TECHNICAL REPORT

PETROLEUM SAFETY AUTHORITY NORWAY (PSA).

JOINING METHODS - TECHNOLOGICAL SUMMARIES

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Summary:

DNV has, upon request from Petroleum Safety Authority Norway (PSA), prepared technological summaries regarding selected joining methods applied by the oil and gas industry. Each chapter contain a brief introduction to the relevant joining method and is followed by a technological review in order to address issues that may influence the integrity of the joints. In addition to the selected joining methods one chapter addressing welding defects in general, and some relevant aspects concerning NDT, has been included.

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1 INTRODUCTION

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2. S-laying girth welds of large X70 type pipes
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7. Welding of 13Cr martensitic - 22Cr and 25Cr duplex stainless steels for subsea applications
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2 BOLTS FOR SUBSEA INSTALLATIONS

2.1 Introduction

Bolted connections are tightened in order to clamp parts together and transmitting loads. The consequences of inadequate tensioned bolts range from vibration loosening to bolt fatigue and leakage. Insufficient tightening lowers fatigue resistance because it does not develop enough clamping force to reduce the fluctuation of loads on the bolt. Overloading of the bolts during tightening can lead to failure of the connection for various reasons (e.g. yielding, bolt cracking).

Flange connections are the main application for of the use of bolts for subsea installation. Bolts are also used on various clamp type connectors. The selection of bolted joints is based on achieving the following objectives:

- Obtain a reliable connection
- Easy and fast fitting

The bolted connections on subsea systems are primarily based on clamping one metal surface to another metal surface. For most subsea systems, any applied gaskets or sealing ring will be metallic. Non-metallic seals are not used on main systems but may be applied for subsidiary connections (e.g. related to chemical lines).

To attain pre-load in a bolt, one of the four main installation methods are used:

- **Torque control**
  Control of pre-load through torque
- **Torque and Turn of the nut control**
  Control of pre-load through turn of the nut
- **Tension control (stretch control)**
  Control of pre-load through tensioning
- **Pre-load control**
  Control of pre-load itself

These above installation methods have uncertainty in the range 10 to 30% (Ref. /1/). The stretch control method has the best uncertainty at about 10 %. However, as will be discussed subsequently, there are several other essential elements which should be taken into account to ensure the integrity of the bolted joint.

Obviously, it is important for the offshore industry to avoid any use of uncontrolled tightening (flogging) and or impact tools in bolting installation. The approach to avoid unacceptable practice in bolting installation is by improved awareness concerning the essential elements of bolted joint integrity.

2.2 Application

Bolted joints are used for all flange type connection systems. This imply that the use of bolted joints represent a significant number of connections on subsea equipment. This includes threaded connectors (bolts and nuts) used on ASME or API flanges.

The technology of bolted joints includes a range of issues from flange design, requirements for tightness and pre-tensioning to issues related to bolt materials selection. Typical standards used for flanges and gaskets are listed in Table 1.

Mechanical connections with the use of bolted flanges are high integrity connections on subsea installations. This embrace a wide range of connections related to flanges and clamp type connectors, typically:

- Xmas trees
- Manifolds
- Tie-in
- Valves and chokes

Stretch control, using hydraulically tensioning equipment, is normally used for subsea flanged and hub connections.

2.3 Technological status

The total integrity of a bolted connection is a complex topic that is influenced by a range of elements. The reported high number of leakages from mechanical connections on offshore installations the UK in the period 1992 to 2000 resulted in focus on the integrity of bolted joints (Ref. /1/).

It would seem that in many offshore projects, adequate installation procedures have not been developed or implemented. Further, the lack of awareness of the requirements for achieving bolted joint integrity has in cases lead to situations where it is "the man with the wrench" who actually controls the bolted joint installation.

UKOOA (UK Offshore Operators Association) has recognised the need for improving the practice for how the bolting installation is handled in the offshore industry (Ref. /1/). In Norway, OLF has documented the occurrence of gas leakage on the Norwegian Continental Shelf (Ref. /2/). The OLF statistics from the period 1994 to 1998 showed that a significant number of leakages (25%) were related to mechanical connections.

In the UK the UKOOA, in co-operation with Institute of Petroleum, has issued a guideline for the management of integrity of bolted pipe joints (Ref. /1/). The UKOOA guideline is intended to provide companies and operators with a framework for management of bolted joints. The essential elements in this guideline are summarised in Figure 1.

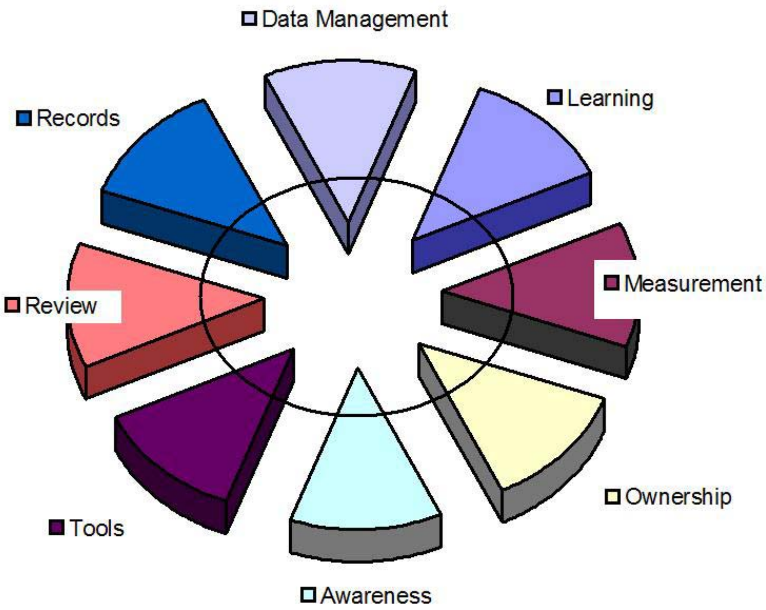

Figure 1. Bolted joint integrity management (Ref. /1/)

The essential elements of the management system described in the guidelines include:

- **Ownership**
  Identification of responsibility for implementation, maintenance and communication throughout the organisation.
- **Awareness**
  Awareness with respect to the management system, its objectives, expectations and effect.
- **Tools**
  Implementation of tools to meet expectations, such as risk assessment, competence management and control of the used practices.
- **Review**
  System reviews, verifications and audits at agreed intervals.
- **Records and Data Management**
  The recording of traceable data will encourage a best practice.
- **Learning**
  Learning from incidents will improve performance.
- **Measurement**
  Quantification of contribution being made by the management system. Evaluation of user satisfaction.

2.4 Limitations for bolted joints

One of the most important tasks for bolted flange joints is to prevent liquid or gas leakage. The typical joint is made up of two pipe flanges to ASME B16.5. Other codes like API 6A, MSS SP 44 and BS1560 describe similar arrangements. Lack of adequate procedures for pre-tensioning of bolts for standard ASME B16.5 –flanges has been identified as a main item for concern. Uncertainty has been found to be related to two main points:

- Variations in the requirements for pre-tensioning in construction standards
- Uncertainty related to the application of the pre-tensioning tools

2.4.1 High integrity bolted connections

High integrity bolted connections embrace both structural items as well as pipe connections. In the offshore industry there are a range of standards which apply, some are listed in Table 1. For subsea installations the bolted connections are mainly related to flanges and clamp connectors.

Table 1. Standards for flanges and gaskets

Code	Name	Section Reference	Application
API RP 14E	Design and installation of offshore production platform piping system	Sec. 4 Sec. 6	Fittings and flanges Considerations and related items
API Spec 6A	Wellhead and X-mas tree equipment	Sec. 303 Sec. 904	Design methods Ring gaskets
API Spec.16A	Drill through equipment	Sec.3 C 4 C 5	Design requirements Hubbed and outlet connectors Clamps
ANSI /ASME B31.3	Chemical plant and petroleum refinery piping	Sec. 304.5	Flanges
ASME /ANSI B16.5a	Pipe flanges and flanged fittings		A general flange standard
M55-SP-44	Steel pipeline flanges		A general flange standard
ASME/ANSI B16.20	Ring –joint gaskets and groves for steel pipe flanges		A general gasket standard

2.4.2 Requirements for pre-tensioning of the flange connection

Eliminating leaks around the flange is difficult, due to the complex mechanics. There must be maintained a "sufficient" contact pressure or gasket stress between the flange and gasket surfaces while bolts or gasket relax. The relaxation depends on initial bolt stress, temperature changes and varying pressure of the contained fluid or gas.

Typically the flange connections are:

- ANSI –flanges
- SPO-flanges/compact flanges

There are disadvantages involved in using conventional ANSI flanges. Large diameter bolts are commonly used, resulting in a large bending moment and the flange joint become sensitive to warping. This is counteracted by increasing the dimensions, making the flange large and heavy. Force from the bolt tensioning and axial forces acts through the gasket. The sealing capacity becomes sensitive to creep of the gasket. Misalignment during mounting and non-uniformly tensioned bolts will often lead to leakage.

Various types of compact flanges have been developed by specialist flange manufacturers. The pressure on the gasket in a compact flange is independent of external loading and pretension of the bolts. This is due to the fact that the fluid is retained by a gasket and contact pressure between the flange parts. The gasket is situated in a groove in one or both of the flange surfaces. Compared to conventional flanges, the compact flanges are more rigid and have a smaller size. Due to the bolts length and diameter ratio of 6:1, the bolts in compact flanges have a more elastic behaviour than the bolts in conventional flanges. Therefore the compact flanges can withstand a high level of make-up tension force.

2.4.3 Adequate procedures for pre-tensioning installation tool

The application of the pre-tensioning tools to establish the required pretension is also a challenge. The initial bolt pre-load normally ranges between 40% and 60% of the yield stress.

The advantage of a high pre-load:

- Increase margin for relaxation (e.g. loose 10-12% pre-load over 30 years)
- Reduce cyclic component of applied stress (avoid variations or cycling of clamping force in service)
- Better leak sealing

In field it is possible to apply 80% pre-load without any danger of excessive bolt stress. However, 90% pre-load is possible in laboratory controlled conditions.

Result of too high pre-loading can result in failures:

- Buckling of gasket
- Permanent yielding of flanges
- Thread stripping
- Yielding of joint members
- Cracking of bolt

Basically, the pretension should be as high as acceptable while striving to have a uniform distribution of the pre-load.

In Table 2 are given a schematic summary of the main bolt installation techniques. The stretch control gives by far the best control of bolt pre-load. Stretch control should be applied for all high risk joints as this will provide pre-tensioning accuracy of about +/- 10%, while torque may provide an accuracy of about +/- 25% (Ref. /1/).

Table 2. Main bolt installation methods

Method	Typical application	Typical drawback	Typical advantage	Improvements
Control of pre-load through torque	No-risk joints / low risk joints	Pre-load accuracy	Easy installation Inexpensive	Evaluation of friction
Control of pre-load through turn of the nut	Low risk joints	Does not eliminate torque problems	Better control of prevailing torque, excessive friction loss etc.	Evaluation of friction
Control of pre-load through stretch	Suited for high risk joints	Expensive	Pre-load accuracy	Elastic recovery

For torque installation it is essential that the friction is taken into account in the procedure. Consequently, for a preloading with a given applied torque, the lack of control of the lubricant can change the friction factor and result in an actual preloading which may be 60 to 80% of the expected value.

2.5 Uncertainties and challenges

There is a need to ensure a more consistent practice for the management of bolted joints by all parties in the Norwegian offshore industry. Improvements are required to ensure that all the integrity of the bolted joint and thereby avoid failure /leakages as reported by UKOOA and by OLF (Ref. /1,2/).

The aspects of hydrogen induced damage may represent an uncertainty for the integrity of bolted joints. Cathodic protection (CP) is always used for the protection of subsea equipment. The CP causes the formation of hydrogen atoms on the metal surface. The hydrogen atoms can permeate into the metal and be absorbed in the metal matrix. This may result in an interaction with the microstructure of the material. For bolts subjected to high stress this may cause initiation and growth of hydrogen related cracks. This effect is referred to as hydrogen induced stress cracking (HISC).

The various alloys will have different susceptibility to HISC. It is therefore important that the materials selection and compatibility with cathodic protection (immunity to HISC) has been verified. The standard bolt materials for bolted joints are based on the requirements given in ASTM A193 Grade B7 or ASTM A320 Grade L7 (both these materials are low alloy Cr-Mo steel). The grade B7 is considered to be resistant to HISC at hardness values of ≤34 HRC (Ref. /3/). For situations were other materials than the Grade B7 or other qualified materials are used (e.g. various CRA's) may be required to qualify the bolting material for compatibility with cathodic protection.

2.5.1 Bolted joint integrity: Need for improvements

The technology for executing high integrity bolted joints is available in the UKOOA report (Ref. /1/). The essential elements of the UKOOA-report should also be implemented for the offshore industry in Norway (Figure 1).

The aspects of the offshore industry practice in relation to bolting installation are a topical matter. While there are rigorous requirements the qualifications of welders, there are no formal offshore requirements for bolting installation personnel.

To improve the integrity of bolted joints, the following suggestions can be made:

- Establish qualification requirements for bolting installation personnel applicable for the various pre-loading methods. (Welders are qualified. Why should not bolt joint installation personnel be qualified?)
- Increase the awareness of bolting technology in the offshore industry (see ref. /1/).
- Review applicable standards with respect to:
    1. Variations in requirements for pre-tensioning and
    2. uncertainty related to the application of the pre-tensioning tools.
- Establish qualification procedure for:
    - HISC immunity for bolting materials
    - The use of corrosion protection coatings for low –alloy bolts

2.6 Important parameters for robust bolted joint

To achieve the most robust bolted joint the operator should highlight each stage in the lifecycle and perform a risk and consequence assessment. The list of items for each stage can then be evaluated with respect to risk. Based on failures/leakages the list for the given stage can be updated to ensure that the items which have resulted in to leaks are revised.

The main stages for a life cycle of the bolted joints are identified to be the following (Ref /1/):

- Design
- Procurement
- Manufacturing stage (e.g. ensure manufacture to given standards)
- Fabrication/Inspection/Testing (e.g. ensure testing to establish possible defects)
- Onsite intervention and maintenance works
- Commissioning
- Operation

2.7 References

Reference no.	
/1/	The Institute of Petroleum,UK (2002) "Guidelines for the management of integrity of bolted pipe joints", Issue 1 June
/2/	"Vedrørende analyser av gasslekkasjer på norsk sokkel" (In Norwegian). Published by Petcon A/S for OLF
/3/	"Guideline for materials selection and corrosion control for subsea oil and gas production equipment" EEMUA Publication No. 194-1999

3 S-LAYING GIRTH WELDS OF LARGE X70 TYPE PIPES

This section covers aspects relevant for the welding of girth welds for large diameter pipelines of grade API X70 or similar to be installed by the S-lay method.

3.1 Introduction

3.1.1 General

As illustrated in Figure 1, S-lay installation takes place with offshore welding of linepipe in the horizontal position where the pipeline is immersed into the sea at a certain angle across a stinger. Hence, the pipeline takes an S-shape from the installation vessel to the seabed. Lay-rate for this installation process is up to 4 km/day (depending on the vessel and pipe size).

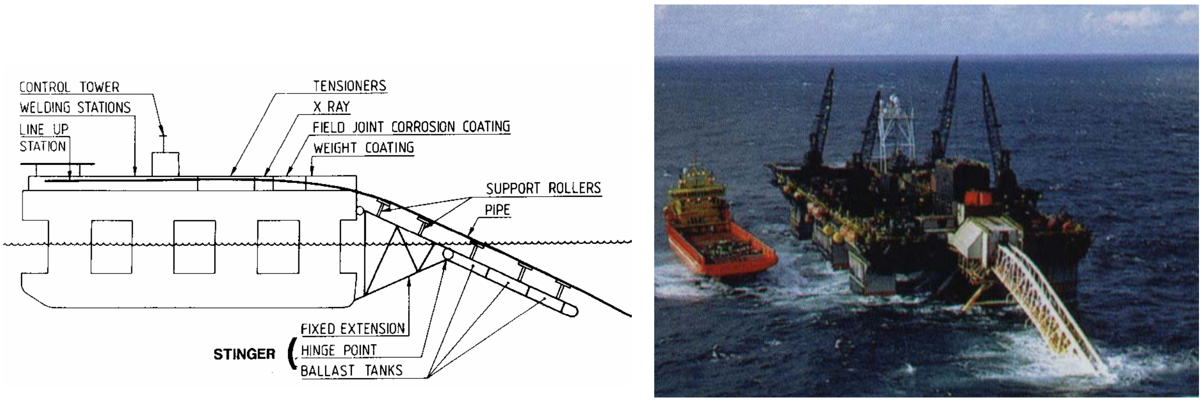

Figure 1. a) Principle sketch of S-lay vessel and b) The S-lay vessel "LB 200" (courtesy of Stolt Offshore).

A typical layout on-board an S-lay vessel is shown below in Figure 2. The layout features two welding lines; the main line and the double joint line.

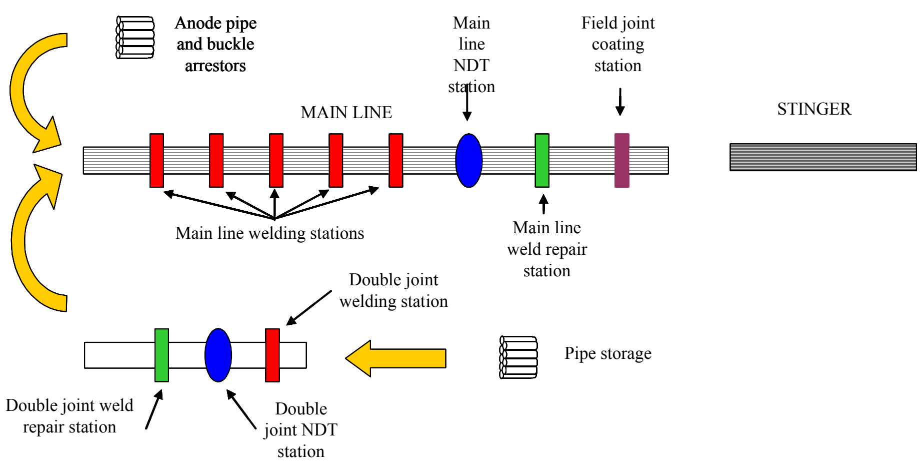

Figure 2. Typical layout for S-lay vessel.

After welding two pipes together into double joints these joints are transferred into the main welding line by using a transverse conveyor. While the pipe is on this conveyor, final pipe bevelling, cleaning and inspection, and in some cases re-bevelling, are taking place. This ensures a clean weld bevel free from protective coating or other impurities, which may affect the weld quality. The double joints are then rolled or lifted onto the support rollers of the main welding line.

3.1.2 Welding

The double jointing of standard 12 m lengths of pipe is normally done by submerged arc welding (SAW) as it is possible to rotate the double joint. The double jointing can also be made by automatic (usually GMAW, and in rare cases GTAW) welding machines as used in the main line.

The first welding station in the main line is combined with the line-up station. The double joint and the pipe string are aligned to obtain the best fit for out of roundness and wall thickness variations as well as offsetting the longitudinal pipe seam welds. A photo of an internal line-up clamp is shown in Figure 3. A root gap is normally not used but may be set by inserting a gauge plate (spacer) between the bevels. Preheating prior to welding, which may be required (main reason is to reduce any excessive hardness) for higher grades such as X70, will also be applied at this point - usually with propane gas torches although preferably by induction heating due to better temperature control.

When the line-up operations of the joints in the main line and preheating (when required) are completed, the line-up clamp is activated to keep the pipe in position and the weld root pass is carried out by automatic GMAW (or GTAW) welding machines. The line-up clamp includes a copper ring that act as weld backing producing a flat root profile. The production welding continues at successive welding stations as the vessel moves forward is steps corresponding to the length of a double joint. The welding machines are fixed onto the pipe using straps and move with the pipe, and hence relative motion between the pipeline and barge do not affect the welding.

It is common practice to <u>not</u> allow removal of the line-up clamp and move the joint before the root pass and hot pass are completed. However, if properly qualified, by the WPQR and by joint integrity analyses (i.e. ECA), it is in some cases allowed to continue installation after completion of the root pass.

The repair rates during S-lay installation are usually well below 2%. It should be noted that burn-through defects are not included in this number since these defects are repaired at the main line stations. It is important to have procedures for proper marking of such repairs in order to avoid confusion for the NDT-personnel when interpreting these welds.

3.1.3 Vessel types

Two examples of quite different vessels both capable of deepwater S-lay installation of large diameter pipe, are the Allseas “SOLITAIRE” and the Stolt Offshore “LB 200”.

Figure shows a Saturnax welding system in use on board “LB 200”. The vessel is semi-submersible which greatly enhances stability. “LB 200” relies on anchors for station keeping during installation. Moving of the vessel is made by adjusting the length of the anchor cables. As a consequence the anchors will frequently have to be moved to new positions by anchor handling vessels and thus establishing a new predetermined anchor pattern. Different configurations of anchor patterns may be required for various sections of the pipeline, especially in the vicinity of existing installations, other subsea installations or other pipelines or cables. An on-board gas blend system capable of providing e.g. 50/50 mix of argon and carbon dioxide for production welding and 80/20 mix for repair work has recently been installed on the “LB 200”.

“SOLITAIRE” is a very large installation vessel which utilises an in-house developed third generation Phoenix welding system, as seen in Figure 3. “SOLITAIRE” relies on its dynamic positioning system (DP) for station keeping during installation and the complications arising from anchor handling and anchor patterns are thus avoided. The vessel is a mono-hull ship which implies larger wave induced motions than those of a semi-submersible vessel.

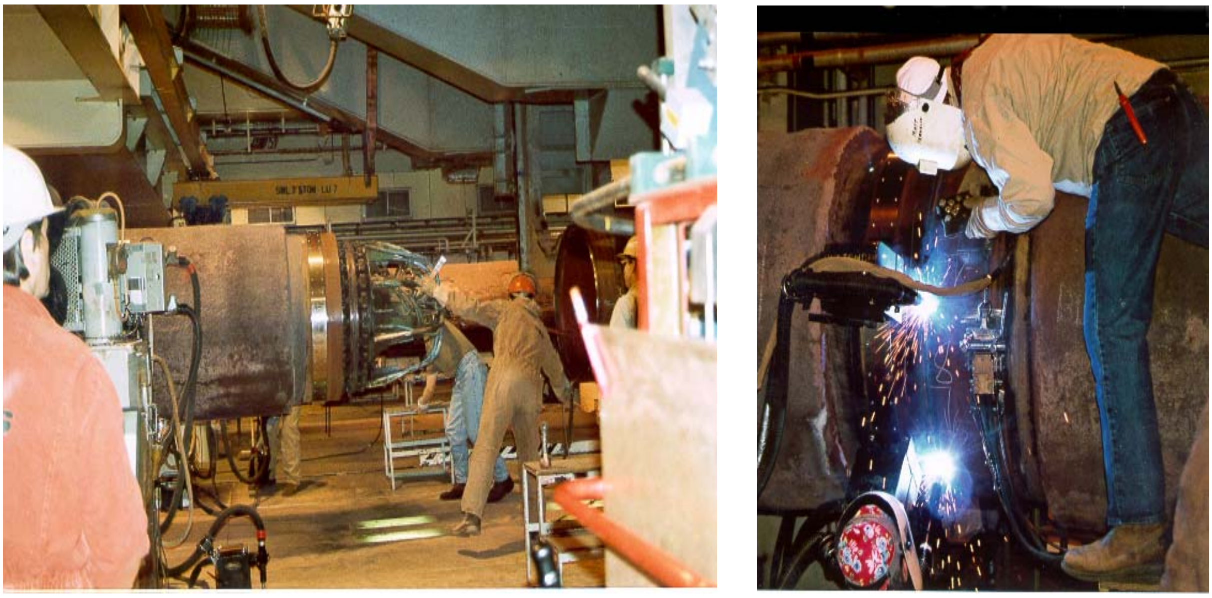

Figure 3. Installation of line-up clamp (SOLITAIRE) and the Phoenix welding system (Soiltaire).

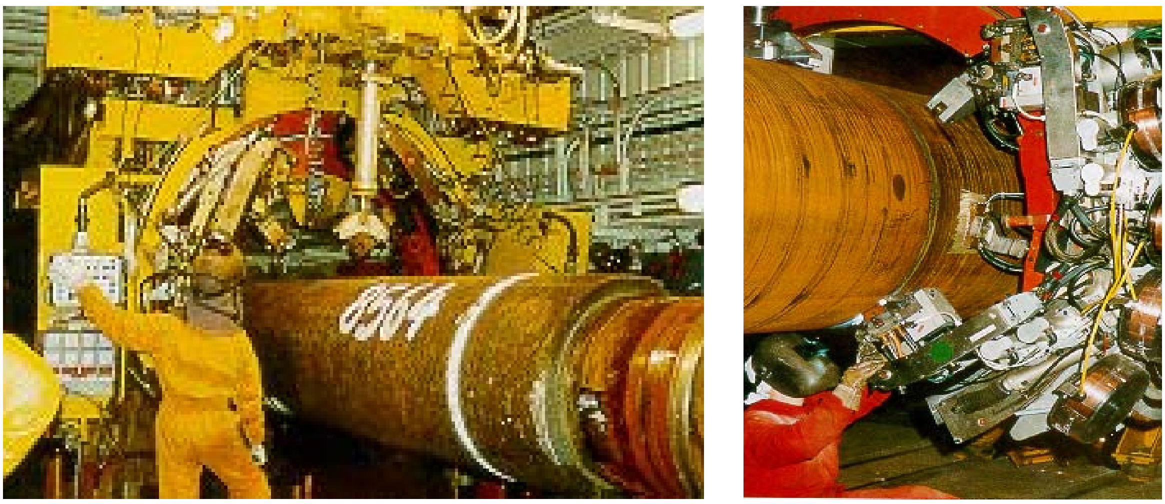

Figure 4. Saturnax welding system (LB 200), and detail of welding heads.

3.2 Application

Large diameter offshore pipes are usually used for export of dry gas and hence sour service requirements are not relevant. In accordance with the commonly used pipeline standards, this implies that a higher HAZ hardness is allowed. It must be noted that a higher hardness will have an adverse effect on the materials toughness and further tends to increase the risk for hydrogen embrittlement and cold cracking, and hence the level of hardness must be taken into consideration during pipeline design.

S-lay installation is suitable for most water depths ranging from shallow waters to ultra-deepwater applications.

3.2.1 Plastic strain and ECA

According to DNV OS-F101, engineering criticality assessment (ECA) shall be performed on installation girth welds when the accumulated plastic strain introduced during installation and operation, including all strain concentration factors, is: $\varepsilon_p > 0.3\%$.

S-lay installation at large water depths may imply significant plastic strains and generally the applicability of ECA should always be assessed.

The ECA shall determine the material fracture toughness required to tolerate the flaws allowed according to the acceptance criteria for NDT, or alternatively to establish the acceptable defect sizes that can be tolerated for a given fracture toughness.

Based on the fracture toughness and mechanical testing, the installation strain, the pipe dimensions and tolerances the ECAs are carried out. Usually the testing comprises tensile testing and SENT (Single Edge Notched Tension) testing. The ECAs consider both Weld Metal (WM) and Fusion Line (FL) defects for the main line, the partial repair and the through thickness repair weld procedures. The results are given as maximum allowable defect sizes. Other considerations made in the ECA may result in limitations on the geometrical shape of the weld cap, depth of undercut and maximum allowed high-low due to the resulting stress/strain concentrations. If large temperature variations or vortex shedding may occur on free spans in the operation phase, fatigue may be a problem and should be considered in the ECA.

3.3 Technological status

X70 has been installed offshore on several projects for the last 10 years. Previous experience with welding and installation of large diameter X70 pipelines offshore includes Europipe II (Kårstø-Dornum) and Thunder Horse (GOM). In addition broad experience from onshore projects exists.

There are no major differences in the welding of X70 material compared to lower grade steels (e.g. X65) except that the welding consumables need to be selected to obtain the specified mechanical requirements and making necessary adjustments to the welding parameters due to change of welding consumable. In some cases, e.g. for heavy wall thicknesses and thus richer chemical composition, preheating before welding may be necessary to reduce hardness.

X70 large diameter pipes can be delivered by all the major international pipeline manufacturers.

3.4 Limitations for this joining method

The maximum depth at which a pipe can be installed in the S-lay mode is governed by the capacity of the tensioners of the installation vessel, the capacity of the A&R and anchor winches and the stinger length, curvature and tip slope.

As mentioned above, welding of high strength material such as X70 may cause high hardness in the HAZ. To cope with this, preheating and “generous” heat input is generally applied. The vessel preheating capabilities may vary and hence in some situations be a limiting parameter.

Local brittle zones (LBZs) can be formed in the HAZ of C-Mn micro-alloyed steels. This should particularly be kept in mind when selecting the chemical composition for steels with SMYS ≥ 450 MPa. These areas tend to exhibit very low cleavage resistance, resulting in low CTOD values. The LBZs are associated with the sections of the HAZ's that are experiencing grain coarsening during the welding operation. The microstructure in these zones consists predominantly of a bainitic structure, with a large amount of martensite/austenite (M/A) constituents (B_I-microstructure). The M/A constituents, as opposed to ferrite/carbide aggregate such as pearlite, may have a detrimental affect on the material's toughness. The implication of the results obtained from toughness testing when LBZs are encountered should be evaluated.

3.5 Uncertainties and challenges

One uncertainty is related to the way the welding procedure qualification is performed. Normally a number of test pieces are required to qualify for the applicable pipe dimensions and the number of material suppliers. The required mechanical testing may be performed with some tests specimens taken from one test piece and some other specimens from another test piece. The welding parameters used during welding of the individual test pieces should hence be the same for the same pass at the same circumferential position. If large variations in welding parameters between the test pieces occur, the resulting range of essential variables should be established with care in order to avoid that the allowable range of welding parameters becomes unreasonably wide.

Another challenge during offshore pipeline welding and installation is to ensure that all the welding parameters are maintained within the limits specified in the respective welding procedure specifications (WPS). This becomes even more important for high grade steels during deepwater installations.

One parameter that may be challenging to maintain is the gas flow rate. The gas supply and monitoring systems usually requires some attention to ensure that no contamination of shielding gases due to leaks or unsuitable hoses will occur.

It is further common knowledge that with regard to shift change, a new fresh crew tend to produce less weld defects than the tired crew at the end of a shift.

It has been discussed if pipes installed during bad weather conditions are inferior to pipes installed in good weather, but as far as DNV knows, no particular increased risk has been identified. However, it is likely that the limits for when to interrupt installation, i.e. when to lay to and stop welding or when to abandon the pipe and lower it to the seabed for later recovery, are parameters that may affect weld joint integrity, at least if plastic deformation may occur during any of these operations. There should be established criteria for when the laying shall be interrupted and the pipe abandoned due to weather conditions.

The criteria should be based on the results of the installation stress/strain analysis and be referred to objective, critical values indicated by measuring devices rather than subjective evaluations of sea state or other conditions.

3.6 Important parameters for robust joints

To achieve robust joints the following major areas have been identified

- Qualification of welding procedures (WPQR):
    - It is vital that welding procedures are thoroughly qualified by running a WPQR (Welding Procedure Qualification Record) meeting all the requirements stated in the governing standard (e.g. by recording all parameters, performing mechanical testing and NDT) without excessive differences between test joints. Cooling of welds with water to allow AUT to be performed shall be qualified and a maximum temperature for starting the cooling specified. It is further important that the allowable parameter ranges for the essential variables are strictly adhered to (e.g. for heat input, wire stick-out and interpass temperature etc.).
- Personnel:
    - It is vital that all personnel are adequately trained and have sufficient possibility to rest.
- Line pipe and consumables
    - Welding of line pipe with homogenous mechanical properties and sufficient dimensional tolerances (diameter, out-of-roundness, wt, squareness) and good logistics onboard in order to make the best mating of pipes with regard to high-low and separation of longitudinal welds.
    - Consumables should definitively be low hydrogen and must be carefully selected and stored. The welding wire and electrodes should be from the same batch as used during welding procedure qualification. If it becomes necessary to change a batch of consumables, batch testing should be conducted to verify that the new batch(es) of consumables will give deposited weld metal nominally equivalent to those used for welding procedure qualification, with respect to chemistry and mechanical properties.
    - Consumables, including SAW flux, must be maintained in a reliable, dry condition and stored and handled according to a procedure that meets or exceeds the manufacturers' recommendations in order to meet the guaranteed maximum value for hydrogen in the weld metal.
    - The classification, designation, purity and dew point of shielding and backing gases should be to be according to recognised standards such as ISO 14175 or EN 439.

- Welding:
    - It is vital that the welding procedures are complied with, i.e. that all parameters are checked regularly. One example of a parameter that may affect quality significantly is the electrode stick-out during GMAW. In some cases, it has been seen that a shorter electrode stick-out than used during qualification, and hence as stated in the WPS, is used for the offshore welding. This leads to reduced resistance heating of the filler wire and hence more hydrogen in the weld deposit, increasing the risk for hydrogen cracking. This is a general observation particularly relevant for welding of higher strength steels, however, not only applicable to S-lay offshore welding.
    - The start and end of weld beads should be staggered to avoid stacked defects at the start and stop of the weld passes.
- NDT
    - The capabilities of the equipment and the skills of all personnel, including the, company representatives are important. The capabilities of the AUT system in detection and sizing of indications should have been determined though a representative qualification of the system
- Production tests
    - Production test should be performed of the production welding to establish that welded joints made onboard the vessel have mechanical properties meeting or exceeding those obtained during welding procedure qualification and to verify that the fracture toughness values used in any ECA are met or exceeded during production welding.

4 J-LAYING GIRTH WELDS OF HEAVY X65 TYPE PIPES

This section covers aspects relevant for the fabrication of girth welds for thick wall pipelines of grade API X65 or similar to be installed by the J-lay method. In this section it has been assumed that pipes delivered to a given project are within the specification of a recognised pipeline/ line pipe standard.

4.1 Introduction

J-lay installation takes place with offshore welding of on-shore prefabricated lengths and where the pipeline is immersed into the sea vertically so that the pipeline takes a J-shape from the installation vessel to the seabed. Hence a prefabricated length is placed in a tower, similar to a drilling rig tower, and circumferential vertical welding is then performed at the single welding station before the pipe is lowered for the next length to be put in place.

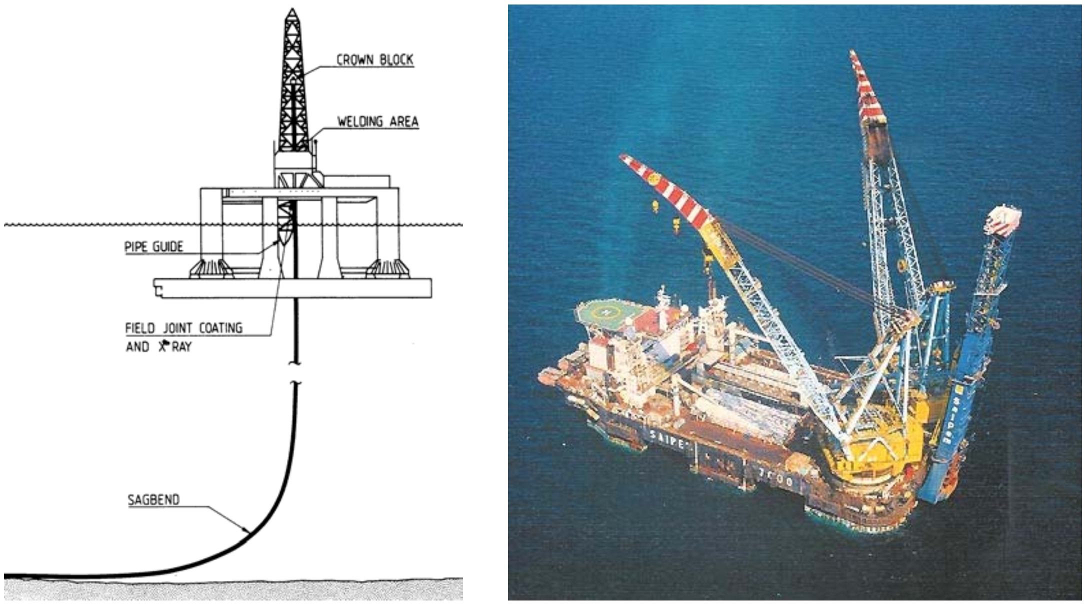

Figure 3. a) Principle sketch of J-lay vessel and b) the heavy lifting and J-lay vessel "Saipem 7000" (courtesy of Saipem).

The load from the pipeline hanging from the vessel is normally transferred by a tensioning system gripping the pipe over a certain length of the pipe (similar to drill pipe slips), while some contractors have developed a system where the tension is transferred via a forged collar of a pup-piece. In addition, a clamp system acting on the pipeline below the NDT/coating-station is applied, acting as an emergency system in case of malfunction of the tensioners. Generally J-laying introduces low installation strains, depending on the water depth and hence the curvature and weight of the part of the pipeline hanging from the vessel.

A principle sketch of a J-lay vessel and the very large J-lay vessel, "Saipem 7000", are shown in Figure 1.

The stiffness of the pipe, including eventual contribution from the coating, its weight and curvature from the vessel to the touchdown point are factors that affect the risk for buckling. Determining the touchdown point is important during J-lay as the touchdown point and the position of the vessel determines the curvature of the pipe and hence also the risk of buckling. The determination of the touchdown point is challenging especially if the seabed is uneven or when laying in steep bottom configuration which requires continuous assessment of the laying conditions. The risk of buckling is increased by laying-down and pick-up operations e.g. due to bad weather conditions.

4.1.1 Onshore welding of prefabricated joints

Fabrication of the quadruple- or hex joints used for J-lay installation is similar to the double jointing on-board S-lay vessels and can be made by automatic rotating welding machines (GMAW – in rare cases GTAW), or, as it is possible to rotate the joint, by submerged arc welding (SAW).

4.1.2 Offshore welding on installation vessel

The single welding station of the J-lay vessel is positioned in the lay tower with a distance of one pipe string length from the NDT and coating station on deck level.

A typical sequence of events during J-laying is:

1. Joints are transferred from the deck to the upper part of the J-lay tower for intermediate storage (several may be stored in the tower) using an integrated lifting device. Both pipe ends has preheat units connected in way of electrical induction heaters which rise the temperature of the weld areas to the required temperature.
2. The relevant joint is transferred to the pipe string by clamps and roller boxes. The lower clamp is a multi directional clamp allowing for rotation and X/Y-tilting of the incoming pipe joint and thereby secure enough movement for the final line-up. Prior to lift into the tower, the pipe ends have been bevelled to produce a tight tolerance narrow (typically 1-4°) joint configuration for the most efficient welding using a pipe facing machine on the deck of the installation vessel.
3. The internal line-up clamp with copper backing for the welding is inserted from the top using an integrated winch of the J-lay tower. This is the preferred option over external line-up clamps in combination with separate internal backing, due to the accessibility for welding. External line-up clamps are mainly used for tie-in welds, for obvious reasons. The line-up clamps used for J-lay welding are similar to those used for S-lay main-line welding.
4. If necessary extra preheating is applied prior to commencement of welding in way of gas burners.
5. Automated vertical position GMAW circumferential welding takes place using between two to four welding heads in a carousel until the weld is completed. Each welding head is normally equipped with two welding torches i.e. for a three headed unit (which is most normal) 6 welding units are run simultaneously. One welding operator monitor each welding head continuously.

6. The WPS's are normally qualified for different inclination of the lay tower with allowable tower inclinations being +/- 5 deg. (essential variable). For tower inclination exceeding approx. 10 deg. the number of welding heads are reduced to two in order to minimise the heat input. Also during root pass the second torch ("slave torch") is omitted reducing the possibilities for root defects. During the cap pass the second torch is omitted to prevent that the cap gets too wide. Movement of the pipe cannot be performed until all passes are completed.
7. When the weld is completed, and the operations at the lower stations (NDE and coating) are completed, the pipe is lowered one joint length to the NDE station for AUT (Automatic Ultrasonic Testing) and coating.
8. If welds are rejected (the repair rate for J-laying is usually well below 2%) weld repair is for through thickness repair (TTR) normally as cut-outs and re-welding. This is due to the large water depth giving heavy air pulsation inside the pipe and thereby problems with root pass. For partial repair this is usually performed with FCAW and SMAW for cap repair.
9. The final event is field joint coating. For pipelines with thermal insulation like polypropylene, the field joint coating is made by a combination of FBE (fusion bonded epoxy) and polypropylene infill material. This requires a rather sophisticated application system comprising automatic sandblasting, preheating, FBE spraying and moulding of PP. For other coatings i.e. no thermal insulation, heat shrink sleeves can be applied, or only PP-spray.

4.1.3 Welding defects and NDT

As for S-laying, the predominant NDT-method for J-lay welding offshore is automated ultrasonic testing (AUT) applying the pulse-echo methods. However, due to configuration of the weld scanned (vertical position) and thereby preventing large scanner units revolving the pipe, phase array systems are applied with only one probe on each side of the weld in combination with Time of Flight Diffraction (ToFD).

4.1.4 J-lay vessels

The construction vessel "Balder" (Figure 4) may be equipped with either of Heerema's two different J-lay equipment systems, the 200 mT and the 525 / 1050 mT. Both may utilize hex joints (72 m) however, the maximum holding capacity of the larger and newer 525 / 1050 mT system requires that quad joints are used. Maximum pipeline diameter for both systems is 32".

Figure 4. ”Balder” deepwater construction vessel (photo courtesy of Heerema Group).

As shown in Figure 5a Heeremas “Balder” has got a so called open J-lay tower which enables installation of in-line structures such as Tees and PLEM’s (PipeLine End Manifolds). The special tension system on this vessel requires that each joint has got a forged collar. Depending on the design and dimensions it appears to be probable that the forged tension system collars may also double as buckle arrestors. “Balder” has got dynamic positioning system (DP) for mooring station keeping during installation.

Figure 5. “Balder: a) Pipeline tower and b) deck area arrangement for pipe-laying (photos courtesy of Heerema Group).

The very large heavy lift vessel “Saipem 7000”, as seen in Figure 3b, was equipped with a J-lay tower for the installation of the two deepwater Blue Stream pipelines across the Black Sea. Saipem 7000” has got a Presto (GMAW) robotised welding system. For the Blue Stream project a full weld run of a 24 inch pipe with 32mm wall thickness was achieved in as little as six to seven minutes in one welding station. When this was combined with quadruple jointing, lay rates of five to six km per day were achieved.

Saipem 7000 has got dynamic positioning system for mooring station keeping during installation. In addition a pipe strength analyser acting as a “real time” FEM analyser was applied showing the applied loads on the pipe during laying.

4.2 Application

J-lay installation systems were developed to enable the installation of pipelines in very deep water and are considered to be suitable for deepwater and ultra-deepwater applications. This system of pipe-laying eliminates the S-lay overbend by laying the pipe in the (almost) vertical position and hence eliminates the requirements for a stinger.

Grade API X65 steel or equivalent grades have been used for offshore pipelines for at least 20 years and have come to be the dominating pipeline material the recent 10 years.

Heavy wall thickness pipes are required at large water depths in order to obtain pipes that can withstand the external pressure when the internal pressure is low, e.g. during installation.

4.3 Technological status

J-lay installation of thick walled pipelines of grade API X65 is a proven method. A relevant project example is the Blue Stream pipelines.

- Most pipeline standards offshore pipelines (DNV, ISO, ASME, etc.) will be applicable.
- However, the design standard/formulas may lead to significantly different wall thickness and hence the actual weight of the pipe may be limiting with respect to installation. Hence, the DNV OS-F101 (and ISO) is the most applicable standard to apply for deep water pipeline projects.

4.4 Limitations for this joining method

Local brittle zones (LBZs) can be formed in the HAZ of C-Mn microalloyed steels. This should particularly be kept in mind when selecting the chemical composition for steels with SMYS ≥ 450 MPa. These areas tend to exhibit very low cleavage resistance, resulting in low CTOD values. The LBZs are associated with the sections of the HAZ's that are experiencing grain coarsening during the welding operation. The microstructure in these zones consists predominantly of a bainitic structure, with a large amount of martensite/austenite (M/A) constituents (BI-microstructure). The M/A constituents, as opposed to ferrite/carbide aggregate such as pearlite, may have a detrimental affect on the material's toughness. The implication of the results obtained from toughness testing when LBZs are encountered should be evaluated.

The weight of a medium diameter heavy wall pipe at deep waters is very high (especially if flooded (if suddenly flooded the vessel/tensioners are not capable of carrying the weight and and pipe to be dropped) and hence the holding capacity of tensioning system of the installation vessel may be a limiting parameter.

4.5 Uncertainties and challenges

The technology of welding and installation X65 pipelines offshore can be characterised as ”well known”. Several projects have been performed successfully for a range of diameters and wall thicknesses.

The general challenge for all J-lay installation projects are the fact that it features only one welding station in addition to a station for e.g. inspection and field joint coating. Hence, if any additional processes, e.g. preheating, are required this may affect productivity and lay rate. No preheat is applied when pipe is "waiting" in the tower.

The geographical conditions of the seabed, i.e. the topography and path for the pipeline require different levels of laying accuracy which may be a challenge for the contractor.

4.6 Important parameters for robust joints

The challenges to the manufacture of robust joint using this method and relevant pipeline data are not mainly to the pipeline welding, but to the limitations of the laying vessel with respect to holding capacity. However, the parameters critical to all welding of heavy wall thickness pipe applies.

The welding procedures should be qualified in such a way that they reflect the variables during installation, e.g. the tower angle.

It is important that the operating limit conditions criteria determining when to discontinue installation and possibly lay-down the pipeline are well defined such that the pipeline is not subjected to excessive strains (larger than anticipated from design). It is not sufficient to monitor only the sea state and wave height, also other parameters such as e.g. current speed and direction, and vessel orientation may affect the relative movement of the pipeline and vessel and should continuously be monitored.

Any bottleneck processes in the production will be pressed to increase the productivity. For the Blue Stream project the field joint coating was a bottleneck when the tower inclination was more than 5 deg. resulting on extensive forces between pipe and aft roller boxes below FJC station. In order to prevent damages of the FJC when acting on the roller boxes, the FJC had to be allowed to cool sufficiently i.e. hardened. Although corrective measures in way of a water-spray cooler acting directly on the fresh FJC, and the curing time was reduced dramatically, a decrease in the lay rate of 25-100% was experienced depending on the tower inclination.

As human error still is the most common reason for errors, also when it comes to welding errors and defects, it is essential that personnel are qualified and adequately trained.

5 WELDING DEFECTS AND NDT

All welds will to some extent contain imperfections. If an imperfection exceeds a given set of dimensions, and is deemed unacceptable according to the acceptance criteria employed, the imperfection becomes a defect.

When defects occur in a weld, it is in most cases due to several unfavourable factors acting together. Often it is found that correction of one unfavourable condition results in an improvement in the weld quality.

Some common weld imperfections relevant for girth welds (see also Figure 6) in pipelines are:

Hydrogen cracks (cold cracks):

These occur in the weld metal as transverse cracks and in the heat-affected zone as longitudinal cracks. They are also called cold cracks since they will not appear until after the weld has cooled down. The formation of hydrogen cracks depends on three factors:

- presence of hydrogen in the weld
- a hardened microstructure (high hardness in the weldment)
- tensile stresses in the weld

If any one of these factors can be eliminated cold cracks will not occur.

Since tensile stresses always will be present and absence of a hardened microstructure is difficult to control the obvious remedy is to limit the hydrogen content of the weld. This is achieved through the use of low hydrogen welding consumables or welding processes. Additionally preheating of the base material is often used to limit the hardness in the weldment.

Hot cracks:

Hot cracks occur as longitudinal cracks in the weld metal, most often along the centre line. Hot cracks are associated with steels with high contents of sulphur, phosphorus and other contamination, and also high heat input weld methods (generally only SAW) with narrow weld preparations. When modern pipeline steels and experienced fabricators are used, hot cracks should not be of a major concern.

Porosity:

Porosity is caused by gas being trapped in the solidifying weld metal. The gases that most often cause porosity are hydrogen, oxygen from carbon dioxide and nitrogen from air. Porosity is most frequently spherical, however, may in some instances also be elongated. Porosity to a limited extent is not considered as a serious imperfection. Porosity may however be an indication of improper handling of welding consumables and insufficient shielding during welding. Porosity may also mask other and more serious imperfections.

It is therefore advisable to limit the allowable extent of porosity, e.g. as in DNV OS-F101 Appendix D, H300.

Lack of fusion:

Lack of fusion occurs when the molten weld metal solidifies without fusing with the base material or the previously deposited weld metal. Lack of fusion is a problem with welding methods using low heat input in combination with a high deposition rate such as gas metal arc welding (GMAW). Lack of fusion can also be caused by oxidation of the surfaces in the weld preparation due to insufficient protection by the shielding gas. In this case the extent of porosity may give an indication of insufficient shielding. Lack of fusion may also occur due to poor control of the weld pool. If the pool gets too large, molten metal may run ahead of the arc and solidify without fusing with the underlying metal. This type of lack of fusion is also called cold lap.

Slag and slag-lines:

Slag is non-metallic remains of electrode cover (SMAW welding) or flux (SAW welding) entrapped in the weld between the layers of multi-pass welds. The cause is most often poor workmanship in removing remaining slag before depositing the next pass or welding outside the optimum welding parameters.

Crater cracks (end cracks):

Crater cracks are cracks formed by stopping the arc in a manner allowing the upper part of the weld deposit to solidify before the central portion. Crater cracks during manual welding can be avoided by proper manipulation of the arc. (i.e. by the movement of the welding torch when finishing the pass). For automatic welding the best practice is to remove crater cracks in the start-stop area by grinding.

Lack of penetration:

Lack of penetration occurs when the weld root is not completely filled with weld metal. Lack of penetration is normally caused by; large electrode diameters, low welding current, narrow welding preparations and welding with the electrode offset from the weld centreline.

Burn through:

Burn through is a portion of the root bead where excessive welding current during welding of the hot pass has caused the weld pool locally to be blown into the pipe.

Undercut:

Undercuts are a groove melted into the base material at the toe or root of the weld and left unfilled by weld metal. Undercuts are normally due to too high welding current or incorrect electrode manipulation. Low welding currents giving a convex surface combined with insufficient filling of the groove may also result in undercut like imperfections.

Other imperfections:

Other imperfections are excessive penetration, excessive cap convexity, concave roots and metallic inclusions (from filler wire or copper backing). Excessive penetration is not a problem during main line welding due to the use of copper backing.

Defects in girth welds:

The most common welding methods used for girth welds are:

- submerged arc welding (SAW) for double jointing
- gas metal arc welding (GMAW)

For repair welding the most common welding methods are:

- shielded metal arc welding (SMAW)
- flux cored arc welding (FCAW)

Imperfections commonly associated with SAW welding:

- slag and slag-lines
- porosity
- undercut
- excessive convexity

With improper handling of welding fluxes hydrogen cracks can be a problem. Hot cracks can be a problem if steels with high contents of impurities are used and also with narrow weld preparations. Lack of fusion type imperfections are unlikely to occur due to the high heat input of SAW, but may occur if welding is done offset from the weld centre.

Imperfections commonly associated with GMAW welding:

- lack of fusion
- porosity

Metallic inclusions in the form of wire and parts of copper nozzles are also occurring. Slag will not occur since covered electrodes and fluxes are not used.

Imperfections commonly associated with SMAW and FCAW welding:

All the imperfection types described above with a possible overrepresentation of volumetric defects may occur. Due to the limited height of the welding passes the imperfections tends to be small.

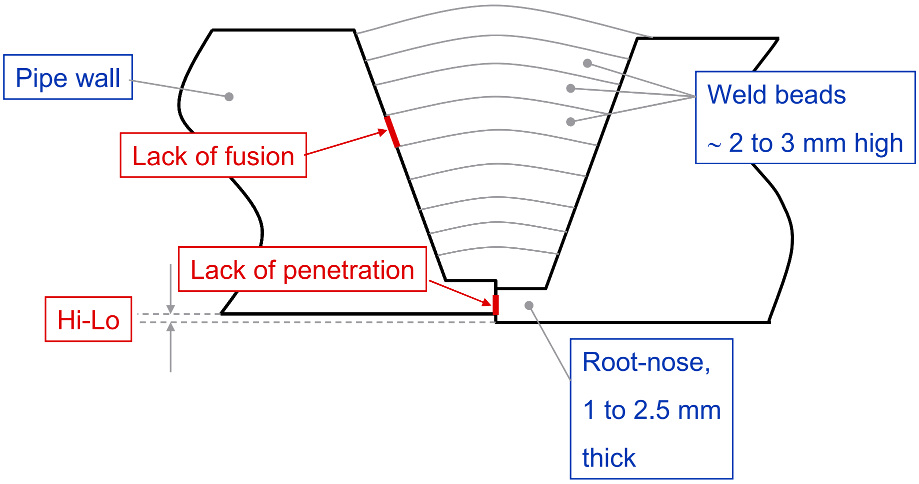

Figure 6. Typical pipeline girth weld defects

There are some tendencies for porosity and minor crater cracks at the start and stop of each weld bead around the pipe girth weld. These types of defects are normally considered to be less critical than a lack of fusion defect. Aligned defects at the start and stop of successive weld passes are reported as stacked defects. The start and stop location for successive weld passes should be staggered in order to avoid such stacked defects; however, this is sometimes neglected in practice.

Non-destructive testing (NDT)

The predominant NDT-method for installation welding offshore is automated ultrasonic testing (AUT) applying the pulse-echo, tandem and time of flight diffraction (TOFD) methods. AUT systems are normally to be qualified for the specific application. The AUT equipment is typically calibrated such that a reference reflector (2 or 3mm flat-bottomed hole and 1 or 2 mm notches for root and cap area) yields 80% of the full screen height (FSH). Indications detected at 40% FSH or more are normally sized by pulse echo or TOFD, but information from all channels, including volumetric channels should also be used as an aid in sizing. Indications between 20% and 40% FSH are normally reported, but may not be sized. The relationship between signal amplitude in % FSH and indication height is complex and dependent on the indication size and position. There is some inaccuracy in the sizing of the weld defects, with a tendency to conservatism, such that over-sizing is more prevalent than under-sizing. The measurement of defect lengths is typically less accurate than for defect heights. Other reference reflectors and thresholds for detection and sizing may be used depending on the applicable acceptance criteria and the results obtained during qualification of the AUT system.

For repair welding the most common NDT method is manual ultrasonic testing often, and preferably, supplemented by AUT to confirm successful removal of the original defect. Acceptance criteria for repair welds are most commonly based on workmanship standards.

6 API 5L GRADE X65 IN PRESSURISED EQUIPMENT

6.1 Introduction

The welding limitations of API 5L X65 for use in pressurised equipment, i.e. pressure vessels and process piping, have been studied.

The specification API 5L concerns line pipe steels suitable for use in conveying gas, water and oil in both the oil and natural gas industry. The main intention of the steel does not cover pressurised equipment.

Wall thickness sizes much above 40 mm are not currently offered by pipe mills. Welding of such thick wall joints require extensive qualifications /1/.

Normally, codes for pipelines, process piping and pressure vessels do not specify any required welding method. Therefore, there are no additional requirements with respect to welding methods for pressurised equipment compared to pipelines.

The main difference is regarding the welding procedure qualification testing. Many pipeline codes subject the weld to a 12.5% strain at bend testing, while codes for process piping and pressure vessels subject the weld to higher staining, e.g. 20% when using ASME IX /2/.

6.2 Application in pressurised equipment

All materials specified in API 5L, incl. grade X65, are line pipe steels intended for use in conveying gas, water and oil in both the oil and natural gas industry.
Steels for pressure equipment are normally killed, not susceptible to strain aging (when applicable) and fully heat treated. This is not explicitly required by API 5L for line pipe.

In general, API 5L, grade X65, is not allowed to be used in pressure vessels. This applies to recognised design codes as ASME VIII Div.1 & 2, EN 13445, PD5500 and AD Merkblatt. However, normally the design codes accept the use of "*non-listed*" materials based on special evaluation and consideration from case to case.

For process piping and gas piping API 5L, grade X65, is allowed by the design code ASME B31.3 and ASME B31.8, respectively. The European design code for process piping, i.e. EN 13480, does not refer to this material. However, X65 may be used based on special evaluation and consideration. Due to the fact that X65 is a line pipe steel it is difficult to predict if the material will be found acceptable after a special evaluation and consideration, or if it will be rejected. It will most probably depend on the involved parts.

For use in pressurised service within the European Union and its Member States the use of API X65, will most probably be restricted due to the material requirements in the Simple Pressure Vessel Directive No. 87/404/EC and the Pressure Equipment Directive No. 97/23/EC. See Ch. 1.3 for technical clarification. *NB! This applies only when these regulations apply.*

6.3 Technological status

6.3.1 Metallurgical status

According to the specification API 5L the line pipe steels are manufactured as structural steels with the following options:

- normalising heat treatment, or equivalent, is not required *(annealing is not considered as equivalent)*
- non-effervescent is not required *(killed steel is not required)*
- non-sensitivity against aging is not required *(N is not restricted, and Al, Ti or V is not required added)*

Steels intended for pressurised service shall normally satisfy these conditions.

6.3.2 Experience in pressurised equipment

Grade X65 is accepted by ASME B31.3 and ASME B31.8. When used the following conditions are specified in ASME B31.3:

- welding procedures shall be qualified separately for each strength class, i.e. separate qualification for X52, X60, X65, etc.
- welding qualification may require special consideration x)

  x) "Consideration" is not further defined

There are limitations with respect to welding method or thickness.

Generally for ASME B31.3 and B31.8 welders and welding procedures are to be qualified according to ASME IX.

It is not reported or observed special welding problems, e.g. due to wall thickness or welding method, that is not known from welding of pipelines.

6.3.3 Research

One study was carried out in 1998 to compare flux cored arc welding (FCAW) and shielded metal arc welding (SMAW) for welding of API 5L X65 for steam pipes with pressure 172 Bar at 343°C (650°F) /2/.

The pipes in question had diameter 400 mm and wall thickness 25 mm. The welding procedures were qualified according to ASME B31.3 which refers to ASME IX.

The study concluded the following:

- The SMAW process required a traditional 60 degree bevel. FCAW process was carried out successfully with a compound bevel. This dramatically reduced the amount of filler weld metal.
- The SMAW process required the use of 176°C (350°F) preheat to prevent hydrogen cracking (E8010G electrodes). The controlled low-hydrogen content of the flux cored wires allowed reduction of the preheat temperature to 93°C (200°F) (E71T-1 flux-cored wire).

These two changes provided dramatic cost reduction when using FCAW (less filler weld metal, less man-hours).

6.4 Limitations for the use of API 5L grade X65 in pressure equipment

The use of API 5L, grade X65, in pressure equipment is mainly limited as follows:

- Limitations are set by the design codes, ref. Ch. 1.2 and h. 1.3.2.
- Limitations are indirectly set by the Council Directive No. 97/23/EC, when applicable

Limitations due to welding problems, e.g. large thickness, for use in pressure equipment are not experienced. The choice of welding method and wall thickness limitation will be the same as for welding of pipe lines.

6.5 Uncertainties and challenges

Within the European Union and its Member States the intention is to use EN 13445 and EN 13480 for pressure vessels and process piping, respectively. Today these codes are not dominating, however, in the future these codes will probably be used more widely.

When EN 13445 and EN 13480 are used the possibility of using non-harmonised materials are depending on a “Particular Material Appraisal”. Depending on the “*Category*”, and if Council Directive 97/23/EC applies, this material evaluation shall be performed by the manufacturer or the notified body.

If the Council Directive 97/23/EC apply it will be difficult to justify the use of line pipe steels in process piping and pressure vessels, ref. Ch. 1.3.1, especially when used in combination with other design codes that ASME B31.3.

6.6 References

Reference no.	
/1/	Ricky Thethi and David Walters, Alternative construction for high pressure high temperature steel catenary risers, 2003.
/2/	Ed Craig, One million dollar cost reduction for field pipe line welding crew, 2001.

7 DEEPWATER PIPELINE HYPERBARIC REPAIR WELDING

7.1 Introduction

Current pipeline repair in the North Sea is performed using the Pipeline Repair System (PRS) equipment pool. This system rely on diver assisted hyperbaric welding for pipe diameters larger than 22”, and for repairs of diameter 8” to 22”, the Morgrip mechanical coupling can be installed without divers.

The PRS is a joint development between Norsk Hydro and Statoil, facilitated by Statoil since 1987 and funded by a consortium of oil companies sharing costs in exchange of access to the system. The PRS system is utilised to provide repair and construction services for the about 8000 km of large oil and gas pipelines in and from the Norwegian continental shelf, ranging from 8-42” and per date down to water depths of 600 m. The operation and management of the equipment is put out to tender, currently to Stolt Offshore and Halliburton.

The PRS system is a comprehensive suit of subsea pipeline construction and repair tools. The system has gradually been extended over the years to include remote control of several subsea activities related to repair, manipulation and joining of subsea pipelines using welding, mechanical couplings etc.

A typical remote controlled “equipment package” for hyperbaric welding consists of:

- H-frames for pipe handling at sea bed
- Habitat, including surface umbilical
- Hyperbaric welding equipment
- Concrete- and corrosion coating removal machine
- Pipe cutting machines

Although the welding is controlled from the surface support vessel, the welding has up to today been diver assisted. However, remote operated pipeline repair systems (RPRS) applied beyond diving depths are currently being developed by Statoil, as an alternative to mechanical pipeline couplings at larger depths. The system is mainly based on:

- The damaged pipeline section is cut out and removed by ROV. Slight oversize sleeves are entered onto each of the remaining pipeline ends, the pipeline section (a spool piece to replace the damaged pipe) is inserted, and the sleeves located centrally over each joint.
- Remote operated welding equipment with habitat is positioned at each sleeve, and prepares a fillet weld at each sleeve end, based on qualified welding procedures for the project specific conditions. Sealing of the pipe by use of pigs is not required, i.e. the welding may be performed with water-filled pipe.
- The welded sleeve repair system to be independent of divers and water depth.

7.2 Application

This welded sleeve joining method will be applicable for replacement of damaged deepwater pipeline sections, independent of diver assistance and water depth. The method is currently being qualified for pipeline outer steel diameters in the range 8” to 48”, and for material API 5L grades X60 to X70.

7.3 Technological status

Both Cranfield University and Sintef have been developing hyperbaric welding systems for several years. Initially TIG welding was utilised. However, today the further development of the PRS - with Statoil in charge - is focused on the MIG-based system developed by Cranfield University.

The new RPRS concept, the Welded Sleeve concept, is developed to eliminate the need for diver assisted weld repair at moderate and large water depths as a supplement to mechanical couplings for large diameter pipes.

The installation of the welded sleeve is fully remote without any diver assistance. The damaged length of the pipeline is replaced by a spool of similar dimensions and material grade. The spool is connected to each cut end of the pipeline by sleeves. Each sleeve is MIG fillet welded to the pipe and spool as illustrated in Figure 7.

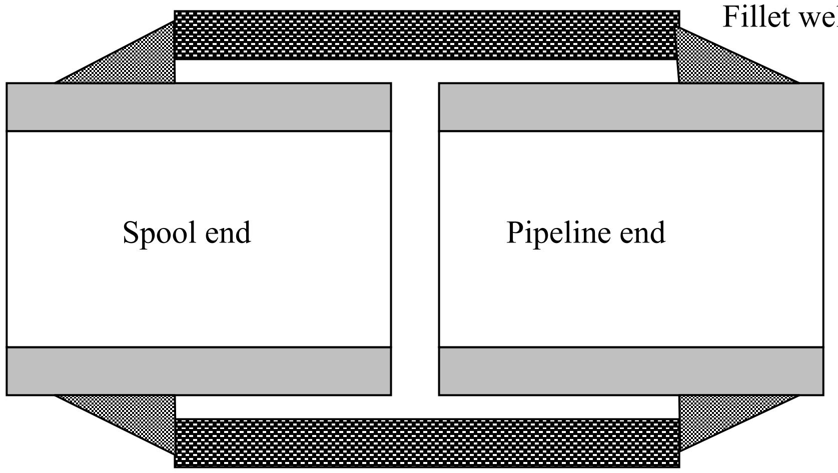

Figure 7 **The principle of the welded sleeve as installed: The outer sleeve connects one of the cut ends of the pipeline with the spool replacing the damaged part of the pipeline.**

This method features less challenges with respect to alignment of the two pipe ends to be joined, and requires no preparation of weld bevel. The main challenge has been to qualify a fillet weld profile such that the sleeve repair joint assembly constitutes the same structural capacity as an undamaged pipe, and to develop a remote operated hyperbaric welding procedure not accessible by NDT, having acceptable reliability of all governing welding parameters.

At present, the welded sleeve pipeline repair system is being qualified for the following functional requirements:

Table 1: Functional requirement of welded sleeve PRS repair system

Description	Units	Data
Transport medium	Oil / Gas	Gas
Fluid description	Sweet/slightly sour / sour	Sweet and slightly sour
Design life	Years	Up to 50
Water depth	M	250+
Production line pressure rating	bara	Up to 250
Axial strength	-	50% of pipe capacity
Moment capacity	-	30% of pipe capacity
Minimum production line steel outer diameter	inch	8”
Maximum production line steel outer diameter	inch	48”
Design minimum temperature	^oC	Typically -10
Design maximum temperature	^oC	Typically +60

The deepwater hyperbaric welded sleeve repair method is expected to be qualified for offshore pipeline repair within approximately a year, for standard carbon steel material. The qualification is carried out in accordance with the following standards:

- DNV RP-A203 “Qualification procedures for new technology”
- DNV OS-F101 “Submarine pipeline systems”
- DNV RP-F104 “Mechanical Pipeline couplings”
- DNV RP-C203 “Fatigue strength analyses of offshore steel structures”

7.4 Limitations

For the welded sleeve, Non Destructive Testing of the filled weld is not feasible, bringing about an increased demand on the welding procedure qualification and the simulation of the subsea conditions during laboratory testing. The qualification of the offshore welding needs to rely on recording of all governing welding parameters, to confirm that the welding has been carried out within the qualified parameter window.

The repair method is qualified for material grades up to API 5L X70. Higher grades linepipe, or excessive weld deposit overmatch increases the risk of Hydrogen Induced Stress Cracking (HISC), and has not been qualified.

Some of the main focus points for the welding operation are:

- Record and document all welding parameters accurately
- Achieve acceptable high fracture toughness, allowing for some margin on tolerances of potential defects in the weld root.
- Reduce humidity in the weld habitat (critical with respect to HISC).

7.5 Uncertainties and challenges

The deepwater pipeline sleeve repair system is at present not fully qualified. The technology qualification has been brought to DNV Statement of Endorsement which implies that the new technology is expected to be proven *Fit for Service* through the remaining planned qualification activities.

7.6 Important parameters for robust joints

The following main parameters govern the robustness of the welded sleeve repair joint.

- Qualified welding procedure covers project specific conditions in all aspects (base material, weld deposit material, dimensions, external pressure, habitat environment, gap between sleeve and spool / pipeline, welding parameters, weld fillet profile).
- Tolerances on the level and variation of the gap between pipeline/ spool outer diameter and the sleeve inner diameter.
- Habitat welding environment:
  - The high environment pressure in the habitat generally causes difficulties in obtaining a stable weld arc. This challenge increases for increasing depth / pressure up to a certain asymptotic pressure head, i.e. indicating that the repair method can be qualified for even larger depths than qualified per today.
  - Humidity, associated with risk of Hydrogen Induced Stress Cracking (HISC)
- Accuracy of measured and recorded welding parameters.
- Control of residual operational loads in pipeline at repair location, after repair.
- Surface condition at pipe end repair fillet weld location, after removing of coatings and cleaning.

8 WELDING OF 13CR MARTENSITIC - 22CR AND 25CR DUPLEX STAINLESS STEELS FOR SUBSEA APPLICATIONS

8.1 Introduction

13Cr super martensitic stainless steels (SMSS), 22Cr and 25Cr duplex stainless steels are used extensively for subsea applications. There are important differences between 13Cr and duplex stainless steels related to materials properties, microstructure, areas of application and typical product forms.

8.2 13Cr Martensitic stainless steels

8.2.1 Application

13Cr steels are primarily used for pipeline applications. This is due to the relatively low cost combined with a suitable corrosion resistance for flowline applications. Norwegian oil companies first installed 13Cr flowlines in 1997. Installation has mainly been by reeling and the flowline diameters have varied from 6" to 16". At least five field development projects have utilized 13Cr flowlines based on seamless linepipe, and more than 350 km was installed by 2001.

The main type of welds made to 13Cr stainless steels are:

- Pipeline girth welds. Since 13Cr flowlines are frequently reeled these welds are often subject to plastic deformations. To the knowledge of DNV, duplex has been the most common filler material to be used for the girth welds of all pipelines currently in service in Norway, however, also 13Cr type filler material has been used. These welds are today always Post Weld Heat Treated (PWHT).
- Another type of welds that have been made to 13Cr steels are anode attachment welds. These welds are fillet welds between the 13Cr pipe and a stainless steel doubler plate (e.g. AISI 316) generally using a 25Cr duplex or Alloy 625 filler material. Such welds have in general not been PWHT.
- In addition to the above, there are other types of welds made to 13Cr stainless steel pipelines. This includes structural fillet welds and welds between dissimilar materials. These welds are usually associated with tie-ins. It is known that duplex filler material is also commonly used for this type of applications.

8.2.2 Technological status

There have been a number of serious problems associated with welds in 13Cr stainless steels over the last years. These problems have been associated primarily with anode attachment welds and girth welds. There are also tie in welds that have failed. The main causes of the failures have been associated the following:

- Too high hydrogen content in the weld filler material during onshore or field joint welding.
- Presence of weld defects
- Too high hydrogen content during hyperbaric welding.
- Hydrogen ingress into the 13Cr material as a result of atomic hydrogen formed on the cathode (material to be protected) as a result of the Cathodic Protection (CP) system. This has led to Hydrogen Induced Stress Cracking (HISC). This problem has been particularly

severe for anode attachment welds. This has been related to the fact that there is an inherent weakness in the coating at these locations due to the fact that the anode bracket penetrates the coating. In addition, the geometry of the fillet weld gives high stress concentrations. The fact that the 13Cr HAZ of the anode attachment welds are not PWHT is believed to give increased susceptibility to HISC.

8.2.3 Limitations for joining of 13Cr

Welding of 13Cr stainless steel pipelines may today be considered as proven technology. A lot of weaknesses have been discovered during the initial years of use, however, many of these have now been resolved.

One of the main remaining issues is to address the susceptibility to HISC when the welds are exposed to CP. It is a general acceptance in the industry that a certain stress / strain level is required to initiate HISC, however, the exact level (acceptance criteria) has still not been determined. It is recognised that the axial, hoop and combined stresses should be established in detail and kept well below the material's yield stress. This may have implications for pipeline design. Configurations with strain based design (i.e. no limit on stress) need to be considered in detail. There are currently no recognized tests method available that can be applied to determine the required stress / strain value for initiation of HISC in 13Cr pipeline materials. Ongoing research and development aim to establish such a test methodology.

There are currently no well recognized standard taking all critical issues related to welding of 13% Cr steel into account. DNV OS-F101, however address 13Cr and give relevant material and welding requirements. EEMUA 194: 2004 contain a series of general recommendations related to welding of 13Cr stainless steel and also address HISC. This does document can however not be considered as a specification.

8.2.4 Uncertainties and challenge

Based on current knowledge the following limitations are considered relevant for welding of 13Cr stainless steels:

- Hyperbaric welding of 13Cr stainless steel is challenging due to the need to limit hydrogen in the weld metal. Reference is made to DNV OS-F101 Appendix C C104 *"Low hydrogen consumables shall give a diffusible hydrogen content of maximum 5 ml/100g weld metal. Hydrogen testing shall be performed in accordance with ISO 3690 or BS 6693-5"*.
- If such welding is carried out, strict requirements should be applied for qualification and on measures to avoid ingress of hydrogen.
- Considerable amount of work has been conducted in order to avoid welding of anode attachment doubler plates directly to 13Cr stainless steels. Suggested solutions are e.g. installing a clad carbon steel pup pieces to which the doubler plates are welded, reducing the excessive hydrogen charging on the cathode by installing a diode controlled CP system which will adjust the negative potential from the normal value of -1050 to -800 $mV_{Ag/AgCl/Seawater}$, or for shorter pipelines to avoid bracelet anodes on the pipeline and rely on CP from connecting structures (e.g. platforms).
- It is by current practice not recommended to use other filler materials than 25Cr duplex stainless steel. The experiences made with using of 13Cr filler material is generally negative. Such welds failed for various hydrogen related reasons on the Tune flowlines.

- Current practice is to PWHT all welds. This is believed to reduce the material's susceptibility to HISC. The mechanism causing the reduction in HISC susceptibility is however not fully understood.
- Testing has shown that when pre-cracked 13Cr specimens are exposed to loading they are very vulnerable to HISC. It is therefore reasonable to assume those 13Cr welds are sensitive to surface defects such as cracks and undercuts.
- As will be detailed later there are issues related to conducting ultrasonic inspection of duplex stainless steels. Since 13Cr pipeline girth welds are primarily welded with duplex stainless steel filler special requirements to the Automated Ultrasonic Testing (AUT) system are required. Special measures are required both related to the setup of the equipment and qualification.

8.2.5 Important parameters for robust joints

There are a number of factors that can contribute to the robustness of the joint.

- HISC is in many cases caused by the steel surface coming directly into contact with seawater and cathodic protection. If a coating prevents contact between the steel and sea water the failure mode is eliminated. A high quality coating preferably without any form of penetrations such as anode bracelets is considered to be an important measure to increase the robustness of the joints.
- Ensuring low hydrogen content in weld filler metal is important. Procedures for how this should be done are well established. It is however important to ensure that they are implemented.
- Maintaining a robust (i.e.~ -800 mV_{SCE}) but not over-protecting cathodic protection potential reduces the hydrogen formation at the protected steel surface.

8.3 Duplex stainless steels

8.3.1 Application

22Cr and 25 Cr duplex stainless steels have been used extensively within subsea units such as manifold and X-mas trees for more than 20 years. These materials are used as castings, forgings, seamless pipe and rolled products.

Duplex stainless steel is also a commonly chosen material for umbilical tubing and other types of instrument tubing. These applications are characterized by small dimensions and wall thicknesses.

Finally duplex stainless steel is also used as a pipeline material. The linepipe can be either seamless or longitudinally welded.

8.3.2 Technological status

Welding of duplex stainless steels for subsea applications has been done for a long time. It has however been acknowledged that welding of these materials is complicated compared to many other materials.

HISC

There have been a number of high profile failures of duplex stainless steels exposed to CP due to HISC. Research and Development work launched to address the failure mode has come up with a number of issues related to welding:

- It has been established that the susceptibility to HISC is dramatically increased if the steel contains sharp defects. This has raised the issue of whether more extensive NDE is required.
- HISC has been found to initiate at local stress raisers. Avoiding irregular weld caps, and in particular sharp weld toes has been identified as an important issue.
- The vast majority of reported HISC failures have occurred at fillet welds. This is due to a combination of high local stresses and unfavourable microstructure with high ferrite content that can occur at such welds.
- Residual stresses from welding are thought to be a contributing factor for the onset of HISC. This should be taken into account in design. There is however currently no specific requirements related to the actual welding operation.

Intermetallic phases.

If duplex stainless steels are held in the temperature range 750 to 950 °C for too long time or cooled slowly through this temperature range, intermetallic phases which have a detrimental effect on the material's toughness and corrosion priorities will be formed (e.g. sigma phase). As a result of this, it is always required to measure the level of intermetallic phases during welding procedure qualification. Many of the international standards state that the material shall be free from such phases, however, it has during the last years been an acceptance to allow a small level of intermetallic phases. Measuring the amount of intermetallic phases with the required level of accuracy may be difficult (e.g. to determine the correct area to perform measurements).

Ultrasonic testing

The are certain challenges with carrying out UT of duplex stainless steels compared to other steels. It is therefore crucial to use competent and properly qualified personnel (e.g. according to EN473/Nordtest Level 2 with supplementary qualification 'Welded joints in stainless steel').

The following recommendations apply to ultrasonic inspection of duplex stainless steel in general:

- Use longitudinal waves (in general avoid shear waves)
- Use focused probes, as appropriate
- Avoid 'skipping' (i.e. reflection from the back wall)
- Use multiple probe angles, from 'creep' to normal probes (with machining of weld surfaces)
- Compensate for variation in attenuation

- Avoid the use of prefabricated amplitude-distance diagrams (DGS or AVG)
- Use reference blocks of the actual material to be tested, if relevant with weld(s)

The following recommendations apply to ultrasonic inspection of duplex stainless steel welds:

- Ultrasonic examination of duplex stainless steel and dissimilar metal welds is a very cumbersome and meticulous task, but can be done with care taken
- Supplementary radiography should be used to ease interpretation of findings (e.g. inter-run lack of fusion or volumetric defect; or possible geometric distortion)

8.3.3 Limitations for joining of duplex

There are currently several well recognized standards taking critical issues related to welding of duplex stainless steels into account. NORSOK and DNV OS-F101 are examples of such codes. There is however no well recognized codes that fully cover the newly gained experience related to HISC. EEMUA 194: 2004 contain a series of general recommendations. In addition there is a NORSOK- and a DNV design guideline under development which aim to give more specific requirements. All these documents give specific stress limits which should not be exceeded. It is therefore difficult to use welded duplex if there are large uncertainties regarding the applied loads.

8.3.4 Uncertainties and challenges

General

- Ensuring correct temperatures and heat input is a critical issue for duplex welds. Too rapid cooling during welding will give too high ferrite content in these welds. This may typically be the case if too low heat input is used. Maintaining the weld metal and HAZ at too high temperatures could lead to formation of intermetallic phases. This may be the case if too high heat input is used or if the weld is not allowed to cool down to the specified interpass temperature According to DNV OS-F101 App.C H204 the heat input should be kept within the range 0.5 - 1.5 kJ/mm, avoiding the highest heat input for smaller wall thicknesses. According to NORSOK M-601 the interpass temperature should not be higher than 150°C.
- Fillet welds should be given particular attention. According to many specifications a fillet weld WPS can be based on a butt weld WPQR. Cooling of the weld metal is however more rapid in a fillet weld due to the geometry of the connection. Fillet welds have therefore in some cases been found to have very high ferrite contents. Furthermore, lack of fusion defects and also too low throat thicknesses have occurred.
- When repair welding is performed on duplex stainless steels welds, the HAZ of the repair weld will be submitted to additional heating cycles compared to the original weld. There is therefore a risk of formation of intermetallic phases. This is a reason for thorough qualification of repair weld procedures. In order to be representative repair weld procedures should be made such that the HAZ of the repair weld is located within the weld metal and HAZ of the original weld.
- Due to the risk of HISC, it is important to ensure that the final weld geometry is as specified.

- Most duplex welds are currently subjected to radiographic testing (RT). Only a few operators specify ultrasonic testing (UT). There is however an ongoing discussion as to whether UT should also be carried out. This is based on the fact that sharp defects such as lack of fusion has not been detected when using RT, but detected with UT. UT of duplex is however more complicated than for other materials, and therefore considered to require specialized personnel. It has not been documented how additional UT will affect the probability of detection (POD) of defects.

Subsea manifolds, X-mas trees, and other subsea equipment:

- In this application welding is characterized by a large variety of dimensions, geometries etc. Welding on this type of equipment is usually manual and rarely standardized. In addition workshops often use a large variety of base materials and filler materials. Using correct filler material and welding parameters for a given weld is therefore a challenge. Sufficient quality assurance related to these issues is therefore critical.

Umbilicals:

These welds are mechanised and made in very large numbers. The dimensions are small. The most important challenge is to ensure that a sufficient level of QA is maintained for all welds.

Umbilicals are in general exposed to a large number of bending cycles. The welds are therefore exposed to significant plastic strain and may also suffer fatigue damage.

Pipelines:

A specific issue related to pipelines is the necessity to use Automated Ultrasonic Testing (AUT). As described previously, ultrasonic testing of duplex requires special measures. Special attention is therefore required regarding both equipment and qualification of AUT.

8.3.5 Important parameters for robust joints

There are a number of factors that can contribute to the robustness of the joint.

- As described above welding duplex stainless steels requires control on heat input and interpass temperatures in order to obtain the desired microstructure with a correct ferrite/ austenite balance and no deleterious phases. It is therefore particularly important to ensure that welding is carried out by qualified personnel using with qualified procedures.
- UT duplex is a preferred method for detecting linear defects in duplex. However, the microstructure set special requirements to how this is conducted. The personnel carrying out the UT will therefore have to sufficiently qualified and trained.
- HISC may be caused by the steel surface coming directly into contact with seawater and cathodic protection. If coating prevents contact between the steel and seawater the HISC is eliminated. A high quality coating without any penetrations such as anode attachments is considered to be an important measure to increase the robustness of joints.
- Ensuring low hydrogen content in weld filler metal is important. Procedures for how this should be done are well established. It is however important to ensure that they are implemented.
- Maintaining a robust (i.e.~ -800 mV_{SCE}) but not over-protecting cathodic protection potential reduces the hydrogen formation at the protected steel surface.

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