work therefore serves as a platform for further studies.

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