Welding of Offshore Structures

By

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ABSTRACT

Offshore structures are complex structural systems. The fabrication, maintenance and repair of these structures make use of conventional and advanced welding technology. This paper reviews the material used to fabricate offshore structures, welding consumables used and current acceptable fabrication practice.

The challenges faced by welding and joining in the future as well as the particular challenges for Africa are discussed.

Welding of Offshore Structures

1. Introduction

Offshore structures are used for particular operational purpose such as exploration, drilling, handling and storage of oil and gas. The environment in which these structures operate varies from shallow to deep water with temperatures ranging from very cold, to mild, to tropical. Furthermore, these structures are subjected to corrosion, operational stresses and the forces of nature that includes but are not limited too wave action, wind, tides, storms and seismic events.

Offshore structures are generally large and complex structural systems, fabricated using steel tubular members, plates, pipes and profiles interconnected through welded joints. These structures include jacket platforms, jack-up rigs, semi-submersible rigs, and floating production, storage and offloading facilities (FPSO) [1]. See Figure 1.

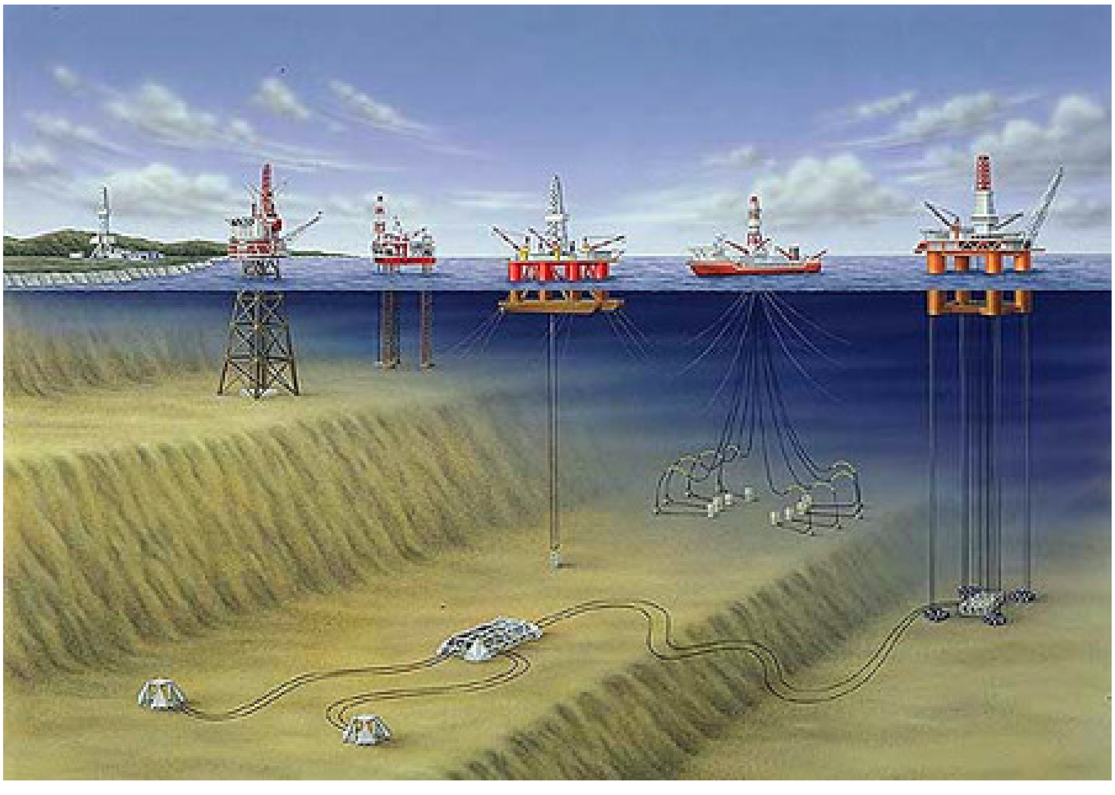

Figure 1. A few examples of offshore rigs, drilling and production platforms. Left to right: onshore platform; fixed platform; jack up rig; semi-submersible; drill ship; tension leg platform.

The search for new energy supplies has resulted in exploration and drilling in remote and more challenging environments. The water depth in which drilling and exploration takes place is moving to ever increasing depths.

In the offshore industry welding is being pushed by ever increasing demands to meet both material design criteria and increased production. Maintaining the structures is a challenge as they have to be repaired and protected after sustaining damage by accidents, corrosion, fatigue and acts of nature.

The correct choice of grade of material, the welding process and welding consumables becomes more critical during fabrication and subsequent repair to ensure efficient, safe and fit for purpose structures.

2. Offshore Structures

Today's multiple options for producing oil and gas from deepwater reserves is still anchored by the welded tubular steel platform jacket, deck, and surface modules. Typical offshore structures [2] (See Figure 2) today would include:

- **Fixed platforms:** Fixed platforms are the offshore production mainstay with economic water-depth limits of about 610 m.
- **Compliant towers:** Floating platforms permanently anchored to the bottom. May be considered for water depths of about 305 to 610 m.
- **Tension-leg platforms:** These structures are attached to the ocean bottom with tendons held in tension. They are used in 305 to 1524 m water depths.
- **Spars:** Buoyant structures shaped like a spar (a single, large-diameter cylinder), with a functional deck mounted on top.
- **Semi -submersible production units:** They can permanently be moored in a field usually producing from subsea facilities.
- **Floating production, storage, and offloading (FPSO) systems:** Ship-shaped vessels with storage and some treatment facilities. Serves both floating and subset production arrays. May be used in water depths ranging up to and beyond 3048 m.
- **Pipeline systems:** Steel pipelines transporting oil and gas in various diameters and operating in various water depths.

A typical structure consists of various modules including a deck, a substructure, foundation piles, piping etc. The substructure in most cases, is a prefabricated tubular space frame, which in shallow to intermediate water depths extends from the sea floor to just above the sea surface, and is usually fabricated in one piece onshore, transported by barge, launched at sea, and upended on site by partial flooding.

Tubular pilings are driven through the main legs to fix the structure to the sea bottom, provide support for the deck, and resist the lateral loads due to wind, waves and currents. Various other structural designs exist to cater for deeper water.

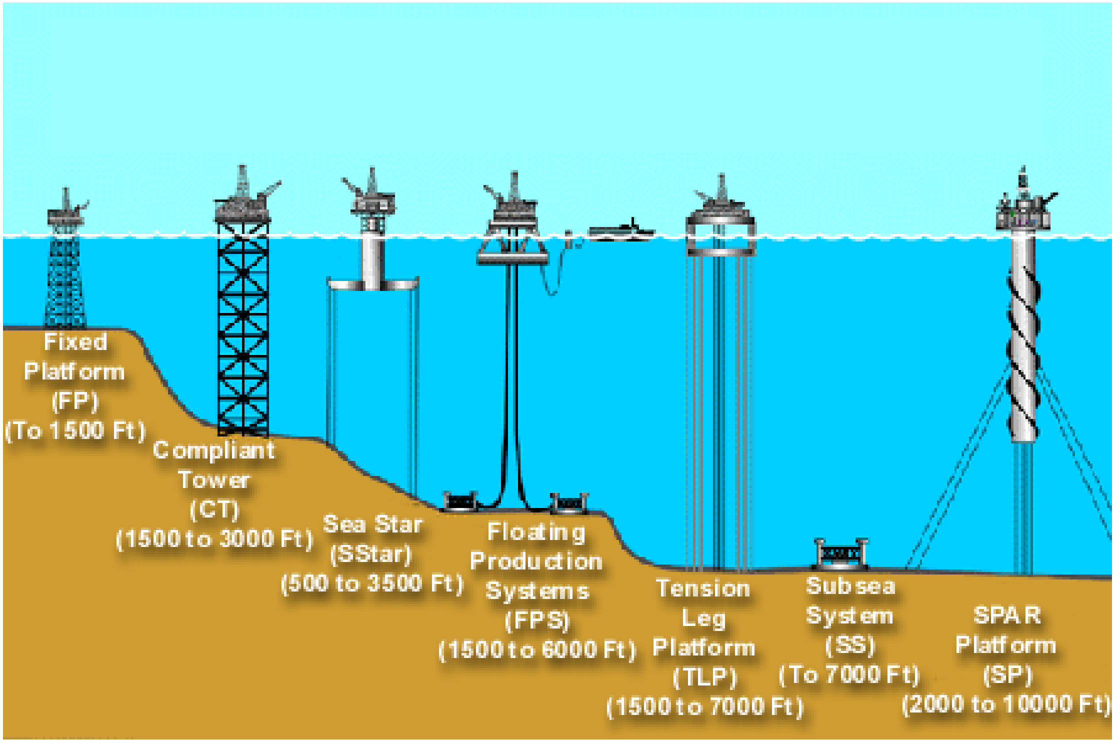

Figure 2. Typical Offshore Structures [3]

The design lives of these structures are typically 20 – 30 years. A large number of these structures have reached, are close to, or have passed their original design lives and continue to operate. Currently, world wide we are faced with aging offshore infrastructure that has to be maintained. The approximate size of the problem is:

- 6000 fixed platforms
- 184 floating production platforms
- 650 offshore drilling rigs
- 175000km of subsea pipelines
- 2900 operating subsea wells

It remains a less costly option to repair, maintain, retrofit and upgrade existing structures compared to fabricating completely new structures.

The next generation offshore structures would be more complex in design, will use more sophisticated materials of construction, will feature increased fabrication complexity, and be expected to have increased production capabilities.

3. Materials used for offshore structures

The materials used to fabricate offshore structures include low to medium carbon manganese steels, high strength low alloy steels, standard and super austenitic stainless steels, duplex and super duplex stainless steels as well as nickel base, copper base, and titanium alloys [6]. These materials are welded to each other to form similar and dissimilar weld joints.

It is expected that steel will be the dominant material into the future. The advantages of structural steels are :

- Excellent availability in different product forms (plate, pipe and profile)
- Long available service history
- Can readily and economically be joined by arc welding
- Strength to cost ratio is favourable.
- Effective corrosion protection technology is available
- Well established design rules for the offshore industry

Fixed offshore structures are conventionally constructed from structural steel with yield strengths in the range of 300 to 350 MPa. The early platforms were fabricated from low carbon steels like ASTM A-7 or equivalent. In 1960 the A-7 grade was replaced with ASTM A-36 or equivalent. In the mid 1990's the dominant steel grades were ASTM A-36 and API 2H grade 50 and their equivalents

For the more critical, higher strength applications steel grades like API 2-Y or equivalent was used. As the size of the offshore structures increase, the size of the members also increases. This drives the demand for higher strength steels with improved fracture toughness and weldability.

The carbon manganese steel grades used for offshore structures depend on the type of structure and the expected service conditions. Jacket tubular products are made from carbon manganese steel with yield strength varying from 350 to 550 MPa. These jacket tubular thicknesses can range from 40 up to 100 mm.

The principal application of very high strength steels offshore has been in the fabrication of jack-ups. Steels with nominal yield strengths in the range 500 to 800 MPa are normally used in fabrication of legs, rack and pinions and spud cans. Thickness ranges from 40 up to 130 mm.

In general, the strength of steel is controlled by its microstructure which varies according to its chemical composition, its thermal history and the deformation processes it undergoes during its production schedule. [5]

Today the low to medium strength steels are produced by the normalised or thermo-mechanically processed routes (TMCP). For the higher strength levels there are processing thickness restrictions to TMCP steels and normalising cannot produce the strength levels required in the necessary section thicknesses. Quenching and tempering is therefore the standard production route for very high strength structural steel. The typical steel strength grades used in offshore structures today are given in Table 1. [5]

Strength Grade (MPa)	**Process route**	**Area of application**
350 (X52)	Normalized	Structures
	TMCP	Structures and Pipelines
450 (X65)	Quenched & Tempered	Structures
	TMCP	Pipelines
550 (X80)	Quenched & Tempered	Structures & Moorings
	TMCP	Pipelines
650	Quenched & Tempered	Jack-ups & Moorings
750	Quenched & Tempered	Jack-ups & Moorings
850	Quenched & Tempered	Jack-ups & Moorings

Table 1. Steel strength grade, process route and area of application in offshore structures.

There are a number of critical factors that need to be considered when dealing with the higher strength steels during the fabrication and repair processes:

- Each steel grade has a range of yield strength, which is not always fully recognized in the design. The yield ratio of the higher strength steels is greater than the current design limits in some codes and specifications. Many engineers and designers do not appreciate that the mechanical properties of a particular steel can vary significantly within a specified steel grade (i.e. steel with a specified minimum yield strength).

- The stress strain behaviour of high strength steels differs somewhat from that of lower strength steels in that they generally show reduced capacity for strain hardening after yielding and reduced elongation.

- The high strength steels have adequate toughness in both the HAZ and the parent material. However we find that with the very high strength weldmetal there is inconsistency in the toughness properties and consequently some concerns regarding brittle fracture.

- Fatigue strength of the welded high strength steel joints does not increase with the increase in yield strength.

- There is limited information of the long term use of high strength steels in a marine environment.

- Most codes and standards relate to the low and medium strength steels. In most cases the use of the design formulae is limited to steels with yield strengths less than 500 MPa. This is a disadvantage for the use of the higher strength steels.

Additional benefits of using the higher strength steels are that there significant time and cost savings due to the use of thinner sections, reduced weld volumes and the possibility of reducing or avoiding post weld heat treatment in some instances.

The stainless steel and nickel based alloys are mainly used in processing, piping and storage applications where the strength and corrosive characteristics of these alloys are essential.

In the late 1950s almost 100 aluminium jackets were installed in Venezuela. The corrosive conditions due to dissolved oxygen and salt content precluded the use of steel. These platforms required the development of new technology incorporating design, fabrication and installation. The platforms performed satisfactorily until they were removed when the oil reserves where depleted.

The trend towards the usage of higher strength and tougher materials in the construction of offshore structures will continue as new material and suitable welding consumables are developed. The use of these materials result in significant cost and weight savings as it allows the use of thinner sections and results in shorter construction times. However these materials require more stringent control during fabrication in terms of welding, cutting, heat treatment and forming to avoid defects.

4. Fabrication and repair of offshore structures

The operational environment as well as financial aspects requires that a large degree of prefabrication must be performed onshore. The amount of offshore work has to be kept to a minimum, mainly through effective design.

All structural welding is normally carried out in accordance with international codes and standards such as API RP 2A, 'Recommended Practice for Planning, Designing and Construction of Fixed Offshore Platforms', ISO 19902 ‘Fixed steel offshore structures’, and the ANSI/AWS and ASME BPV IX codes, latest revision.

4.1 Welding Technology

Welding is a fundamental technology in the fabrication and repair of structures in the offshore industry. These structures can be above or below sea level, or onshore. Welding is the enabling technology without which the offshore industry cannot operate at its present level of sophistication. Yet welding technology is often taken for granted as a mature and established technology and mostly remains in the background, almost forgotten. Welding has like most technologies developed steadily over time, allowing new benefits in terms of what can be achieved, and in terms of process economics.

Welding technologies already reach across 140 different processes and process variants. Whilst no fundamentally new arc welding techniques have emerged in recent years, there have been significant developments focused on improving process efficiency and productivity together with the facilitation of increased welding automation. Welding in the offshore industry is dominated by the conventional arc welding processes.

Typical welding processes used in the offshore industry are :

- Shielded Metal Arc Welding (SMAW)
- Gas Metal Arc Welding (GMAW)
- Gas Tungsten Arc Welding (GTAW)
- Submerged Arc Welding (SAW)
- Flux Cored Arc Welding (FCAW) – mostly gas shielded

The different welding processes, welding consumables and process combinations are suitable to meet the fabrication and repair requirements of the offshore applications. The ability of some of the welding processes to operate on site is a major advantage.

The use of higher strength steels in offshore applications is ever increasing. These demanding applications require a wider range of welding processes, offering flexibility and higher productivity, to be competitive and produce acceptable quality welds. In turn there is a growing need for high strength steel welding consumables that maintain toughness and are easy to use.

A requirement for the high strength consumables is that their weld metal properties should be reasonably insensitive to variations in welding procedure parameters, such as heat input and interpass temperature, especially during manual welding. [6]

High strength steel welding consumables have typical compositions in the range 0.04-0.08 % Carbon, 1- 2 % Manganese, 0.2-0.5 % Silicon, 1-3 % Nickel along with some additions of Cr, Mo and sometimes Cu [7]. As the alloying content and strength increase, bainite and martensite gradually become the dominant microstructural components rather than the softer phases associated with strength levels less than 690 MPa. Although well-balanced mixed (martensitic / bainitic / ferritic) microstructures can offer attractive combinations of properties, the microstructure, and hence the mechanical properties, tend to become sensitive to the cooling rate. Table 2 [8] gives typical mechanical properties for commercial welding consumables.

Minimum Yield Strength (Mpa)	350	400	420	500	550	690
Minimum Tensile Strength (Mpa)	490	520	550	610	670	770
Minimum Impact Energy (J) @ -60°C	35	35	35	35	35	35

Table 2. Typical mechanical properties of commercially available welding consumables.

During welding the consumable should overmatch the yield strength of the parent material and the associated heat affected zone. If the weld under matches in strength then any enforced deformation will be concentrated in the relative small weld metal volume which increases the risk of failure.

Welding on offshore structures is regulated by international codes and standards, ship class rules, engineering specifications and client specifications depending on the service environment. These standards can place additional strength, cracking resistance and toughness requirements on the weldmetal.

Welding procedures used during the fabrication and repair of offshore structures must take into account the factors related to the properties of the steel grade used. This includes strength, microstructure, impact properties, hardness of the heat affected zone and numerous others.

Most of such repair procedures include welding which is quite different from joining during fabrication regarding the parameters, the weld sequences as well as the metallurgical conditions and the design features. This means that ideal welding conditions cannot always be achieved during repair welding. Additionally, poor material conditions of the component segments to be repaired might result from previous service operation.

The factors contributing to failures of welds are well known. They include residual stresses, defects or microstuctural imperfections, loss of optimal bases metal microstructures during the weld thermal cycle, toughness changes, dissimilar material properties and the stress raising effects of geometrical discontinuities at the joint. Add to this the welding process variables, joint configurations and the variations in base material and welding consumable composition and we experience an extremely complex environment.

Research is ongoing in using friction stir welding, laser welding and other welding processes in the fabrication and repair of offshore structures. The main aims are to provide increased efficiency and increased quality of welding during fabrication and repair. In the near future we will see these welding processes used.

4.2 Jacket Fabrication

The jacket legs are normally fabricated from tubular sections, which are welded. The fabricators normally use plate to roll and fabricate their own structural steel pipe. The welds are full penetration welds in order to withstand the design and operating stresses.

Figure 3. Typical offshore jacket structure

The large diameter thick section pipes are typically manufactured as follows [9] :

- Steel Plate (355 – 550 MPa yield strength, 40 – 100 mm thick) is cold formed.
- Tacking on the external side by SMAW.
- The main longitudinal seam is welded using SAW.
- Non destructive examination using ultrasonic test on the longitudinal weld is carried out.
- Girth welding of rotatable pipes using SAW or gas shielded FCAW.

The length and throat thickness of the tack weld must be sufficient to prevent cracking during the SAW welding and must maintain the pipe dimensions.

The welding efficiency on the longitudinal seam is maintained by using multi-wire submerged arc technology. For girth welding mostly single wire SAW is used.

Pipes with inner diameter of 750 mm or less, fixed or rotated, are normally welded from one side only. The root pass is deposited using either SMAW or GTAW. GMAW or FCAW are commonly used for the fill and capping passes.

4.3 Complex Node joints

A typical complex node structure is given in Figure 4.

Figure 4. A typical node structure

To weld the structural pipe to pipe connections successfully, care must be taken to ensure that the fit up is correct. The root gap must be constant and must be maintained. From figure 5 it is clear that the weld geometry, position and access for the welding vary around the circumference.

The important aspects to consider when welding the node joint are :

- The joint changes groove angles along the joint.
- Groove size must be accurate especially for one sided welding
- Weld surfaces must be smooth to improve fatigue strength and fatigue life
- Confined spaces around the joint eliminates the use of automatic welding

The root pass of the node joint is usually welded by GTAW or SMAW from one side only. The subsequent filling and capping passes are welded either by SMAW or FCAW.

Figure 5. Typical pipe to pipe connection – access from one side only.

In an attempt to ensure that the welded node connections contain minimal levels of residual stress due to fabrication, thermal stress relieving or post-weld heat treatment (PWHT) of the heavier more restrained welds may be prescribed.

4.4 Jack up rig – Rack to rack and rack to chord

The high strength steel grades of particular importance for jack up rig construction today are A514 grade Q, ALDUR 700QL1, A517 grade F.

A typical jack up rig can be seen in Figure 6. The jack up rig leg has heavy sections reaching thickness up to 180 mm for the racks. The material used is normally high tensile strength steels with yield strength ranging from 550 to 780 MPa.

Typically rack to rack and chord to chord joints are butt welded either using GMAW or SMAW. The rack to chord joints are butt welded using FCAW and SAW (See figure 6). The root and first hot pass are welded using FCAW. The subsequent fill and capping passes are welded with SAW.

Column-to-brace and brace-to brace joints are welded by FCAW and SMAW. The node joints of braces require strict welding procedure control to prevent lamellar tearing and provide smooth bead appearance for better fatigue strength.

Figure 6. Jack up offshore rig.

780 MPa high tensile strength steel is the main material for the legs of jack-up rigs. These structures require stringent welding procedure control to prevent cold cracking of the welds because of the heavy thickness of the components. These are normally welded either using SMAW, GMAW, FCAW or SAW or using a combination of these welding processes.

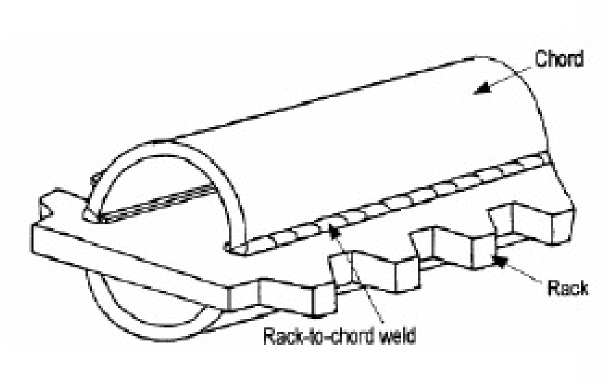

Figure 6. Rack to chord joint.

4.5 Topside and other construction

The steel grades of particular importance for topside construction are DIN StE 355 (St E 36), T St E 420 (TT St E 43) and EN S (P) 235-S (P) 500. ABS mild steel Gr.A, B, D, E. ABS HT Gr.AH36, DH36, EH36 EN 10225: S460 G2+Q. The yield strength varies from approximately 350 MPa to 460 MPa.

Blow Out Preventers and Well Head Constructions are typically fabricated from AISI 4130, or similar low alloy steel, and matching strength properties are specified.

4.6 Piping Systems

Pipe lines, process piping and process vessels are constructed from carbon steel, stainless steels, nickel base alloys and duplex stainless. The grade of material used is dependant on the operating environment.

A summary of pipeline applications and welding processes used in the 1980's, the predicted technologies for 2000 and the current reality in 2007 is given in Table 3 [10].

Application	Past	1980's	Prediction	2007 Reality
Short Pipelines	SMAW	SMAW	SMAW	SMAW, Semi-GMAW
Tie Ins	SMAW	SMAW	SMAW	SMAW, FCAW, Semi-GMAW
Long Pipelines (Small diameter)	SMAW	SMAW, SAW (Pre-	SMAW, Flash, MIAB,	SMAW,GMAW,FCAW,Mech-GMAW,SAW(Pre-Fab)

		Fab)	Mechanical Joining	
Long Pipelines (Large diameter)	SMAW	SMAW, SAW (Pre-Fab), Mech GMAW	Mech-GMAW, Hot wire GTAW, Flash	SMAW,GMAW,FCAW,Mech-GMAW,SAW(Pre-Fab)

Table 3. Summary of welding technology for piping systems

4.7 Underwater repair welding

Underwater welding can be divided into three main types [11]:

- Wet underwater welding : SMAW is the most common process. FCAW has been widely used in the former Soviet Union. Friction welding, which has the advantage of being relatively insensitive to depth, and which lends itself to robotic operation, has the potential for use in deep water repair.
- Coffer dam welding: A rigid steel structure to house the welders is sealed against the side of the structure to be welded, and is open to the atmosphere resulting in dry welding.
- Hyperbaric welding, in which a chamber is sealed around the structure to be welded, and is filled with a gas (commonly helium containing 0.5 bar of oxygen) at the prevailing pressure.

Wet welding is preferred over dry (hyperbaric) welding, simply because it can be mobilized quickly and be easily completed in areas where construction of a physical habitat is impossible. Thus wet welding is significantly cheaper than hyperbaric welding[12].

Welders can be used too depths up to 250 m but for depths beyond that remote pipeline repair systems are used for repair welding. Gas metal arc welding in a hyperbaric environment has been qualified in applications such as fillet welded sleeve repair and remote hot tapping. The process can weld to depths of 1000m [13].

Research continuous to improve the weld quality and to extend the welding to ever increasing water depths.

5. Future challenges

Covering both upstream and downstream requirements, the technologies of future importance related to welding and joining are [14]:

- Structural integrity of joints in deep water pipelines and risers
- Structural integrity of floating production systems
- Risk based inspection of pipelines, tanks, etc
- Use of 13% Cr steels
- Wider use of welded Ti alloys
- Long range inspection techniques
- Integrity of duplex steels with cathodic protection
- Lower cost manufacture and pipe laying e.g. by the use of hybrid welding processes
- High strength line pipes, e.g. X 100 types

Weld designs should pay greater attention to the importance of complete joint penetration groove welds, and the elimination of "notch effects" at the root especially where the high tensile strength materials are used. Emphasis should be placed on weld joint design to ensure welding from both sides. Welding from both sides makes it easier to achieve high quality welds.

The importance of underwater repair welding techniques increases with the ever increasing exploration and operational depths. Automation and robotic welding will feature as the main research thrusts.

For the oil and gas industry in Africa the main challenge would be to develop the technical and operational capacity to costs effectively fabricate and repair almost all the structures locally to international standards.

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