Tanker Structure Co-operative Forum

Guidance Note on Welding

SUMMARY

It is recognized that welding and weld quality are critical factors with respect to the structural performance of a tanker. Ensuring good quality of welding is a means to improve the reliability of tanker structures with a consequent reduction of costs for both shipyards and owners. The aim of this paper is to provide a "layman's" guide to welding for superintendents, inspectors, staff naval architects, etc. who are not necessarily welding experts.

Reference	Revision N°	Revision Date
TSCF IP 007/2016	Revision 0	2016/07/01

CONTENT

1 Introduction

1.1 Purpose

Welding and weld quality are recognized as being critical for the structural integrity and reliability of tanker structures. Many of the damages observed on tankers are cracks related to weld execution. Many of these damages can be traced back to poor weld execution, poor fit-up or other factors which could have been addressed when the welding was carried out. In addition it is well known that weld quality can have a dramatic effect on the fatigue life in service.

By providing practical information with respect to welding it is hoped that the number of damages, and consequent cost for both yards and owners, can be reduced.

The aim of this guidance note is to provide a practical “layman’s” guide to welding. It is primarily intended for superintendents, inspectors, naval architects and others working in the field with responsibility or interest in welding quality. The information presented is applicable to both new building at the yard as well as in-service repairs.

1.2 Scope

Section 2 of the Note presents a basic introduction to welding, including a description of the most commonly used welding procedures.

The remaining sections present the information which is typically of interest for personnel on site, for example welder qualification, fit-up, typical defects, etc.

The guidance note is not intended to be a textbook on welding. If more detailed information is required then some of the documents referenced here may be of interest.

1.3 Safety

Safety is outside the scope of this note but is an issue which must be addressed anytime welding is carried out. Welding can be a dangerous activity and proper procedures should always be adhered to. This includes such factors as gas freeing to avoid explosion danger, safe access, proper training, etc.

The welding process can be dangerous and damaging to the human body if the correct precautions are not taken. Since many common welding procedures involve an open electric arc or flame, the risk of burns and fire is significant. It is known as a ‘hot work’ process. To prevent injury, welders should wear the correct Personal Protective Equipment (PPE), usually consisting of but not limited to: heavy gloves, boiler suit, safety glasses and welding helmet with UV shield. Should the reader intend to undertake welding activities, relevant HSE material must be used in association with the correct training and risk assessment prior to commencement of the job. Reference is also made to “The International Safety Guide for Oil Tankers and Terminals” (ISGOTT).

2 Welding Basics

2.1 The Welding Process

Welding is a fabrication process for joining metals. The process takes place at a high enough temperature to cause the base material (the pieces to be joined) to melt and then fuse. In many welding processes additional material is added to the joint. The additional material forms a pool of molten metal which then cools and fuses with the base metal. The resulting joint can be as strong as or stronger than the base material.

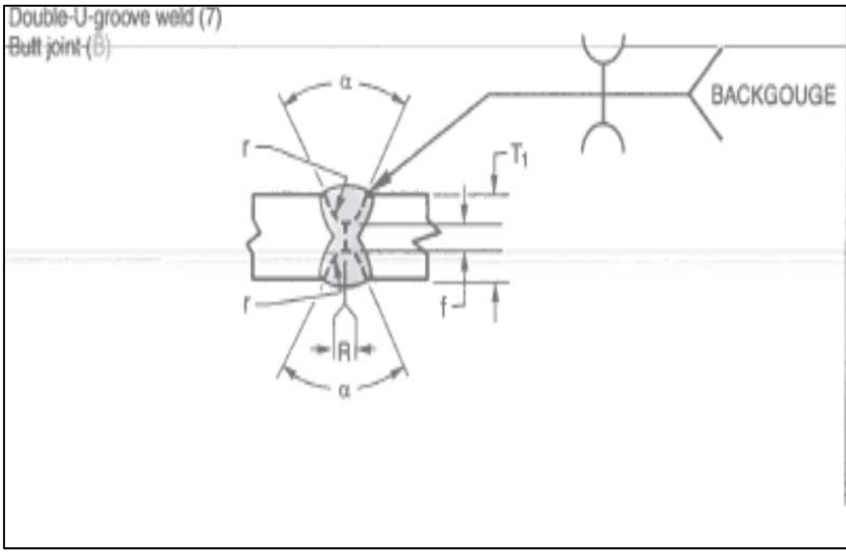
This is in contrast to other processes such as brazing or soldering. In these processes the temperature is not high enough to melt the base material and no fusion takes place. These are essentially mechanical joints.

2.2 Joint Types

A joint is the name for the connection where the individual plate ends/edges, which are suitably prepared and assembled, come together and are joined by welding.

2.2.1 Butt Joint

A Butt Joint is where the connection between the ends/edges of the plate is between 135° and 180°.



Tolerances	
As Detailed (see 3.13.1)	As Fit-Up (see 3.13.1)
For B-U7 and B-U7-GF	
R = +1/16, −0	+1/16, −1/8
α = +10°, −0°	+10°, −5°
f = +1/16, −0	Not Limited
r = +1/4, −0	±1/16
For B-U7-S	
R = +0	+1/16, −0
α = +10°, −0°	+10°, −5°
f = +0, −1/4	±1/16
r = +1/4, −0	±1/16

Figure 2.2-1 Typical butt joint

2.2.2 T-joint

A T-joint is where the connection between the ends/edges of the plate makes an angle to one another of more than 5° up to and including 90° in the region of the joint. T-joints can be done as fillet, partial or full-penetration welds. Selection of the type of weld will depend on the geometry and stress level in the joint.

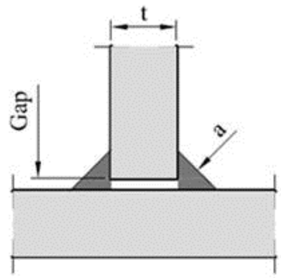


Figure 2.2-2 Typical T-joint – fillet weld

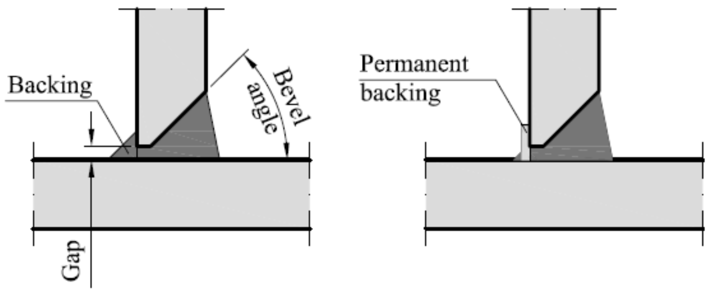


Figure 2.2-3 Typical T-joints – full penetration

2.2.3 Corner Joint

A Corner Joint is where the connection between the ends/edges of the plate makes an angle to one another of more than 30^{o} but less than 135^{o} in the joint region.

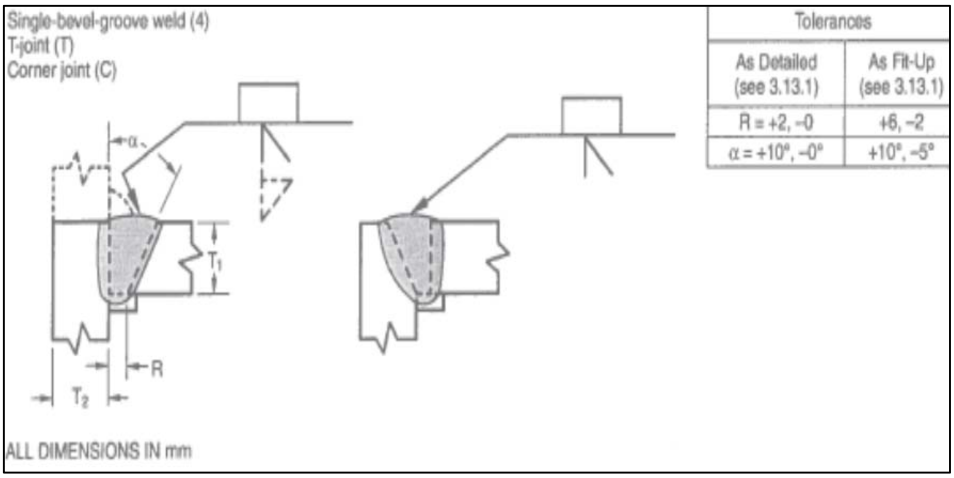


Figure 2.2-4 Typical corner joint, with backing

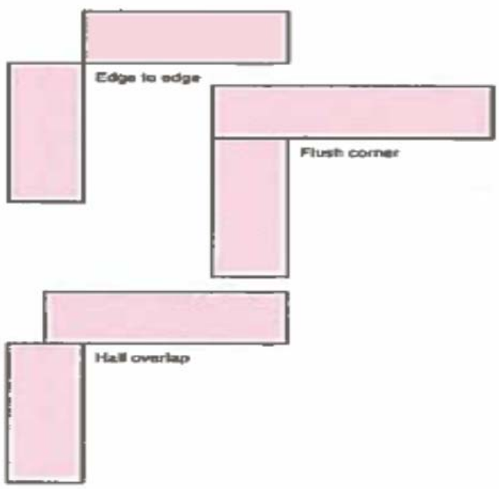


Figure 2.2-5 Corner joint geometries

2.2.4 Edge Joint

An Edge Joint is where the ends/edges of the two plates making an angle to one another of 0^{o} to 30^{o} inclusive, in the region of the joint. This joint is used for welding the membrane in some types of LNG containment systems.

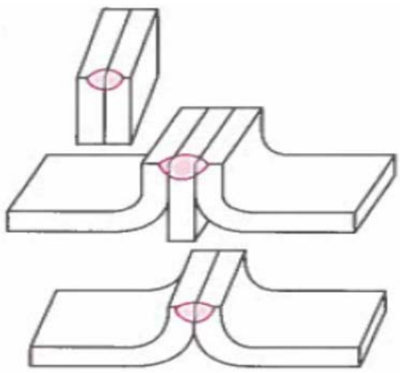


Figure 2.2-6 Edge joint geometries

2.2.5 Cruciform Joint

A Cruciform Joint is where two flat plates or stiffeners are welded to another flat plate at right angles and on the same axis.

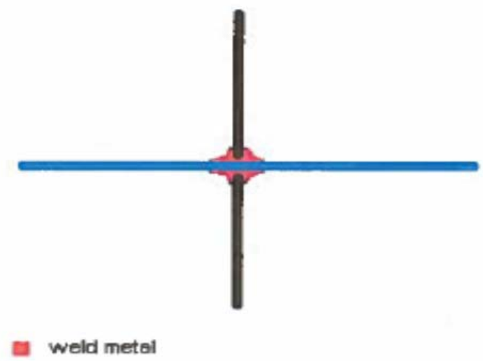


Figure 2.2-7 Cruciform joint

2.2.6 Lap Joint

A Lap Joint is when the connection between two overlapping plates makes an angle to one another of 0^o to 5^o inclusive in the region of the weld or welds.

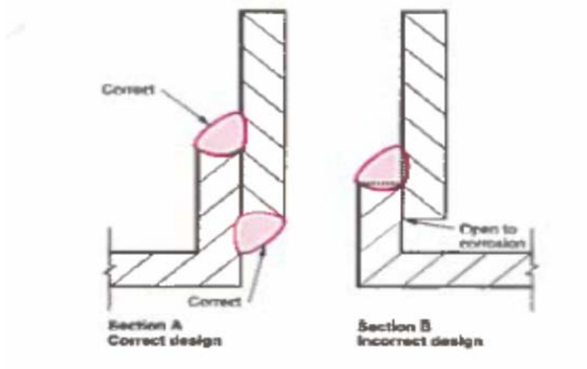


Figure 2.2-8 Overlap joints

2.3 Welding Positions

The weld position is the orientation of a weld which is expressed in terms of:

- (i) Working Position;
- (ii) Weld Slope;
- (iii) Weld Rotation.

2.3.1 Flat

A welding position where the welding is horizontal with the centerline of the weld vertical.

2.3.2 Horizontal

A welding position where the welding is horizontal with the centerline of the weld horizontal.

2.3.3 Vertical

Vertical up is where the welding is executed vertically upwards. Vertically down is where the welding is executed vertically downwards.

2.3.4 Overhead

A welding position where the welding is horizontal and overhead, with the centerline of the weld vertical.

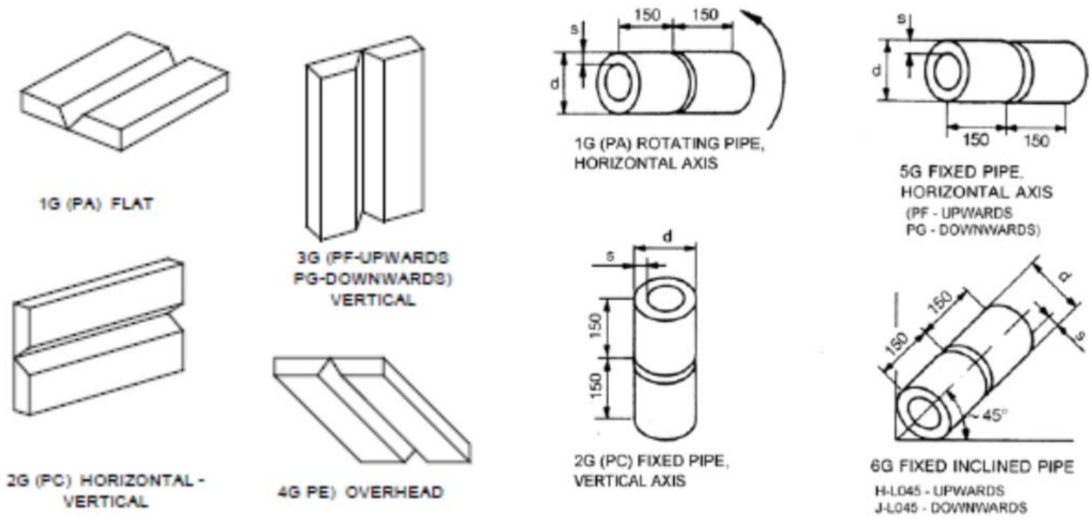


Figure 2.3-1 - Groove welds positions

2.4 Features of a Weld

This section covers the terminology of the different parts of a weld.

2.4.1 Parent Material

The metal to be joined through the welding process.

2.4.2 Filler Metal

The metal added during the welding process.

2.4.3 Weld Metal

All the metal melted during the welding process to make up the weld which is retained in the weld.

2.4.4 Heat Affected Zone (HAZ)

The area of the parent material that is metallurgically affected by the heat of the welding process but which is not melted.

2.4.5 Fusion Line

The boundary between the weld metal and the HAZ.

2.4.6 Weld Zone

The area containing the weld metal and the HAZ.

2.4.7 Weld Face

The surface of a fusion weld exposed on the side from which the weld has been made.

2.4.8 Root

The zone on the side of the first run which is furthest from the welder.

2.4.9 Toe

The boundary between the weld face and the parent metal. This is an important feature of a weld given that they are points of high stress concentration and are often initiation points for cracking. In order to reduce this stress concentration, the toe area must blend smoothly into the parent material surface.

2.4.10 Wetting

The bonding of a liquid filler metal or flux on a continuous solid base metal.

2.4.11 Coalescence

Where two or more work pieces are bonded together by liquefying the places they are to be bonded, joining these liquids (coalescing), and allowing the coalesced liquids to solidify. At the end of the process the two work pieces have become a continuous solid metal that will be as strong as the original material if the weld has been carried out properly.

2.5 Shielding Gases

Shielding gases used with gas metal arc welding processes and tungsten inert gas welding (TIG) protect the molten weld pool from atmospheric contamination.

2.5.1 Argon

Argon is an inert gas which can be used either on its own or in combination with other gases to achieve an arc for the welding of ferrous and non-ferrous metals, i.e. aluminum. Almost all welding processes can use argon or argon mixtures to create efficient weldability. When using ferrous metals, argon is usually mixed with other gases such as oxygen, helium, hydrogen, carbon dioxide and nitrogen. With non-ferrous metals such as aluminum, nickel based alloys etc., argon is used alone. The low ionization of argon creates an excellent current path and good arc stability. Argon produces a constricted arc column at a high current density which causes the arc energy to be concentrated in a small area.

2.5.2 Carbon Dioxide

Carbon dioxide is used frequently in welding carbon steel, due to its ability to influence the quality of the weld as well as its low cost and simple installation. Pure carbon dioxide is not an inert gas because the heat of the arc breaks down the CO_2 into carbon monoxide and free oxygen. The oxygen will combine with elements transferring across the arc, to form oxides which are released from the weld puddle in the form of slag.

2.5.3 Helium

Helium is an inert gas which is used on weld applications requiring higher heat input for deeper penetration welds and higher travel speeds. However, in the Gas Metal Arc Welding (GMAW) process, helium produces a less stable arc compared with argon and therefore is often mixed with argon to take advantage of the good characteristics from each gas. The argon improves arc stability and cleaning action when welding aluminum and magnesium, while the helium improves wetting and weld metal coalescence.

2.6 Welding Processes

2.6.1 Manual Metal Arc Welding (MMAW)

Manual Metal Arc Welding (MMAW) is also known as Shielded Metal Arc Welding (SMAW) and is a process that uses a consumable electrode covered in a flux coating. An arc is initiated and maintained between the end of the consumable electrode and the work piece. Intense heat from the arc causes the surface of the work piece to melt and form a weld pool. In parallel the tip of the electrode melts and small particles of the filler metal travel across the arc into the molten weld pool to form a weld. The arc is initiated when the welder momentarily touches the electrode tip onto the work piece, which causes a current to flow. At this point, the welder retracts the electrode to give a gap of around 3mm between the electrode tip and the work piece, however the current continues to flow across the gap. At the start of the arc process, the flux coating of the electrode disintegrates forming both a slag and gas shield which protects the weld from atmospheric contamination. Due to the versatility and simplicity of this process, MMAW is one of the most popular welding processes. Its dominance can be seen in the maintenance & repair industry. However, flux-cored arc welding is growing in popularity. MMAW is essentially used in the construction of steel structures and industrial fabrication and the process is used primarily to weld iron and steels.

2.6.2 Submerged Arc Welding (SAW)

Submerged Arc Welding (SAW) is a very common arc welding process which uses a continuous solid or cored wire electrode fed by motor driven rollers. The arc is struck between the continuous wire and the parent metal where the arc, electrode end and molten pool are submerged in a fused powdered flux. The flux turns into a slag layer when subjected to the heat of the arc, ensuring the weld is protected from contamination. The flux is fed from a hopper which is fixed to the welding head with a tube spreading the flux in a continuous elongated mount in front of the arc, along the line of intended weld. Given this arrangement, there is no spatter, the weld is shielded from the atmosphere and there are no ultra-violet or infra-red radiation effects seen. The un-melted flux can be reclaimed and used again in the process. The use of the powdered flux does however restrict the process to the flat welding position. The process is noted for its ability to use high weld currents due to the properties and function of the flux. Such high currents can give deep penetration and high dilution where twice as much parent metal as wire electrode is melted.

2.6.3 Metal Inert Gas/Metal Active Gas Welding (MIG/MAG)

Known in the USA as gas metal arc welding (GMAW), MIG/MAG welding process is a versatile technique which is suitable for welding most metallic materials of different thicknesses. In a MIG process, often used for welding non-ferrous metals, inert gasses such as argon and helium are used. In a MAG process the shielding gas is often a mixture of argon, oxygen and carbon dioxide. During the process, an arc is stuck between the wire electrode and the work material, melting both to form a weld pool. The arc at the end of the wire provides the source of heat and filler metal for the joint. A copper contact tube, through which the wire is fed, conducts welding current to the wire. A shielding gas fed through the nozzle surrounding the wire protects the weld pool from the surrounding atmosphere. The selection of shielding gas is dependent on the materials being welded and the welding application. The wire required is fed from a motor driven reel, and the welder or machine moves the welding gun along the joint line. The process provides high productivity and is economical because the consumable wire is fed continuously.

This process can be carried out in three ways:

(i) Semi-Automatic Welding: This means that the equipment only controls the electrode wire feed with the movement of the welding gun being controlled by hand.
(ii) Machine Welding: This operation uses a welding gun that is connected to a manipulator of some kind and an operator has to constantly set and adjust controls that move the manipulator.
(iii) Automatic Welding: When the welding equipment doesn't need constant adjusting of controls by a welder or operator. On some equipment, automatic sensing devices control the correct gun alignment in a weld joint.

Today MIG/ MAG processes are two of the most common industrial welding processes due to its versatility, speed and relative ease for adapting to automation.

2.6.4 Flux Cored Arc Welding (FCAW)

Flux-cored arc welding (FCAW) is a semi-automatic arc welding process. It is a wire welding process in which a continuous hollow wire electrode is fed through the welding gun into the weld joint. An externally supplied shielding gas is sometimes used, but often the flux itself is relied upon to generate the necessary protection from the atmosphere, producing both gaseous protection and liquid slag protection to the weld. Use of external shielding gas is more common due to fumes created when using only the flux core as shielding. FCAW is a process similar to GMAW where both processes use continuous wire feeds and similar equipment. GMAW is also considered as a semi-automatic process and has a very high production rate. FCAW however is the most productive of the manual welding processes. When comparing GMAW to FCAW, there is a large difference in the production capacity, i.e. length of weld per hour. For this reason, FCAW is more frequently used in the ship building industry. FCAW produces high quality welds very quickly, even in poor outdoor environmental conditions.

2.6.5 Electroslag Welding

Electroslag welding is a highly productive welding process designed for welding thick materials in a vertical position. It is considered the most productive of any welding process in joining very thick plates due to its high deposition rate. The process can weld materials with thicknesses between 25mm and 300mm. Electroslag Welding is used in only a minor portion of all welding done and is mainly used in industries such as shipbuilding, machine building, bridge construction etc. It is technically not an arc welding process, however it does utilise a current carrying electrode. An electric arc is initially struck by wire that is fed into the desired weld location where flux is then added. Additional flux is added until the molten slag reaches the tip of the electrode and extinguishes the arc. The wire is then continually fed through a consumable guide tube into the surface of the metal work piece and the filler metal is melted using the electrical resistance of the molten slag. The thicker the material is, the larger the current needs to be. Given that the arc is extinguished early in the process as detailed above, it confirms that electroslag welding is not an arc welding process.

2.6.6 Tungsten Inert Welding (TIG)

TIG welding is a process where the melting is produced by the heat of an arc which is struck between a non-consumable tungsten electrode and the work piece. With this type of welding, there is a need for an inert gas shielding of the electrode and the weld zone to prevent oxidation of the tungsten electrode and atmospheric contamination of the weld/filler metal. Tungsten is used given its high melting point which is above any other common metal and is therefore not consumed during the welding process. A filler metal is usually used, although some welds, known as autogenous welds, do not require a filler metal. The filler metal is typically in the form of a solid metal rod, with compatible properties with the base material, and is manually added to the weld pool. This process produces high quality welds and in general is spatter free. There is no slag formed as part of the process which makes the TIG process well suited to welds requiring high degrees of cleanliness. Given the requirement for the shieling gas, it can be difficult to shield the weld zone properly in windy conditions therefore it is not often used on exposed work sites.

2.6.7 Plasma Arc Welding

The plasma welding process was introduced to the welding industry as a method of sustaining control in the lower ranges of current. This process provides an advanced level of control and accuracy to produce high quality welds in miniature or precision applications. It also helps to prolong electrode life for high production requirements. Plasma is a gas which is heated to an extremely high temperature and ionised so that it becomes electrically conductive. This plasma arc welding process uses the plasma to transfer an electric arc to a work piece. The metal to be welded is melted by the intense heat of the arc and fuses together the parent material.

2.6.8 Electro Gas Welding

The electro gas welding process was developed in 1961 for continuous vertical position arc welding. The arc is struck between a consumable electrode and the work piece. A shielding gas is usually used, but the pressure is not applied. This process makes square-groove welds for butt joint. The major difference between EGW and ESW (electroslag welding) is that the arc in EGW is not extinguished, and instead remains struck throughout the welding process.

3 Certification

3.1 Weld Engineer Qualification

A welding engineer is responsible for all design aspects related to welding. This includes specifying what type of welding is to be applied, preparing the welding procedure specifications, dimensioning the weld, etc. This is specialized work and it is important that the weld engineer is properly qualified.

A degree in welding engineering from a recognized university would generally qualify the individual. Other organizations, such as the International Institute of Welding (IIW), The Welding Institute (TWI) and the American Welding Society (AWS), offer certification programs for welding engineers.

3.2 Welder Qualification

One of the major factors affecting the quality of a weld joint is the skill of the welder. Making sure welders are properly qualified for the work they are performing is very important. Not only should the welder be qualified, but his or her work should be monitored. If welder skill is lacking, welders may need to be retrained and/or requalified.

With an approved Welding Procedure Specification (WPS), welders are required to demonstrate that they can produce the joints it describes. This testing procedure is called the Welder Performance Qualification (WPQ). The requirements of the WPQ test (such as position, mechanical tests, non-destructive examination etc.) depend on the work that the welder is to be qualified for and the standards to which the welder is being qualified. A WPQ may be certified by the employer or a third party in accordance with a manufacturer's standard or standards provided by organizations such as Classification Societies, AWS, ASME, API, CSA, and ISO. Having a third party representative certify test results in accordance with recognized standards allows others outside the welder's company to have confidence in WPQ results. For ships, the certification is typically performed by the classification society that classes the vessel(s) for which the work is being carried out.

When a WPQ is certified, a Welder Qualification Test Record (WQTR) is issued to the welder. WQTR's are usually valid for 2 years before the welder must be requalified. A qualified welder is someone who has passed a WPQ test for a specific WPS and has obtained a WQTR. The qualification is valid only for that WPS.

3.2.1 Welder Certification

A certified welder is a welder that has been through a certification program that is accredited by a technical society (such as AWS). The certification process typically involves exams and certain WPQ's, depending on the type of work for which the welder is being certified. AWS welder certifications are valid indefinitely provided the welder uses the welding process at least every six months, otherwise the welder must be requalified. A welder that is certified by a society is not to be confused with a welder qualified to a specific WPS by passing a WPQ test. In order to be qualified to a specific WPS, a certified welder is generally subject to the same requirements and testing as any welder, and must pass a WPQ test and obtain a WQTR. When referring to welders, sometimes the terms “certified” and “qualified” are used interchangeably, so it is important to understand and clarify, as necessary, what a person means when they say a welder is certified or qualified.

3.3 Weld Procedure Certification

Before a weld procedure is used in practice it needs to be properly certified by an appropriate body, for instance a classification society. This involves acceptance of the Welding Procedure Specification (WPS) which specifies all the details of the procedure. In addition, sample welds are to be tested through a Welding Procedure Qualification Test (WPQT) to demonstrate that the welding procedure produces the required mechanical properties in the finished weld. The results of the testing are noted in a Welding Procedure Qualification Record (WPQR). A WPQR can also be called a Welding Procedure Approval Record (WPAR).

3.3.1 WPS – Welding Procedure Specification

Before the skill of a welder to make a joint can be evaluated, the welding procedure must be defined. The welding engineer develops a Welding Procedure Specification (WPS). This document provides detailed information on welding conditions (variables) for a specific application to assure repeatability by properly trained welders.

The welding variables in the WPS include:
1. Identification of builder/subcontractor
2. Welding process
3. Base material (grade, delivery condition, etc.)
4. Range of base material thickness/pipe diameter
5. Filler metal/welding electrodes
6. Weld type/geometry (groove/fillet, gap, bevel) including tolerances
7. Welding position(s)
8. Shielding gas type, purity, and flow rate
9. Minimum and maximum preheat and interpass temperature
10. Post weld heat treatment
11. Electrical characteristics (polarity, current, voltage, travel speed, wire feed speed, mode of metal transfer, electrode size)
12. Welding progression (upward or downward)
13. Backing (metal, ceramic)

The scope of a WPS may be limited to a specific company, site, project, or certifier, and requalification of a WPS may be required as companies, sites, projects, and certifiers change.

3.3.2 WPQT/WPQR – Welding Procedure Qualification Test/Record

The WPS must be qualified (proven) to show that joints made using the WPS meet the prescribed requirements. This is done by performing a test weld according to the actual welding conditions as given in the WPS. The sample weld is subjected to tests. The results of the tests of the weldment are recorded in a Welding Procedure Qualification Record (WPQR). The testing requirements depend on the standard to which the WPS is being performed and typically include bend tests, tensile tests, and toughness tests. Testing may also include micrographic and non-destructive examination and hardness tests. Passing these tests forms the basis for issuing an approved WPS.

Figure 3.3-1 and Figure 3.3-2 below show a representative test weld and give an indication of the types of mechanical tests which may be required and where the test pieces are taken. Note that the ends of the sample weld are not used for testing since defects are often found at the start and stop points of the weld.

Figure 3.3-1 - Typical test weld

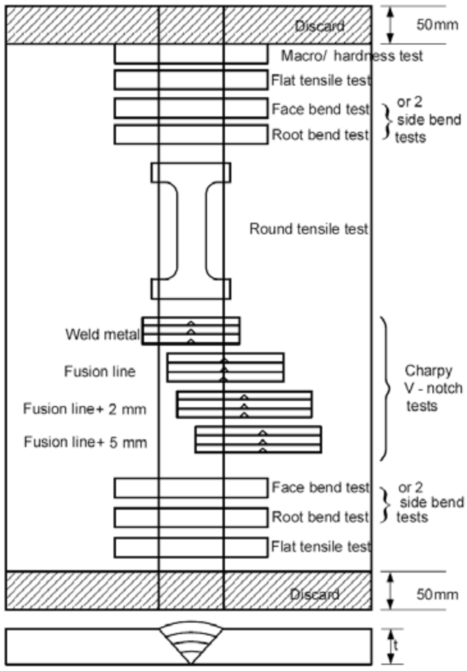


Figure 3.3-2 - Test samples for welding qualification

3.4 Certification of Consumables/Type Approval

Welding consumables are to be obtained from a manufacturer that has been approved by the pertinent regulatory body and/or classification society. Upon successful completion of testing in the approval process, the inspector representing the regulatory body and/or classification society shall issue a Welding Consumable Certificate (WCM CERT). The WCM is called a Type Approval Certificate of Welding Consumables (TAW). Lists of approved products can be found on the internet sites of the classification societies. The information contained on the WCM CERT must accurately represent the properties of the consumable such as trade name, position, grade, current/polarity, sizes, shielding gas and special information, as appropriate.

Welding consumables and electrodes of all forms must be stored and handled correctly in order to avoid moisture and surface contaminants from accumulating on them. Otherwise, the welds produced by the consumables could be more prone to forming defects such as cracks, pores, and voids. Most consumable manufacturers have guidelines for storing and drying their electrodes and fluxes. In general, moisture and rusting is avoided by using sealed packaging and heated cabinets. Shielded electrodes used for SMAW are particularly prone to absorbing moisture and usually must be dried at elevated temperatures before use. An electric oven is often used for storage of electrodes. Other contaminants such as oil, grease, and paint must be avoided at all times when handling, storing, and welding with consumables.

Figure 3.4-1 Typical electrode storage devices
(Copyright Unitor, ref. 1)

3.5 Certification of Weld Inspectors

There are multiple national and international organizations that have programs for certifying a welding inspector. These organizations include, but are not limited to, the American Welding Society (AWS), the European Federation for Welding (EWF), The Welding Institute (TWI) and the Asian Welding Federation (AWF). Typically, each of these organizations has a tier system for certification. Each successive tier certifies the inspector for more responsibilities and usually requires more education, work experience, and exams than the previous one. Entry level inspectors usually operate under direct supervision of a more highly certified weld inspector.

An example of this tier system is the CSWIP system (Certification Scheme for Personnel), developed by The Welding Institute. The Welding Institute is accredited to administer the examinations required to achieve certification for the various CSWIP levels. These levels are:

i) CSWIP 3.0 Visual Welding Inspectors
ii) CSWIP 3.1 Welding Inspectors
iii) CSWIP 3.2 Senior Welding Inspectors

Below are brief explanations of the competence of the three levels:

3.5.1 Visual Welding Inspectors

Visual Welding Inspectors will typically visually inspect a weld for defects and confirm that the various requirements of the weld procedure have been adhered to (e.g. fit up, weld consumable, pre-heat, etc.).

3.5.2 Welding Inspectors

Welding Inspectors will conduct the activities identified above for the Visual Welding Inspector and in addition:

i) Supervise Visual Welding Inspectors
ii) Conduct welder and weld procedure approval tests

3.5.3 Senior Welding Inspectors

Senior Welding Inspectors will conduct the activities identified above for the Welding Inspector and in addition:

i) Supervise Welding Inspectors and Visual Welding Inspectors
ii) Interpret NDT results
iii) Have an appreciation of what factors create what defects in a weld.

3.6 Equipment Calibration

Almost all equipment used in the welding process and associated inspection/tests shall be calibrated, some before each use as required by Class, agreed procedures or applicable standards.

It is the Yards or shops responsibility to carry this out but it needs to be followed up by Class and Owner/Purchaser by witnessing tests and spot checks during the fabrication.

Welding machines.
The welding parameters are essential, they should comply with the parameters in the WPS. Since the machines can suffer from wear and tear over time it is important that they are controlled regularly and by random spot check. This should be part of the fabricators QA/QC, Class and Owners/Purchasers scope of work.

The machines should be controlled by measurement by ampere meter and volt meter, to verify that the correct current and voltage are indicated/shown on the machine. The gas flow should also be measured. For larger yards this is normally done by a separate service department integral to the yard. For smaller companies and workshops this is to be done by an authorised service company.

For automatic welding machines, the actual welding speed should be verified by measurement and compared to the indicated speed on the machine. This could be done during monitoring of the fabrication, to ensure that the welding process is in accordance with the WPS.

Temperature and humidity
Temperature and humidity are important parameters of the WPS. Calibrated thermometers or thermocouples are to be available for continuous measuring of ambient and plate temperature, for pre/post heating, and inter-pass temperature. Equipment for measuring humidity is also to be available.

Dimension control
Special equipment such as lasers, theodolite, etc. used for more advanced dimension control should have a certificate issued by an accredited company showing that the equipment is working and properly calibrated, no more than 6 months old.

Tightness control
If pressure testing is applied by compressed air, the manometers are to be calibrated and certified.

Test equipment used for verifying material quality

The equipment used in the test facilities, for hardness test, impact and tensile strength etc. should be certified by an independent body, i.e. Class or similar. Certificates are to be available. Normally such facilities have some certification of the type of tests that they are entitled to carry out and the equipment used.

Non-Destructive Testing (NDT) equipment

Ultrasonic Testing (UT) Equipment

UT machines shall be certified by an accredited company, at least every 12 months. The serial number on the certificate shall match the identification number on the machine. It is recommended that calibration is carried out every second month. The calibration of the UT machines and probes are to be described in a procedure submitted to Class and Owner for approval. The UT machines and the UT inspections are complicated and special competence is required.

It is important that adjustments and calibration of the amplification of the machine for different tasks, probes or material are verified by control measurement using a calibration block before use. The calibration block shall have the same acoustic properties as the test object. The probes shall be calibrated after 4 hours use.

The sensitivity calibration shall be verified as a minimum at the end of each shift and for any change in operator, ultrasonic instrument, transducer, coaxial cable, battery, or if the operator has any doubt about the accuracy of the calibration. However, it is good practice to verify the instrument calibration on a more frequent basis

A machine calibrated for normal steel cannot be used for casting or stainless steel or vice versa. The details of the calibrations are further described and regulated in Rules and standards, e.g. EN 1711 or ASME V.

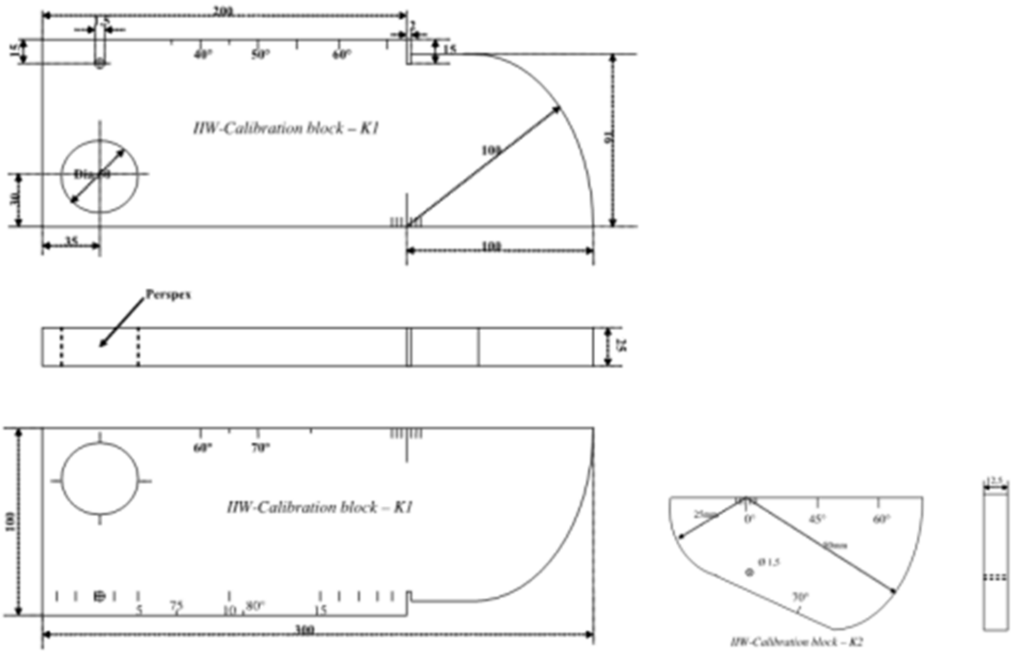


Figure 3.6-1 - Figure of calibration blocks, from DNV CN07

Magnetic Particle Inspection (MPI) Equipment
It is important to ensure that the magnetization is sufficient and requirements are stated in the rules (e.g. DNV Classification note 7, DNV CN07). This should be stated in the agreed procedure depending on the type, either AC or DC. For DC, each yoke shall have a lifting force of at least 175 N (40 lb.) at the maximum pole space that will be used. For AC the requirement is at least 45 N (10 lb.). This can be verified randomly with a steel plate of known weight. The detecting media shall also be checked with respect to the concentration of particles in the media and be traceable to a batch certificate or data sheet in compliance with a recognized standard.

Radiographic Testing (RT) Equipment
This type of testing is heavily regulated and controlled, and difficult for a non-expert to check. Calibration and checks of the equipment are done by qualified companies.

However, on site tests or qualifications can be carried out in order to verify that the complete set-up of film, radiation source and distances is suitable for the material such that it gives a good quality of the image/optical density. This is checked using an Image Quality Indicator (IQI) and is described in the standards or Class guidelines, for example DNV CN07, Sec 5.5.1. Basically a set of thin wires is placed in the exposure area and they shall be clearly visible on the developed film. The parameters used, i.e. exposure time, distance type of film etc., are to be noted and be the same as for the actual RT used.

3.7 QA/QC at Yard/Shop

Per AWS D1.1/4.2.3.1 and ASME Section IX/QW-322.1*(a)*.

4 Welding Execution

4.1 Pre-Weld Preparations

Correct pre-weld preparation, as described in sections 4.1.1 to 4.1.6, is essential to ensure good quality welding.

At the design stage a Welding Table shall be prepared and typical welding sequences shall be determined as described below (see Sections 4.1.1 - 4.1.2).

On-site pre-weld preparations include edge preparation by cleaning, beveling and fit-up of members for welding with respect to alignment and gap (see Sections 4.1.3 - 4.1.6).

Pre-weld preparations shall also include check of base and filler materials against their respective specifications.

Welding should not be allowed to start before all pre-weld preparations have been completed satisfactorily.

Another important weld preparation, not mentioned in detail in this Guidance Note, is that for manual welding there has to be sufficient room for the welder to get in position and perform the welding at a steady state without obstructions. In general the structural designer has to consider proper space for welding at the design stage. Improper or inadequate space will lead to lower quality welding. For spaces not allowing proper access, one sided welding, alternative welding sequences or temporary access holes can, amongst others, be considered. An example of a location where one-sided welding is necessary is closure of rudder plating where access inside the rudder does not allow sufficient room for proper welding. For this case a permanent backing bar is often used.

4.1.1 Welding Table

For larger re-buildings and newbuilding of vessels the designer or the Yard shall submit a Welding Table to the Classification Society for approval. Normally the Welding Table or a yard standard shall include:

- General definitions of gap and weld sizes
- Welding factors depending on position of weld in vessel
- Table with sizes of fillet welds depending on weld factor and plate thicknesses
- Staggered welding and where this is allowed
- Definitions of partial and full penetration welding
- Working examples

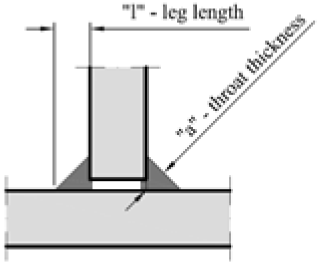


Figure 4.1-1 – Definition of Throat Thickness and Leg Length

4.1.2 Welding Sequence

The welding sequence is a means to reduce residual stresses and reduce shrinkage and distortion of elements (see Section 4.1.2.1), which are essential for good quality welding. This is particularly important to consider when the edges of the plates are constrained, i.e. during assembly of blocks.

All yards and repair companies shall present a welding sequence which shall be reviewed by the client. A welding sequence is a complicated matter which relies very much on experience and tests. Unless specialized in welding it is hard to evaluate a welding sequence.

Below are a few examples of typical weld sequences for some general weld joints seen in shipbuilding.

For smaller repair jobs, such as inserting plates, IACS Rec. No. 47 includes several welding sequences to follow.

Example 1: Butt cross joint sequence

Figure 4.1-2 shows a typical example of a shipyard's proposed sequence for welding butt cross joints on a newbuilding project.

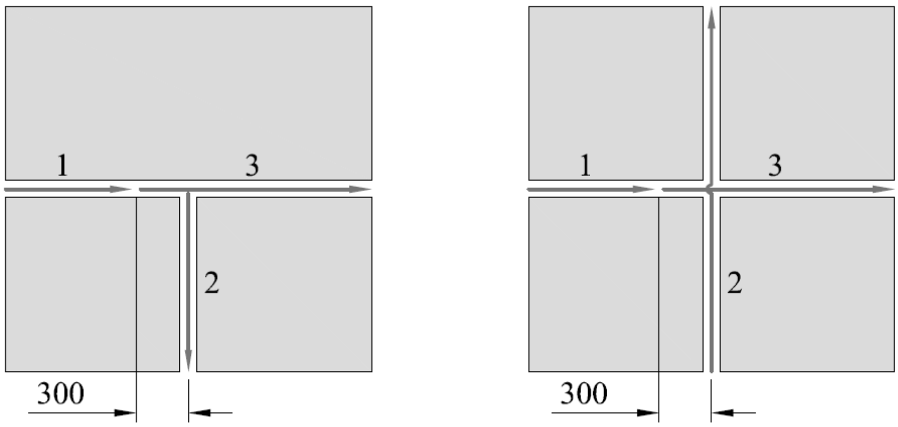


Figure 4.1-2 - Sketch of butt-cross joints sequence

Example 2: Fillet cross joint sequence

Figure 4.1-3 below shows a shipyard's proposed sequence for fillet welding at cross joints consisting of a primary and a secondary member for a newbuilding project. As it is seen in Figure 4.1-3 the primary member has to be welded first and then secondary member. During inspection the welded cross joint shown in Figure 4.1-4 was observed and rejected as the secondary member had been welded first.

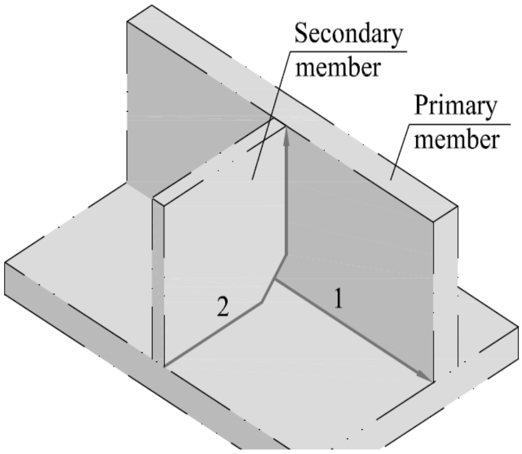


Figure 4.1-3- Sketch of Fillet Cross Joint Sequence


Figure 4.1-4 – Rejected Fillet Cross Joint

4.1.2.1 Shrinkage and Distortion

When a steel material is heated during welding it expands and when welding is completed and the steel material cools off it contracts again. This expansion and contraction can lead to distortion and residual stresses if the welding sequence is not properly planned.

The heating and cooling cycle may not just distort the members. In severe cases the material properties of the members can be affected. When a steel material is heated and cooled rapidly the material can turn brittle.

One of the most renowned examples of brittle cracking of vessels in way of welding are the Liberty Class auxiliary vessels which were built in the US during the 2nd World War. Many of these ships were lost due to cracks in the hull girder originating from brittle cracking as welding at that time was a new assembly procedure and not all factors were accounted for.

A second example which relates to distortion due to a poorly planned welding sequence resulted in a permanent and visible distortion of the complete hull girder. A poorly planned block joint erection of a thin-skinned vessel, where excessive welding of the block joints was performed, forced the entire vessel to be in a permanent hogging condition. The keel area in the midships region on the slipway was lifted more than 100 mm on a vessel with a length of approximately 150 meters in spite of the weight of the vessel.

A third example of how severe distortion and residual stresses can be relates to the sandwich deck construction described in Section 4.2.3 and shown in Figure 4.2-6. For this specific case the sandwich deck (deck doubling plates) extended over more than half the vessel length on a vessel with the main engines located forward. With this forced deflection at deck level, combined with very long propeller shafts, the actual deflection of the propeller shafts had to be considered. A detailed welding sequence was prepared by an accredited institute to minimize stresses. The calculated stresses were imported to a beam model with the same cross sectional properties as the vessel, and the actual deflection could be estimated. The deflection of the propeller shafts was acceptable given that a certain welding sequence was followed.

4.1.2.2 Residual Stresses

The shrinkage and distortion as described in Section 4.1.2.1 can lead to residual stresses when the structure is fixed and not allowed to move freely. Dimensioning of a vessel's plate thicknesses, stiffener properties and size of welding are determined for a certain set of loading conditions that the vessel is expected to experience throughout its lifetime. A plate thickness of a strength deck plate can be given on basis of a buckling load when the vessel is in a sagging condition. This buckling load does not take into account any residual stresses due to welding. Should such residual stresses be present they have to be added to the buckling stress. This addition can, in the most severe cases, mean rupture of plating and possible loss of the vessel.

A good example of when to be aware of residual stresses is when a vessel is to be repaired afloat in the midship region close to the strength deck or the bottom. Given the loading condition of the vessel the structure can be exposed to a hull girder bending stresses which will be superimposed to the introduced welding residual stresses. This can lead to a higher stress level in the welding than it is approved for. When doing welding afloat always do this in a sheltered area with no waves and use the vessels loading computer to determine a loading condition of the vessel where the hull girder stress level in the area of welding is close to zero.

4.1.3 Edge Preparation

Proper edge preparation can be visually checked. Edges of members to be welded are to be clean, straight and within acceptable surface roughness limits.

With respect to cleanliness of edges these shall be visually inspected for foreign matter such as paint, oil, water, grease, rust or scale. Poor cleaning of edges may lead to poor side wall fusion of welding filler and porosity of welding due to inclusion of foreign matter in the weld.

With respect to surface roughness and straightness of edges these shall be visually inspected. Surfaces intended for welding shall in general be planar, free of local discontinuities and with a surface roughness within acceptable limits. IACS Rec. No. 47 gives guide lines on both surface roughness and straightness.

Surface roughness and straightness outside specification may lead to poor side wall fusion with the welding filler material.

Figure 4.1-5 and Figure 4.1-6 below show examples of a poor edge preparation where the member edges for a closed butt weld joint and a single-V butt joint have not been grinded smooth prior to fit-up.

Figure 4.1-5
Poor Closed Square Butt Preparation

Figure 4.1-6
Poor Single-V Butt Preparation

4.1.4 Beveling

Preparation of members for welding by beveling depends on the joint type, loads to be carried by the weld, welding position and accessibility, welding location on the vessel and thickness, type and shape of the members to be joined. As an example of beveling requirement depending on the location on the vessel, the “IACS Common Structural Rules for Bulk Carriers and Oil Tankers” requires full penetration welding between the lower end of vertically corrugated bulkheads and the lower stool top plate.

Beveling is normally done by machining, gouging or flame cutting.

Re-beveling can be necessary if poor fit-up of plates with misalignment requires cutting of the plate edges.

4.1.5 Gap, Alignment and Fit-Up

Acceptable tolerances for alignment should be specified in a yard or workshop standard. This in turn should reflect a recognized industry standard, for example as given by the classification societies or IACS guideline number 47, “Shipbuilding and Repair Quality Standard”.

IACS Rec. No. 47 has guidance as to what gap size and alignment is adequate for specific joints. The guidance includes limits and appropriate remedial action if the limits are exceeded. For repair jobs with companies not used to working with ship structures the IACS Rec. No. 47 is a good starting point and should be included as a reference. Repair companies and shipyards working with ship structures on a regular basis will have their own procedures for gap size and alignment which are approved by the Classification Society. Normally shipyards procedures and standards for this are based on IACS Rec. No. 47.

In general the gap has to be large enough to ensure proper side wall fusion through the entire member thickness. The gap shall however not be larger than necessary to avoid excess use of filler material from an economical point of view as well as possible problems with distortion of members and residual stress in the weld. Figure 4.1-7 shows a fit-up where the gap is too large. The proper way to handle this would be to release enough of the completed weld so that the elements can be adjusted and the gap reduced, or if this is not possible use an insert piece.

Figure 4.1-7 – Large Gap

Edges of members are to be parallel and with a specified gap which is important for the later straightness and overall tolerances of the construction. In general plate edges shall be as parallel as possible and distance “d2-d1” shown in Figure 4.1-8 shall be as small as possible.

Figure 4.1-8 - Alignment of Member Edges

Alignment of members before welding is very important for the quality of the weld and for the stress concentrations in and around the welding. For distributing the stresses in a structure the most efficient way, the path of the stress shall be as smooth as possible. Abrupt changes in sectional properties will lead to stress concentrations and subsequently possible cracks depending on the actual loading of the joint. In general distance “dt” given on Figure 4.1-9 and Figure 4.1-10 shall be as small as possible and for highly stresses areas “dt” shall be close to zero.

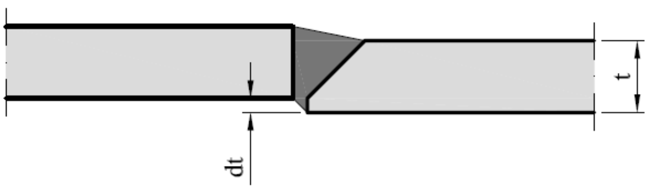


Figure 4.1-9 - Alignment of Members at Butt Joint

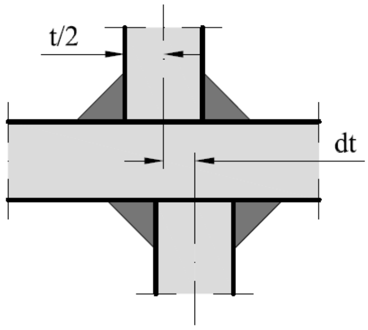


Figure 4.1-10 - Alignment of Members at Cruciform Joint

In addition to the gap and linear alignment as described above, angular alignment must be checked. Angular misalignment is when there is misalignment between two welded pieces such that their surface planes are not parallel with each other or at the intended angle. It is often caused by inaccuracies in the assembly procedures or distortion from other welds. Angular misalignment can also be caused by local deformation of the edge of a plate if it is not properly supported or has been distorted by heating due to welding.

Gap and alignment of plates shall be secured by fixation of the members to be welded. Use of tab pieces for this purpose is described later in this section.

Two examples of poor alignment are shown in Figure 4.1-11 and Figure 4.1-12. Figure 4.1-11 shows a misalignment of a butt joint also shown in Figure 4.1-9. The actual misalignment was measured to 8 mm compared to 3 mm allowed misalignment. Figure 4.1-12 shows misalignment of a butt joint of the welded flange of a stiffener.

Figure 4.1-11 – Poor Butt Joint Alignment

Figure 4.1-12 - Poor Alignment of Stiffener Flange

When proper edge preparation, beveling, gap and alignment is in place, it is essential that the members up for welding are fixed to secure proper quality and strength of the weld, smooth transfer of stresses from member to member and straightness and tolerances of the finished structure.

Fit-up of smaller structures to ensure acceptable gap and alignment can be done by clamps whereas larger structures are normally fit-up using welded strong backs (see Figure 4.1-13) and wedges (see Figure 4.1-14) or hydraulic jacks.

Figure 4.1-13
Fit-up with Welded Strongback

Figure 4.1-14
Fit-up with Welded Strongback and Wedges

Fit-up can also be designed to take account the deformations the welding will impose on the connection of members due to the shrinkage of the filler material when cooling off. Figure 4.1-15 shows an example of such a fit-up. The example of the sandwich deck construction described further in Section 4.2.3 and shown in Figure 4.1-15 did not allow such an angled fit-up, which could have reduced residual stresses considerably. For the case only one-sided welding was possible.

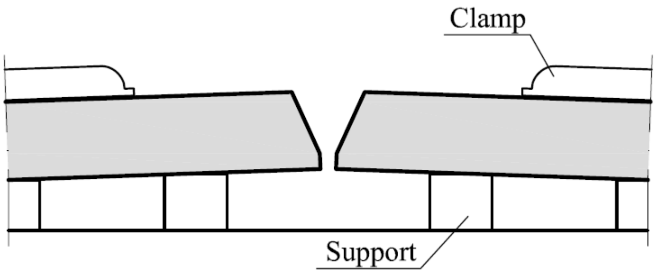


Figure 4.1-15 - Fit-Up of Butt Joint in Angle

Tab pieces are fitted to ensure a good “end” of the weld. As ends of welds are often prone to have defects tab pieces at the ends of the weld are introduces to extend the welding. As a rule of thumb a tab piece should extend as far out from the plate or stiffener as the thickness of the plate or stiffener. After welding of the member the tab piece is removed and the area properly cleaned and ground.

In Figure 4.1-16 and Figure 4.1-17 the correct use of tab pieces is shown. The tab pieces have an adequate length and the shape of the tab piece matches the beveling of the members.

In Figure 4.1-18 and Figure 4.1-19 the incorrect use of tab pieces is shown. In Figure 4.1-18 the tab piece is missing and in Figure 4.1-19 the weld is not extended sufficiently over the tab piece.

Figure 4.1-16
Correct Use of Tab Piece

Figure 4.1-17
Correct Use of Tab Piece

Figure 4.1-18
Missing Tab Piece

Figure 4.1-19
In-Correct Use of Tab Piece

4.1.6 Pre-Heating

Pre-heating of members up for welding is mainly done for 3 reasons:

1- Welding is done in an exposed climate where ambient temperature is around 0°C.
2- Members have large thickness
3- Members are high-carbon or alloy steel

For item 1, IACS Rec. No. 47 recommends pre-heating of members to 20°C.

For item 2, pre-heating can be necessary to slow down the cooling rate in the weld to avoid hydrogen cracking. Increased thickness and increased carbon content in members can increase the risk of hydrogen cracking. IACS Rec. No. 47 again gives good guidance as to the extent of required pre-heating as a function of member thicknesses and carbon content.

For item 3, high-carbon steel or alloy steel welding will contain a high percentage of martensite which is brittle. Pre- and post-heating will reduce the martensite content in the welding.

Any requirements to pre-heating will be given in the WPS and should be carefully followed.

Pre-heating shall preferably be done by electrical resistance heating as it gives a constant heating especially in erection joints where FCAW welding is used. Gas torches or radiation heaters can be considered alternatives for smaller joints.

4.2 Welding of joints

When fit-up of the members is completed the welding can commence.

In general a good joint design will provide proper access for the welder, adequate root opening to permit proper side wall fusion of welding filler and at the same time secure the least possible amount of welding filler.

In Section 2.2 several joint types are described. In the following sections beveling and gap is described for the most common joint types in ship building, i.e. butt joints, T-joints and cruciform joints.

In general “Gap” and “Bevel angle” in the following Section shall be described in the Welding Procedure Specification “WPS” (See Section 3.3.1). Furthermore IACS Rec. No. 47 has guidelines.

In the following section the abbreviations as shown in Figure 4.2-1 will be used.

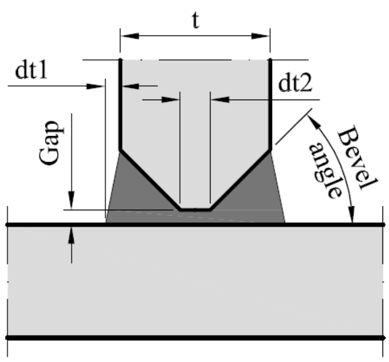


Figure 4.2-1 - Abbreviations

Where:
“t” is thickness of abutting plate.
“dt1” is defined in the Welding Table and is normally between 0.2 – 0.3 times the thickness of the abutting member.
“dt2” distance gives type of welding. When distance “dt2” on figure 4.2-1 is 1-2 mm the welding is classed as “full penetration”. When “dt2” is less than approx. 1/3 of the thickness of the abutting member the welding is classed “partial penetration”.

4.2.1 Open Square Butt Joint

The open square butt joint welding as shown in Figure 4.2-2 is one of the most economical as the joint preparations are limited. It is widely used at the shipyards where plates up to 20 mm can be welded using SAW welding during block production. Some yards only have facilities for welding from one side, however most yards turn the plate over and weld from both sides.

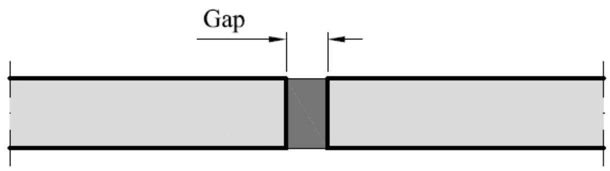


Figure 4.2-2 - Open Square Butt Joint

In order to perform welding with a larger current and reduced welding time, a backing can be applied for all types of butt joint welding as shown in Figure 4.2-3. The backing reduces the risk of filler material burning through the intended weld area. When both sides of the member are accessible after the joint is welded, a temporary ceramic backing - often provided in the form of self-adhesive tape - is used. When one side is not accessible after welding a permanent backing is used. The permanent backing shall be of same material as the members to be joined. Normally the backing is not to be less than 6 mm in thickness and it is welded to one of the members to be joined. A weld with a permanent backing will have an additional stress concentration in the root of the weld and they are generally not allowed in areas with high stresses.

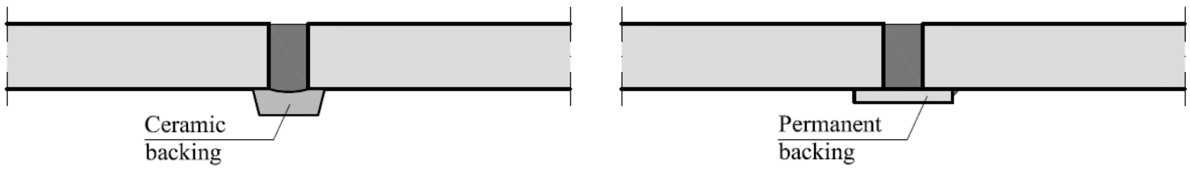


Figure 4.2-3 - Open square butt joint with permanent backing

4.2.2 Closed Square Butt Joint

A closed square butt joint is similar to open, but where the gap between the plates is closed as shown in Figure 4.2-4 below. The closed square butt joint is widely used at the shipyards due to the low preparation costs. In general closed butt joint is used for thinner plates than open butt joint. Yards will have a standard practice for the maximum thickness of plates to be welded by closed butt joints.

Figure 4.2-4 - Closed square butt joint

4.2.3 Single-V Butt Joint

Single-V butt welding as shown in Figure 4.2-5 is used for welding of thicker plates and plates where stress level is not low. More filler material is used than for the open square butt weld and hence the welding is not as economical as the open square butt weld. The increased amount of filler material can also affect residual stresses, distortion and shrinkage if the welding sequence (see Section 4.1.2) is not correct.

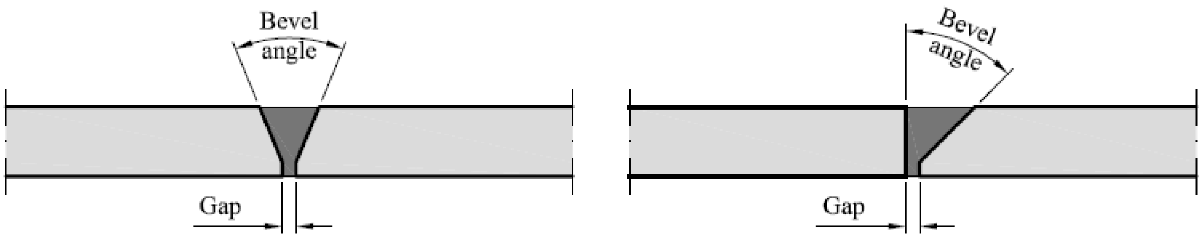


Figure 4.2-5 - Single-V butt joint

The V-shape joint normally has an angle between 40° to 50° depending on the welder's qualifications and the yards standard practice for the chosen weld method. The bevel angle has to be large enough to ensure proper side wall fusion, but as small as possible to avoid excess use of weld filler and minimise residual stresses. For thicker plates where distortion, residual stresses and amount of necessary filler material increase excessively, double V-shape penetrations are preferred. Single-V butt joints are most often used for welding of horizontal joints and welding this type of joint in an overhead position should be avoided. As described in the example below, this is for some cases not an option when only one-sided welding is possible.

Figure 4.2-6 shows an example of welding 30 mm deck plates on top of an existing deck structure forming a sandwich construction. The sandwich deck construction was introduced as the as-built working deck of an anchor handling vessel did not have sufficient thickness and loading capability for an increased deck load requirement. Extensive testing and inspection of weld method and angle of single-V were investigated to minimize residual stresses and the amount of weld filler and at the same time ensure proper strength of welding as deck plates are subjected to hull girder bending moment as well as local load from heavy cargo on deck. Testing and inspection of welds included slicing up sections of the welded sections to visually ensure proper side wall fusion. The angle of the single V beveling was by this procedure decreased to 30° and accepted by Class.

Figure 4.2-6- Single-V welding of thick plate.

4.2.4 Double-V Butt Joint

Double-V penetration welding as shown in Figure 4.2-7 is used instead of single-V for thicker plates and when both sides are accessible for welding. Advantages compared to single-V are less filler material and less residual stresses as welding from both sides will balance stresses. The procedure is however more time consuming as welding from both sides is required. Double-V butt joint is normally used when welding position is vertical up.

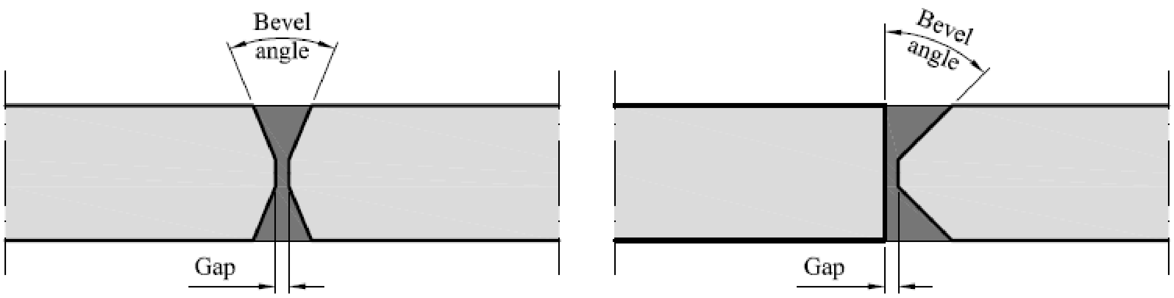


Figure 4.2-7 - Double-V butt joint

4.2.5 Single- and Double-U and J Butt Joint

Single- and double-U and J butt joints are all shown in Figure 4.2-8 and Figure 4.2-9 below. U- and J-joints require special machine cutting to prepare edges and are subsequently more costly than V-preparations. U- and J- joints are used when joining very thick plates as they provide a stronger weld with less filler material than V.

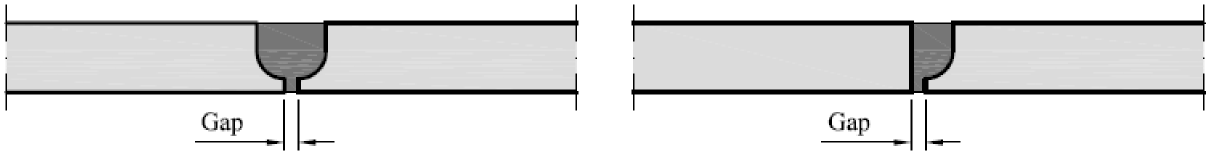


Figure 4.2-8 - Single-U and Single–J Butt Joint

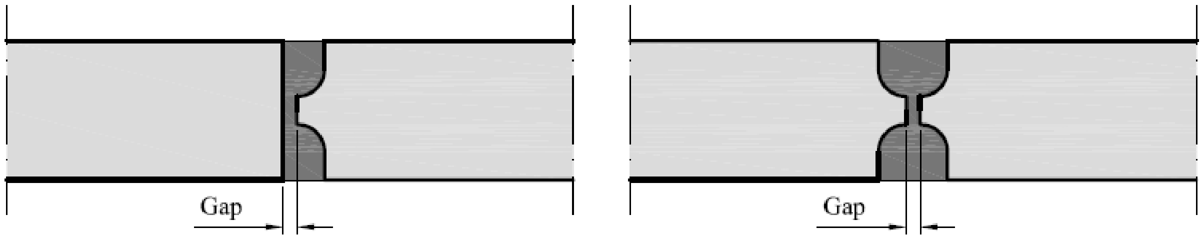


Figure 4.2-9 - Double-U and Double–J Butt Joint

4.2.6 T-Joint

T-Joint welding as shown in Figure 4.2-10 is used to weld to members at an angle generally larger than 30 degrees. The welding of the joint is based on the expected stress level in members and position of the joint. Figure 4.2-10 shows a regular fillet weld of a T-joint. In a fillet weld the welding is defined by the throat thickness “a” (or the leg length “l”, see Section 4.1.1) which is a function of the thickness of abutting plate and the position of the weld on the vessel. Throat thickness is normally between 0.1 - 0.5 times the thickness of the abutting member (t) and is specified in the welding table (see Section 4.1.1).

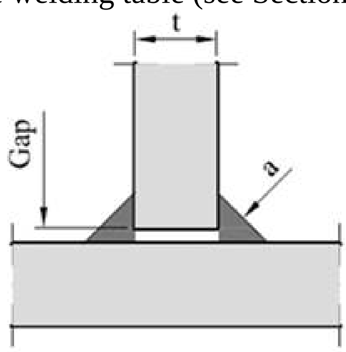


Figure 4.2-10 - T-Joint

4.2.7 T-Joint with Single Bevel

Depending on the expected stress level in members or the location of the weld, the welding can be required to be performed with a beveled edge. Under normal circumstances welding from both sides of an abutting member forming a T-joint is preferred, but for some cases one-sided welding is necessary due to lack of access.

Figure 4.2-11 below shows a typical single bevel of a T-joint for both 90° and 45° angle. When it is difficult to access the area behind the weld for post treatment of welding by gouging, a small backing strip can be applied before welding, as seen on the left most figure. Instead of a backing strip a permanent backing can be applied, by fillet welding, before welding the actual member, as seen in the center figure. For definitions of full and partial penetration welds see Section 4.2.

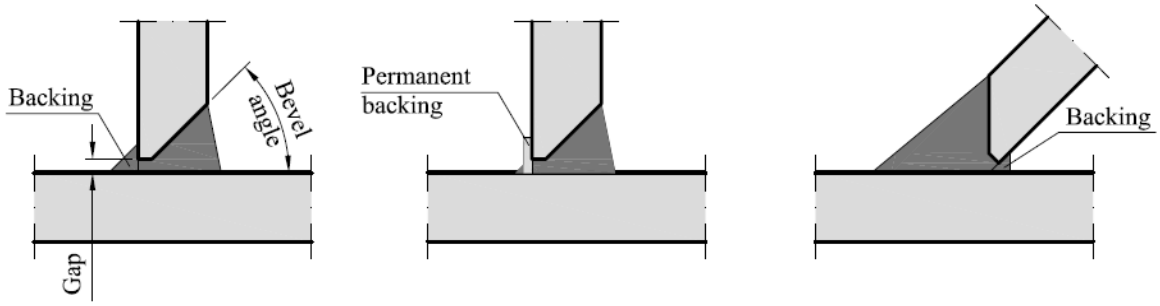


Figure 4.2-11 - T-Joint with Single Bevel

4.2.8 T-Joint with Double Bevel

General T-joint welding with double bevel as shown in Figure 4.2-12 is preferred to a T-joint with single bevel as the welding on both sides of the abutting member will decrease distortion. As for the single bevel joint, the double bevel joint can be classed as both “full penetration” and “partial penetration”, see Section 4.2.

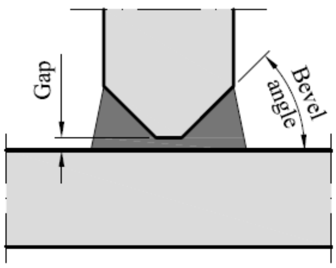


Figure 4.2-12 - T-Joint with Double Bevel

4.2.9 Cruciform Joints

Cruciform joint welding as shown in Figure 4.2-13 is similar to T-joints however with members abutting on both sides. For cruciform joints, alignment of members as shown in Figure 4.1-10 is of great importance for the force transfer without stress concentrations. Cruciform joints do not require the same type of welding above and below as indicated in Figure 4.2-13 below with a full penetration above and a fillet weld below. The horizontal member could be the tank top, the upper vertical member the inner shell forming a cargo tank barrier and the lower vertical member a double bottom girder. It is however recommended for best possible force transfer that the upper welding and plate properties are as close to the lower as possible.

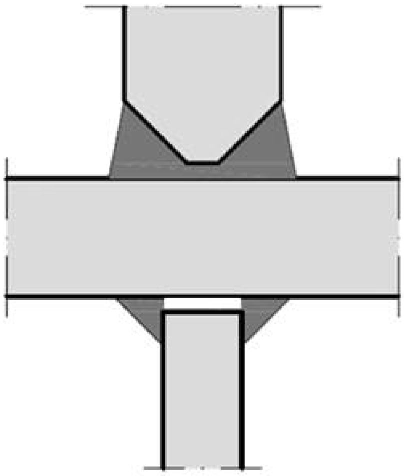


Figure 4.2-13 - Cruciform Joint

4.2.10 Intermittent Welding

Intermittent welding as shown in Figure 4.2-14 can be used in selected areas of a vessel. Normally the classification society allows such welding for welding of profiles to plating inside accommodation blocks except in wet areas.

The advantage of intermittent welding is the minimized use of filler material as well as lower distortion and residual stresses.

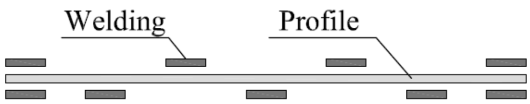


Figure 4.2-14 - Intermittent Welding

4.3 Post Weld Treatment

4.3.1 Post Weld Heating

Post weld heat treatment is very rarely used during a regular shipbuilding process. For castings however, post weld heating can be a part of the production procedure. Any requirements for post weld heat treatment will be specified in the WPS.

4.3.2 Grinding of Welds

Grinding of welds can improve the fatigue life of the joint. Classification Societies have certain welding surface roughness limits in different areas of the vessel which must be met. Today vessels are designed with extensive use of finite element modelling and here reduced plate thicknesses can be compensated by increased requirement to welding surface roughness to obtain an acceptable fatigue life of the joint.

Increased requirements for welding surface profile can in some cases also be used to repair cracks in an existing weld. If the scantlings and material of a joint are appropriate, it may be sufficient to gouge, re-welded and grind to achieve less surface roughness or a better profile than the cracked weld.

Before and after grinding, the weld and adjacent member surfaces should be cleaned properly by burr grinding or similar. To gain any advantage from grinding the weld it is important that corrosion is avoided, so coating is critical.

5 Welding Defects

5.1 Defect Types and Causes

5.1.1 Crack

An imperfection in the weld which is produced by a local rupture in the solid state. Cracking may happen due to the effects of cooling or stresses acting on the structure. This is one of the most serious defects as the geometry of a crack in a weld produces a very large stress concentration at the crack tip, which can cause crack propagation. There are different types of cracks which can be situated in different areas, including the weld metal, the HAZ and/or the parent material.

5.1.2 Lack of Side Wall Fusion

This is where the fusion between the welding consumable and the parent material is not complete. It is often caused when the joint preparation is too narrow. During the welding process, the arc is attracted to one side of the joint causing causing a lack of fusion on the other side. It can sometimes be caused when there is inadequate penetration onto a previously deposited weld bead. Other causes can include: incorrect welding parameter settings; poor welding techniques; lack of cleaning of oily surfaces or with scaled surfaces.

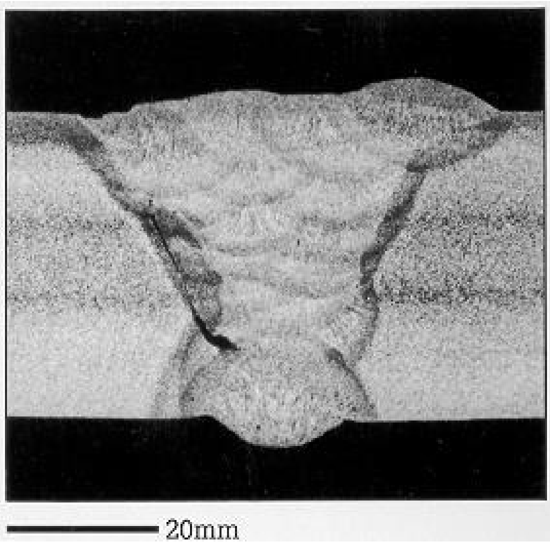


Figure 5.1-1 - Lack of side wall fusion (courtesy TWI Ltd.)

5.1.3 Incomplete Penetration

Incomplete penetration is when the initial root weld bead does not start at the root of the weld groove. This leaves an incomplete penetration channel in the root of the weld where both sides of the joint are unfused with the parent material.

Lack of penetration is found when:

(i) The weld bead does not penetrate the entire thickness of the base plate.
(ii) The two opposing weld beads do not interpenetrate.
(iii) When the weld bead does not penetrate the toe of a fillet joint but only bridges across it.

Welding current has the greatest effect on penetration. Incomplete penetration is usually caused by use of a low welding current. It can be eliminated by simply increasing the input amperage. Other causes can be the use of too slow a travel speed and an incorrect torch angle. Both will allow the molten weld metal to roll in front of the arc, acting as a cushion to prevent penetration.

5.1.4 Incomplete Fusion

Incomplete fusion occurs when there is no fusion between the weld metal and the surfaces of the base plate. The most common cause of lack of fusion is poor welding technique. Either the weld pool is too large, meaning the travel speed was too slow, or the weld metal has been permitted to roll in front of the arc. It can also result if the width of the weld joint is too large. In this case, the arc is directed down the centre of the joint and the molten weld metal will only flow and cast against the side walls of the base plate without melting them. It can also occur if the welding voltage is too low. As a result, the wetting of the bead will be poor.
Lack of fusion can however be prevented by taking a number of precautions:

(i) Good travel speed appropriate to the welding method.
(ii) Using the correct current input for the welding process.
(iii) Using good joint preparation with a good weld size.

5.1.5 Spatter

Spatter is beads of weld metal or filler metal which are expelled during the welding process and stick to the surface of the parent metal. It can be caused by a high arc current, damp electrodes or the selection of the wrong shielding gas for a given welding process. It is a cosmetic defect which doesn’t affect the integrity of the weld profile however it is usually a sign that one of the input parameters is wrong and hence the welding conditions are not correct. Anti-spatter compounds can be used on the parent material to avoid the spatter sticking. This allows the spatter to be simply scrapped off. If not used, spatter usually has to be ground off.

5.1.6 Slag Inclusions

Slag is formed when flux, or solid shielding material used in the welding process, melts on top of the welding zone. Slag is the solidified remaining flux after the weld area cools. It is possible for areas of slag to become embedded within the solidified metal if it does not float to the top of the molten metal. This is called a slag inclusion. Slag inclusions are of an irregular shape and therefore differ from a gas pore. They usually occur if slag isn’t properly removed from underlying surfaces of multi-pass weld runs or if the slag becomes entrapped into the work surface. To avoid slag inclusions, complete slag removal must be ensured before welding and ensuring the slag is always behind the arc.

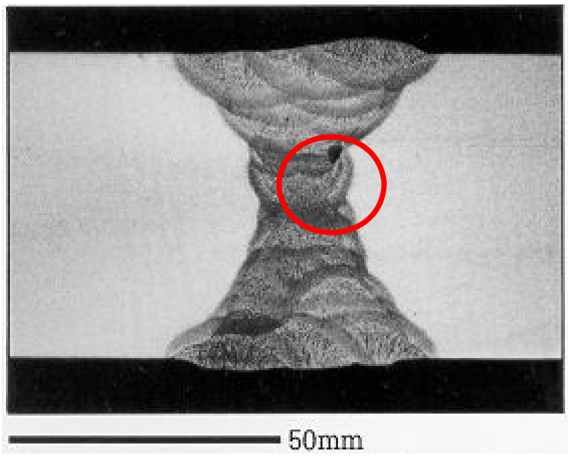


Figure 5.1-2 - Slag inclusion (Courtesy TWI Ltd.)

5.1.7 Gas Pores and Surface Porosity

A gas pore is when a gas cavity of a typically spherical shape is trapped within the weld metal. The gas pockets can be either isolated, uniformly distributed or locally clustered. Gas pores can be caused by a number of factors including damp flux, corroded electrode, water contamination of prepared surface, air entrapped in the gas shield and too high a shielding gas flow rate. To avoid gas pores, weld areas should be kept dry and clean, utilizing the correct gas flow rate where required. Surface porosity is a gas pore which penetrates the surface of the weld.

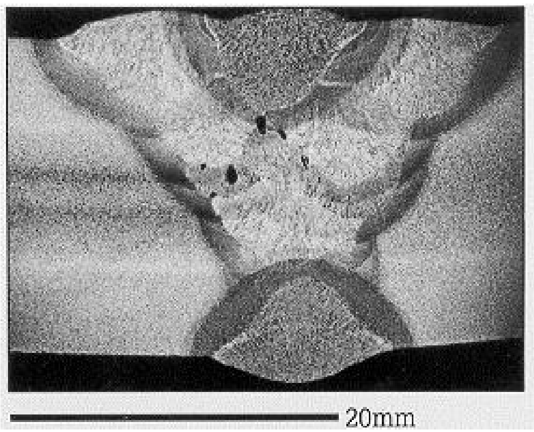


Figure 5.1-3
Gas pores trapped within the weld metal
(Courtesy TWI Ltd.)

Figure 5.1-4
Surface Porosity on the weld surface

5.1.8 Undercut

Undercut is a defect that appears as a groove in the parent metal directly along the edges of the weld. It is characterised by its depth, length and sharpness. It is most common in lap fillet welds but can also be found in fillet and butt joints. The undercutting defect is normally caused by improper welding parameters such as incorrect travel speed or high welding current. When the current is too high or the travel speed is too slow, the top edge of the parent material melts at the free edge creating a groove. Undercut can either be a continuous defect along the edge of the weld or found intermittently.

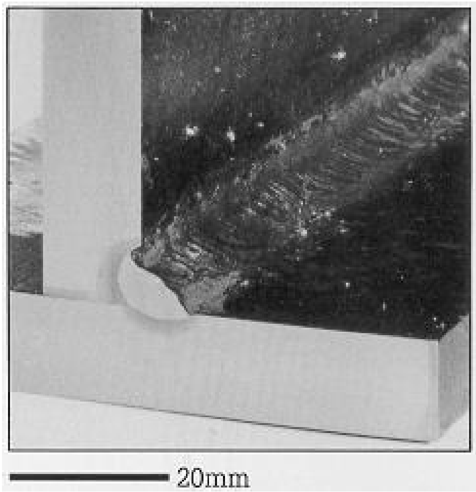


Figure 5.1-5 – Undercut (Courtesy TWI Ltd.)

5.1.9 Worm Holes

Worm holes are elongated or tubular cavities formed by entrapped gas. These areas of entrapped gas can occur during the solidification of the weld metal and can be seen both singly and in groups. Some worm holes can be seen to break the surface of the weld. They are often caused by a contaminated surface or work surfaces which have crevices due to joint geometry.

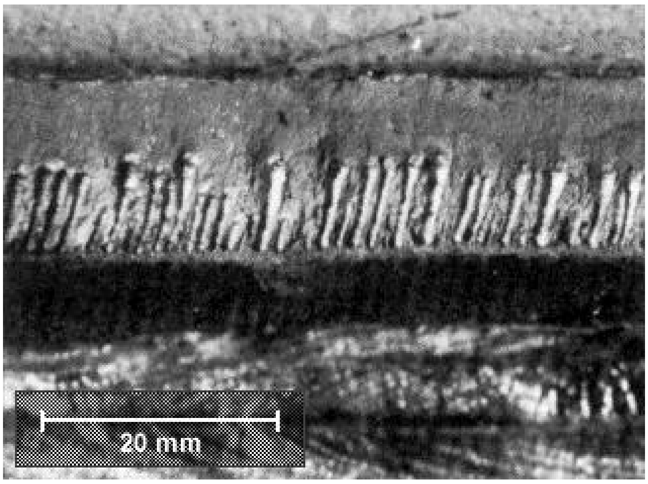


Figure 5.1-6 - Worm holes (Courtesy TWI Ltd.)

5.1.10 Crater Pipe

Crater pipe is a shrinkage cavity at the end of a weld run. The main cause of the defect is shrinkage during solidification of the weld metal. Although it looks similar to other gas defects, it is a metal shrinkage imperfection not a gas defect. It is caused by the use of too high a current input.

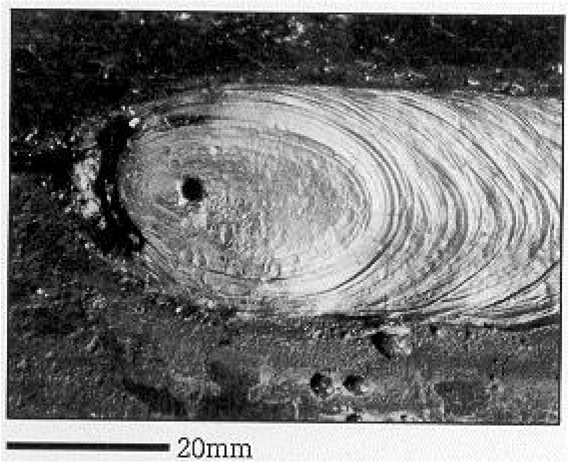


Figure 5.1-7 - Crater pipe (Courtesy TWI Ltd.)

5.1.11 Excess Weld Metal

Excessive weld metal is the extra metal which produces an excessively convex weld profile in a fillet weld and a butt weld which has greater thickness than the parent metal. It is only classed as a welding defect when the height of the excess weld metal is greater than a specific limit. It can be caused by the use of a wrong size of electrode, excess arc energy or too slow a travel speed. Where excess weld metal is referred to as reinforcement, this is misleading as this excess metal does not normally produce a stronger weld. The imperfection can be an issue as the angle of the weld toe can have a sharp profile, leading to an increased stress concentration at the toes of the weld and therefore fatigue cracking.

5.1.12 Excess Penetration

Excessive penetration is when there is a projection of the root penetration bead beyond a specified limit. This can either be local or continuous along the weld bead. It can often be caused by having too high a weld heat input, incorrect weld preparation or lack of welder skill. The use of permanent or temporary backing bars can be used to assist with the control of the penetration extent.

5.1.13 Overlap

Overlap is an imperfection at the toe of a weld which is caused by metal flowing onto the surface of the parent metal without it fusing onto the metal. It can be caused by poor electrode manipulation, incorrect welding position and/or high heat input with a low travel speed causing the metal to flow onto the parent material surface.

5.1.14 Irregular Width

Irregular width is where there is excessive variation on the width of the weld profile. This defect does not necessarily affect the integrity of the complete weld but it can affect the width of the HAZ and reduce the load carrying capacity of the joint. It can be caused by severe arc blow or from an irregular weld bead surface.

5.1.15 Root Cavity

Root cavity is a shallow groove that occurs due to shrinkage at the root of a butt weld. It can be caused by poor welder skill or insufficient arc power to produce a positive bead profile. The use of a backing strip can be used to control the extent of the root bead.

5.1.16 Burn Through

Burn through is when the weld pool collapses resulting in a hole in the weld. It is an imperfection that occurs basically due to the lack of skill of a welder. It can be repaired by bridging the gap formed of the joint although this requires a great deal of attention to be a successful repair. Burn through is often caused by insufficient travel speed, excessive welding current or excessive root gap.

5.1.17 Stray Arc

Stray arc is a local damage to the surface of the parent material next to the weld resulting from an arcing or striking of the arc outside the weld groove. It can produce a hard HAZ which may contain cracks. If not addressed when found, it can lead to serious cracking in service. It is better to remove and arc strike by grinding rather than by use of a weld repair. It is often caused by poor access to the work piece or failure to provide an insulated resting place for the electrode holder or torch when it is not in use.

5.1.18 Poor/un-even Weld Surface, Excess Weld Metal

Several of the defects mentioned above, as well as poor workmanship in general, can result in a very poor and uneven weld surface. Excess weld metal is weld filler lying outside the plane of two plates being joined and can also be referred to as overfill. This can result in two problems. The first is that if the surface is very poor it can lead to additional stress concentrations which in turn can lead to fatigue cracks. The second is that the surface can be very difficult to coat properly. Early breakdown of the coating at the weld, which is usually a high stress area, can result in aggressive corrosion and reduced fatigue life. Remedial action such as dressing or grinding the weld profile should be considered for a poor weld profile.

Figure 5.1-8 – Example of poor weld profile

5.1.19 Hydrogen Cracking

Hydrogen cracking, also known as cold cracking or delayed cracking is caused by the diffusion of hydrogen in the highly stressed, hardened part of the weld material or heat affected zone (HAZ). The cracking will typically occur immediately on welding, or a short time after welding, usually within 48 hours. There are four key factors which contribute to cracking:

1. High hydrogen content
2. High tensile stresses
3. Susceptible microstructure
4. Low temperature

There are a number of ways to prevent hydrogen cracking, some of these include:

- Ensure all welding electrodes are stored and baked as per the manufacturers requirements. A common source for hydrogen is the moisture contained in flux.
- Heat treatment, either one or a combination of preheat, interpass heat treatment or post weld heat treatment to control the cooling rate or reduce residual stresses.
- Ensure the weld joint is clean, with no rust, paint or other possible contaminations, and avoid excessively large root gaps.

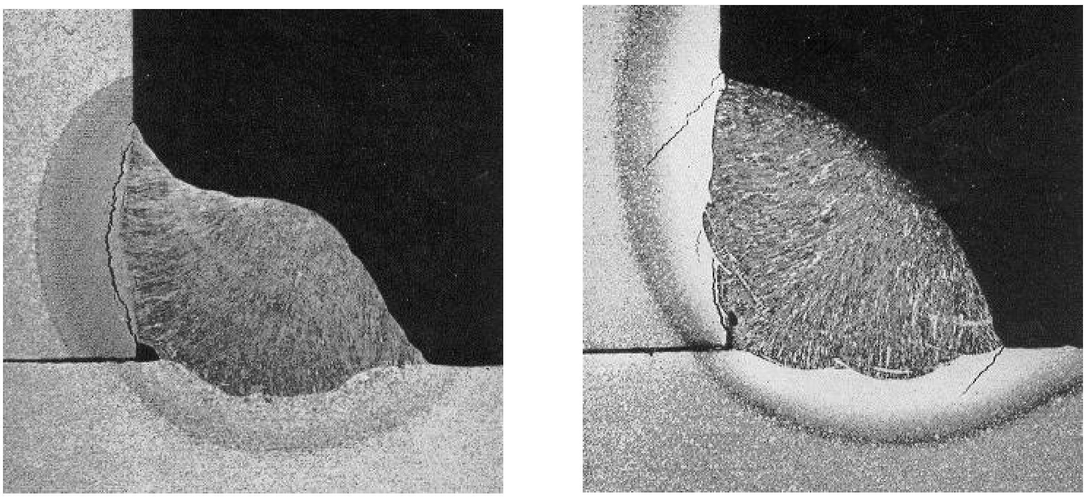


Figure 5.1-9 – Macros of hydrogen cracks (Courtesy TWI Ltd.)

5.1.20 Lamellar Tearing

Lamellar tearing occurs when a rolled steel product, i.e. a plate, is subjected to stresses in the through-thickness direction, perpendicular to the plane of the plate. This situation is found in T-joints. When steel is rolled into plates non-metallic inclusions, very often sulpher, are rolled into very thin platelets. When subjected to through-thickness stresses the plate can split along these platelets resulting in the terraced defect shown below.

In some cases the thermal strain due to welding is sufficient to cause lamellar tearing. Lamellar tearing can be prevented by using steel with a low percaentage of impurities, particularly sulpher. It is also possible to use steel with guaranteed through-thickness properties, denoted “Z-quality” steel. Ultrasonic testing can be used to identify lamellar tearing.

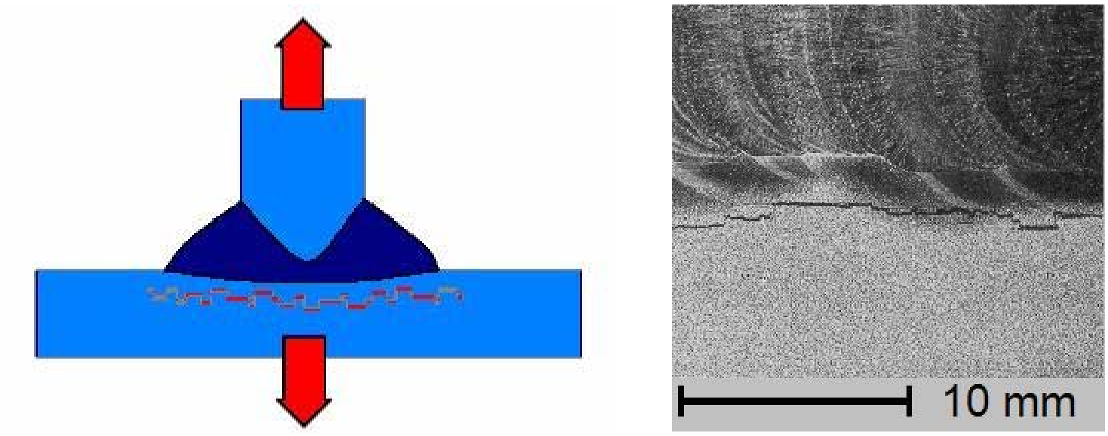


Figure 5.1-10 – Lamellar tearing

5.2 Non-Destructive Testing (NDT)

Non-destructive Testing (NDT) is a wide group of inspection techniques used in the industry to test welds or components without causing them any damage throughout the testing process. Given that it doesn't do any damage to the area in question, it is a highly valued technique that can save both time and money in product quality evaluation. To ensure the test is reliable the following are required:

(i) Qualified NDT personnel.
(ii) Correct methods/techniques.
(iii) Acceptable procedures/reports.
(iv) Satisfactory inspection capabilities.

NDT is divided into various method groups, where each group is based on a particular principle. Each method group may be further subdivided into various techniques which can be applied for that testing group. The following sections explore the different NDT groups that are available.

5.2.1 Magnetic Particle Inspection (MPI)

This method is accomplished by inducing a magnetic field in a ferromagnetic material and then dusting the surface with iron particles. Surface and near-surface imperfections distort the magnetic field and concentrate iron particles near imperfections, giving a visual indication of the flaw

Advantages:
- This is a quick and simple process.
- Most reliable method of surface inspection on ferritic materials.
- Can be carried out at almost any location, including underwater.
- It is possible to detect (shallow) sub surface defects.
- Relatively low cost method.

Limitations:
- Difficult to use on rough surfaces.

- Applicable to ferromagnetic materials only.
- Requires skill and recognition of irrelevant patterns. False indications, for example, can occur at changes of section or weld undercut.
- Defects will only be detected when they give rise to leakage in the magnetic field. Planar defects or small rounded defects can sometimes be difficult to detect.
- Only detects imperfections down to a depth of approximately 2mm.

Figure 5.2-1 – MPI equipment (©Force Technology[3])

5.2.2 Dye Penetrant Inspection (DPI)

Dye Penetrant Inspection is where a liquid is applied to the surface of a material which is absorbed into narrow surface openings such as cracks. Excess liquid is then removed from the surface leaving traces of the liquid contained in the openings. The traces of indicator fluid are drawn out of the defects by applying a "developer" powder/fluid, revealing any defects upon close examination. DPI can be applied to virtually any non-porous material surface and it is not affected by the surface orientation or material grain structure. The penetrant liquid contains a dye which is bright red for high visibility against a white background. Fluorescent dye may be used for a more sensitive inspection as it appears very bright against a dark background when viewed under ultra violet light. The inspection process is to thoroughly clean the surface in question, coat the inspection with dye penetrant liquid, leave the liquid to work for some time allowing it to penetrate into any cracks in the surface, carefully remove the excess penetrant from the surface using wipes (not a surface spray), apply a thin coating of developer powder to draw penetrant out onto the surface and then view indications as they appear, allowing the results to be assessed after a suitable time frame.

Advantages:

- Can be used on most materials for surface breaking defects.
- Equipment is portable and inexpensive.
- For the visible colour contrast, no power supply is required as long as light levels are adequate for inspection.

Limitations:

- Cannot be used on porous surfaces.
- False indications can occur on rough surfaces where excess dye is difficult to remove.
- It is a less sensitive method than MPI for in-service inspection on ferritic materials.

- Cannot detect cracks filled with water, grease, oil or paint.

Figure 5.2-2 – Penetrant testing (©Force Technology[3])

5.2.3 Ultrasonic Testing (UT)

Ultrasonic testing uses the transmission of high-frequency sound waves into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, wherein sound is introduced into a test object and reflections (echoes) are returned to a receiver from internal imperfections or from the parts' geometrical surfaces.

Advantages:
- The location and size of internal defects can be detected.
- It is sensitive to both surface and sub-surface defects.
- Thick and thin work pieces can be inspected at the same time.
- UT is suitable for castings and forgings (thicker materials).
- Inspection can be completed with access to only one side of the component.
- Permits probing of joints inaccessible to radiography.
- There is no radiation hazard in UT examination and therefore no disruption of work. This is not the case for radiography.
- Planar/linear defects can be detected irrespective of their orientation.

Limitations:
- Requires high degree of skill in interpreting pulse-echo patterns.
- Permanent record is not readily obtained.
- In some materials, such as austenitic steel, the large grain size found in welds can hide defects when inspected by UT.
- Misreading of signals or false signals can lead to unnecessary repairs.
- Components of a thickness less than 8mm can be difficult to inspect.
- Surface must be accessible to probe and coupling medium.

Figure 5.2-3 – UT equipment (©Force Technology[3])

5.2.4 Radiographic Testing (RT)

Radiography involves the use of penetrating gamma or X-rays to examine parts for imperfections. A radioactive isotope is used as a source of radiation. Radiation is directed through the part and onto film or other imaging media. Possible imperfections are indicated as density changes on the film in the same manner as an X-ray shows a broken bone in a human body.

Radiographic inspection is very useful for welders and welding processes. Due to its cost however, its use should be limited to those areas where other methods will not provide the assurance required.

Advantages:

- Gives a permanent record when imperfections are recorded on film.
- Can be used to inspect a wide range of materials and thicknesses.
- Detects surface and sub-surface defects.
- It provides a low cost method of internal inspection when viewed using a fluoroscopic screen.

Limitations:

- Requires skill when operating equipment and also choosing the angles of exposure.
- Access to both sides of the structure is usually required.
- Requires safety precautions to prevent radiation exposure.
- Not generally suitable for fillet/partial penetration weld inspection due to the existing void at the root of the weld.
- Orientation of the radiation beam to non-volumetric defects is critical. It can be difficult to detect defects such as solidification cracks, hydrogen cracks, lack of fusion etc.

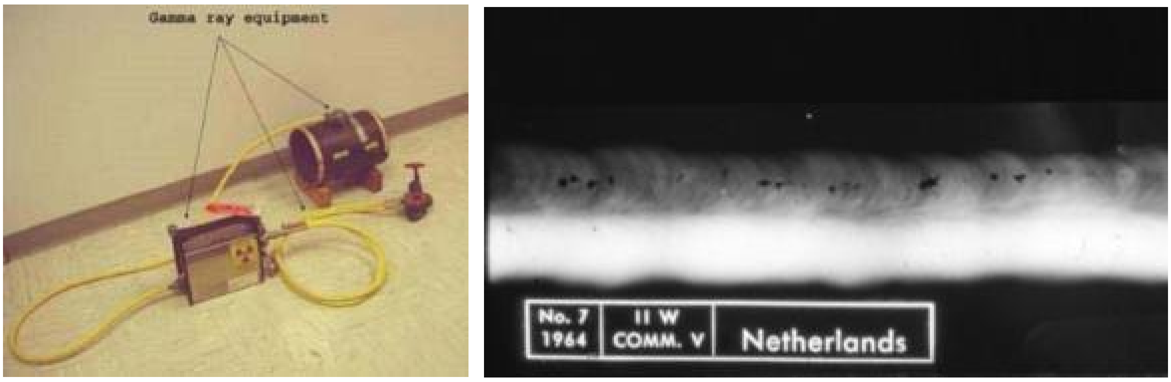


Figure 5.2-4 – RT equipment and exposed film (©Force Technology[3])

5.2.5 Eddy Current Inspection (ECI)

Eddy Current Inspection can be used for many applications including defect detection, coating thickness measurement and material sorting. ECI involves scanning a probe coil over the surface of the material and monitoring the electrical properties of the coil to interrogate the material condition. The ECI equipment is designed to display changes to the eddy current field caused by discontinuities in the material. Testing is most sensitive to surface defects but there is some penetration into the material which can give sub surface indications. The extent of the penetration is however dependent on the material being tested and the frequency at which the probe is driven. Although the process may detect a defect, it doesn't give any indication on the defect depth. Some signal amplitude gives indication as to when a defect is deeper than another, but it cannot work out the actual depth.

Advatages:

- Detects surface and near surface defects.
- It is not necessary to remove the coating when carrying out eddy current. Hence making this a popular option for offshore operations.
- This method can be used for measuring coating thickness.

Limitations:

- Only conductive materials can be inspected.
- Ferromagnetic materials require consideration to address the magnetic permeability.
- The depth of a defect indication is limited.
- A high level of skill and training is required for this method.

Figure 5.2-5 – ECI probes and equipment (©Force Technology[3])

5.2.6 Phased Array Ultrasonic Testing (PAUT)

This is an advanced technique not commonly used due to the cost and requirements for equipment and the operator. Phased Array Ultrasonic Testing uses a multiple element probe whereby the output pulse from each element is time delayed in such a way to produce constructive interference at a specific angle and depth. The time delays are incremented over a range of angles to sweep the UT beam over a wide angular range allowing inspection of the weld under consideration.

Advantages:

- Investigates more angles through one testing procedure.
- There is a permanent record of the inspection.
- Has the ability to define flaws in 3 dimensions.

Limitations:

- PAUT equipment is expensive.
- Equipment is more complex.
- There is no dedicated international standard.
- There are fewer manufacturers than conventional UT equipment.
- Transducers are expensive.

5.2.7 Alternating Current Field Measurement (ACFM)

Alternating Current Field Measurement is an electromagnetic technique to detect surface breaking cracks. This method involves passing alternating current onto the testing surface which induces a uniform electromagnetic field. The electromagnetic field is disturbed by surface-breaking defects. The sensors located on the probe measure the disturbance and locate the defect. The interaction is recorded and modelled to provide the depth and length of a defect without the need for on-site calibration (for steel). Similar to the Eddy Current inspection, no electrical contact is required allowing the probes to work on paints and coatings. In comparison to MPI, this technique gives fewer false indications and predicts both length and depth without the use of ink. In comparison to the Eddy Current inspection, this technique is more reliable for detecting cracks and can determine the depth of cracks to around 25 mm deep. Knowing the depth of the crack is important for fracture mechanics. ACFM can be used underwater, where the divers run the probe against the steel surface and the measurements are recorded and interpreted on the deck. Lately, this technique has been deployed remotely using Remote Operated Vehicles (ROVs).

Advantages:

- Detects surface breaking cracks and can size length and depth of cracks (up to around 25mm deep)
- It works on paints and coatings and underwater and therefore a popular option for offshore structures
- Lower false calls reducing costs from investigating spurious indications and all data is saved for a later review and audit
- Can be deployed remotely by ROVs

Limitations:

- Only conductive materials can be inspected

- Only surface breaking cracks are detected leaving the root cracks that have not yet surfaced undetected
- Skilled or experienced technicians are needed to operate the ACFM equipment

Figure 5.2-6 – ACFM equipment (photo courtesy of TSC Inspection Systems)

6 Special Welding

6.1 Introduction

This part of the information paper considers those types of welding other than the conventional butt or fillet welds used in the majority of welded connections in a ship. It is limited to welding of structural elements and thus the welding of machinery parts has not been considered.

6.2 Cast Steel

6.2.1 Introduction

The process of building a ship will, at various limited points of construction, require the welding of steel castings. The thickness of a casting is normally much greater than a typical steel plate used in ship construction. This greater thickness provides a larger heat sink which cools the newly-formed weld more quickly, increasing residual stresses and producing a coarser grain structure with associated higher hardness values of the weld and parent metal.

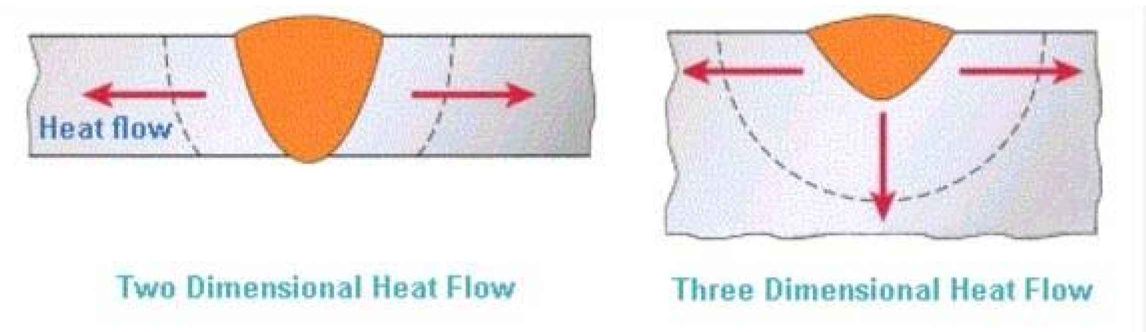


Figure 6.2-1 - Welding heat flow, courtesy of Lloyd's Register

To counter-act these effects, pre-heating and post-weld heating are typically required or specified. Pre- and post-weld heat treatment will be a function of both the material thickness and chemical composition, particularly the carbon content. Necessary heat treatment will be specified in the WPS.

Welding of castings in ship repair and construction is typically found in the following areas:

i) Welding of rudder, rudder horn, stern boss, stern frame, etc. for new construction.
ii) Welding of propellers

There are certain limitations when considering welding of propellers and so this will be covered separately in this paper.

6.2.2 Preheating and Post-Weld Heat Treatment

Pre-heating the casting and plates to be joined helps in two ways:

i) Reduces the effect of the heat sink and thereby slows the cooling rate, improving the weldability of the steel casting
ii) Helps to eliminate cracks in the weld by removing moisture from the area to be welded.

Post-weld heat treatment of the casting and plates to be joined reduces residual stresses in the weld but does not change the grain structure of the materials.

Pre-heating and post-weld heating are typically achieved through the use of gas-torches (using propane gas for example) for smaller weld areas or electric heated blankets for larger welding areas such as large castings (e.g. rudder horns). Care should be taken not to heat the work piece too quickly as this can increase residual stresses as thinner sections of the casting will heat more quickly than thicker sections.

During post-weld heat treatment the temperature of the work piece is raised, allowed to 'soak' for a defined time and then slowly reduced (see figure below).

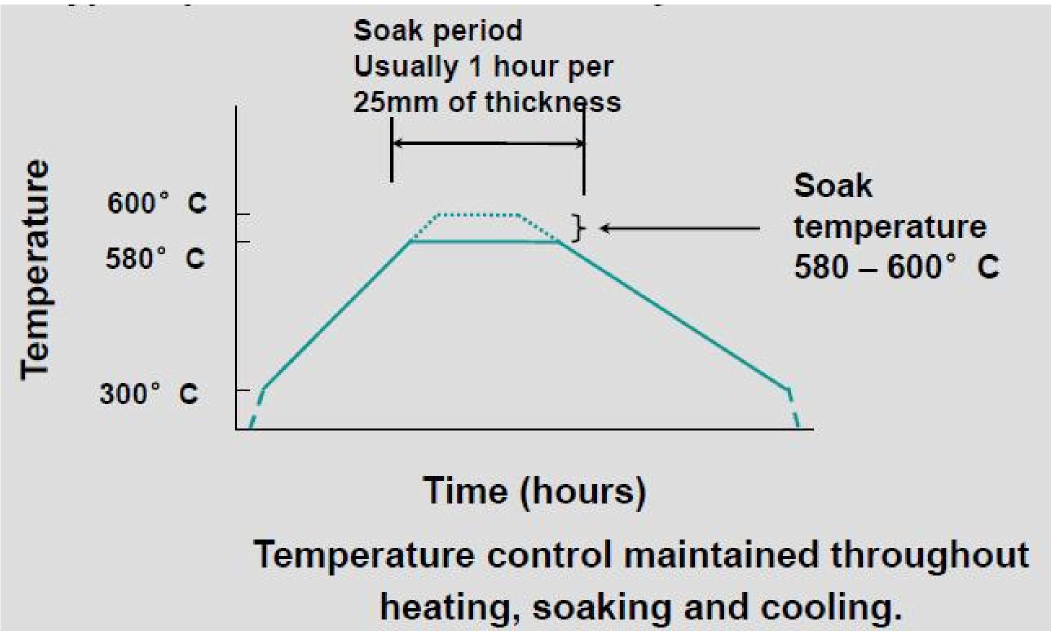


Figure 6.2-2 – Temperature evolution, courtesy of Lloyd's Register

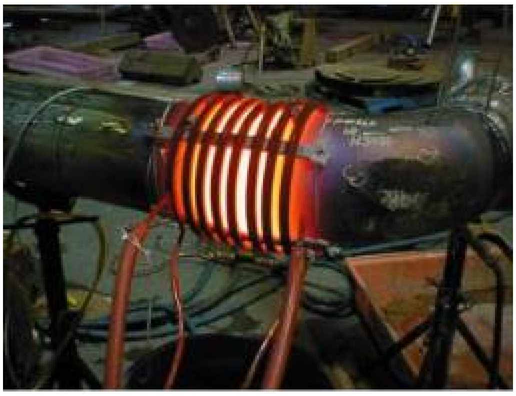


Figure 6.2-3 – Pre-heating of rudder horn, courtesy of DNV GL

Figure 6.2-4 – Pre-heating of pipe

The temperature of pre-heating and post-weld heating can be checked using tempilstiks (crayons whose mark melts when the required temperature is reached), thermocouples and digital thermometers attached to the workpiece which provide a constant temperature readout, or optical pyrometers.

6.2.3 Class Requirements

The various Class Societies include requirements in their Rules for welding of castings but generally they stipulate similar requirements.

If welding is to be done on a casting to rectify a defect, the defect must first of all be completely removed and confirmed as such via suitable non-destructive examination (e.g. magnetic particle inspection, dye penetrant). Any resulting excavations must be shaped to enable sufficient access for welding.

All castings in alloy steels, other than duplex and austenitic steels, are to be pre-heated before welding. After welding is completed the weld and neighboring casting should be subjected to further heat treatment, at a temperature not less than 550°C, to remove any residual stresses that may have built up during the welding process. The approved weld procedure used should include the details of the pre-heat and post-weld heat treatment requirements.

6.3 Stainless Steel

6.3.1 Cleanliness of Materials Before and After Welding.

Stainless steels are often used in the construction of equipment due to their corrosion resistance, which results from a protective oxide layer forming on the surface of the metal when it comes into contact with air.

However, this oxide layer may prevent a good quality weld being achieved and so must be removed prior to welding. This is typically achieved through wire brushing of the areas to be welded but blasting or machining can also be used. If blasting is to be used then care should be taken that the blasting material does not introduce contaminants into the stainless steel (e.g. grit blasting which may contain steel).

Once the weld is completed then passivation, typically using nitric acid, is performed to remove any contaminants introduced during welding and to help with the formation of the protective oxide layer.

6.3.2 Welding Types and Consumables

Most conventional welding methods can be used for welding stainless steels (e.g. GMAW, GTAW, FCAW, SAW). For those welding methods that leave a slag (SMAW, SAW) the flux helps in removing the protective oxide layer to enable a good weld quality to be achieved. Typically calcium and sodium flourides are used in the flux to achieve this. However, these flourides are corrosive to the stainless steel and so the slag needs to be completely removed after welding.

The high expansion coeffiecient and low thermal conductivity (low dissipation of heat) of stainless steel can cause problems with distortion when welding stainless steels. Rigid fixing of thin plates, welding sequences to reduce distortion (e.g. sequence welding) and chilled metal backing can help to reduce distortion.

6.4 Propellers (Bronze)

6.4.1 Class Requirements

Welding of propellers would normally be limited to repairs, although Class Rules do generally allow some repairs to new propellers. Class Rules allow the welding of propellers only under strict limitations. Typically the propeller is split into a number of areas with differing degrees of repair allowed for each area. An example is shown below:

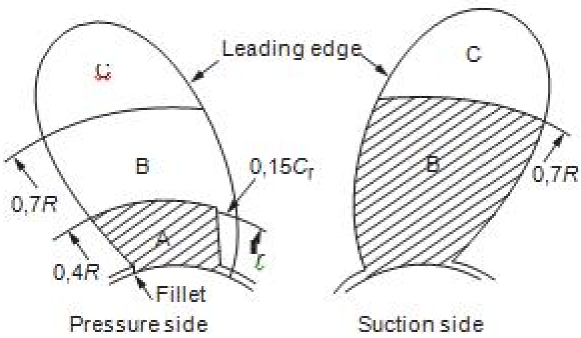


Figure 6.4-1 - Figure from LR Rules (Pt2, Ch.9, Section 1)

Typically weld repairs are not permitted in area A, weld repairs are permitted in area B with the prior approval of the Class surveyor, weld repairs in area C are permitted provided they are carried out to an approved procedure. More detailed requirements can be found in Class Rules. Typically, the propeller will require stress relief heat treatment after welding followed by dye penetrant inspection. Pre-heat may also be required.

6.5 Slot Welding

Slot welding is used frequently where access to complete a conventional weld is limited. For example, when constructing the rudder the web frames are welded to the side shell plating on one side but there is insufficient room within the rudder for the welder to weld the other shell plate from inside the rudder. Therefore this other side shell must be welded to the webs from outside the rudder, using slot welds.

Figure 6.5-1 shows a rudder with the side shell plate welded to the internal stiffening with numerous slot welds, together with a close up photograph of those slot welds.

Figure 6.5-1 - Slot Welds on a Rudder

Classification Society Rules contain requirements for the design and execution of slot welds. For example for slot welds of rudder shell plating Lloyds Register's Rules require:

- i) Length of the slot shall be no less than 75mm
- ii) Width of the slot shall be no less than twice the side plating thickness
- iii) The ends of the slot shall be rounded and spaced not more than 150mm apart.

Other requirements for slot welds, used elsewhere in vessel construction, include the slots being free of notches and not to be completely filled with welding.

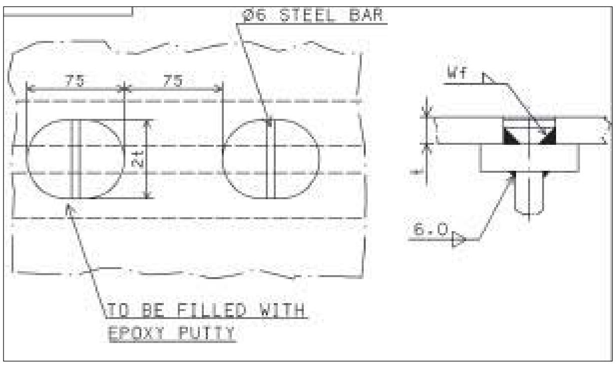


Figure 6.5-2 - Typical slot weld detail

In Figure 6.5-2 the slot design includes a 6mm diameter round bar used to help locate the epoxy putty used to fill the slot. The epoxy putty provides a smooth external surface on the ruder shell plate and thus prevents erosion of the slot edges.

As with any welds, care should be taken when producing them. Defects in the slot welds can act as stress raisers and cause premature failure of the weld as shown in Figure 6.5-3 below.

Figure 6.5-3 - Fracture initiated by poor weld profile and excessive vibration of rudder

6.6 Repair of Pits by Welding

Repair of pitting by welding may be a practical solution provided the remaing thickness in the pit is not too small and the pitting intensity is not excessive. The Class societies have requirements for the minimum remaining thickness in a pit for weld repair to be acceptable. If pitting intensity is too severe repair by an insert is normally required. Where pitting is to be repaired by welding the pit should be ground out to clean base metal, removing any sharp edges. The weld run should start and finish outside the pit as per the IACS Rec.47 requirements shown below. Depending on the pitting depth, multiple passes may be required. Weld cap cleaning and grinding should be completed between each run and all welding should be ground smooth upon completion.

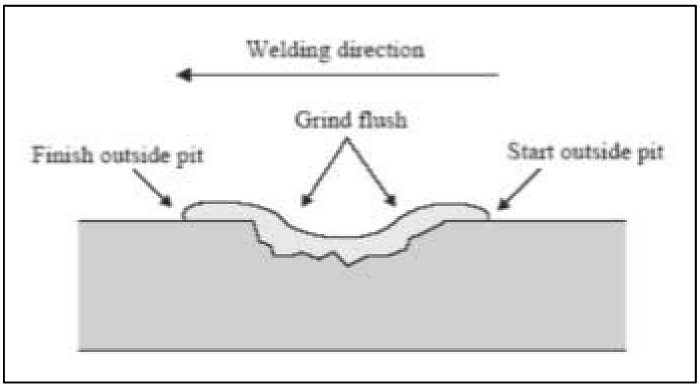


Figure 6.6-1 – Repair of Pits with Welding (IACS Rec. 47)

6.7 Welding Against Water

Welding against a water backing, e.g. welding pits of bottom shell plating whilst afloat, is generally not recommended due to the sea acting like a large heat sink, cooling the weld and parent metal plates too quickly resulting in a poor quality weld. Class Rules typically, therefore, do not permit this type of welding.

However, the Class Society may consider its use on the basis of certain criteria being met, which may include:

a) The welding procedure having been performed and tested with water backing of suitable temperature and flow rate.
b) The welding procedure having been performed on plating thickness equal to the minimum hull plating thickness.
c) Pre-heating, for example by torch, to prevent rapid cooling and condensation with the subsequent risk of hydrogen cracking.
d) Additional non-destructive testing of the welds.
e) The use of low hydrogen electrodes.

6.8 Underwater Welding

Underwater welding can take place either wet in the water itself or dry within a positively pressurized cofferdam. Underwater welding is more commonly used for offshore structures rather than ships structures due to the expense of docking offshore structures in order to perform a dry weld repair. When performed in a wet environment it is typically called ‘underwater welding’ and when in a dry environment it is referred to as ‘hyperbaric welding’. Generally dry hyperbaric welding is used in preference to wet underwater welding when high quality welds are required. In the past wet welding has been considered as temporary repairs but work is currently underway by companies such as TWI to develop weld procedures that provide permanent repairs.

Dry hyperbaric welding is performed in an air-tight cofferdam fixed to the structure to be welded from which the water is removed by pumping the cofferdam full of air or helium. Under these conditions the welder can produce a high quality weld under similar conditions to those found on the surface, with the addition of breathing equipment when helium is being used as the surrounding medium.

Wet underwater welding uses DC current and insulated gloves to maximize the protection of the diver from being electrocuted. The electrodes typically used are similar to the Manual Metal Arc electrodes used for dry welding in that they are comprised of an electrode core surrounded by flux which is then protected by a waterproof coating. This waterproof coating protects the flux from absorbing water and burns away as the welding rod is consumed.

With wet welding hydrogen cracking presents a significant risk to the quality of the resulting weld. During the welding process the welding arc dissociates the sea water into oxygen and hydrogen. The oxygen reacts with elements in the weld resulting in an environment rich in hydrogen. This hydrogen can dissolve into the molten weld and become trapped as the weld cools. If the dissolved hydrogen is present in sufficient amounts it can cause porosity in the weld or even crack the weld.

The hydrogen produced by the welding process not only adversely affects the quality of the weld, it also poses a danger to the welder. If the environment in which the wet weld is produced does not enable the rapid dispersion of the produced hydrogen as small bubbles it can accumulate into gas pockets that could cause an explosion when ignited by a heat source, such as a piece of hot slag.

6.8-1 - An underwater welder, courtesy of TWI Ltd.

6.9 Explosion Welding

Explosion welding is a method of joining differing metals that cannot be welded using conventional methods. For example, where mild steel is to be welded to aluminium this could not be achieved with conventional welding because of the largely differing melting temperatures of the different materials. Explosion welding does not cause either metal to melt but instead causes the surface of both metals to plasticize. Explosion welding is not applied during construction at the yard. It is used during manufacturing of pre-fabricated elements at a sub-supplier.

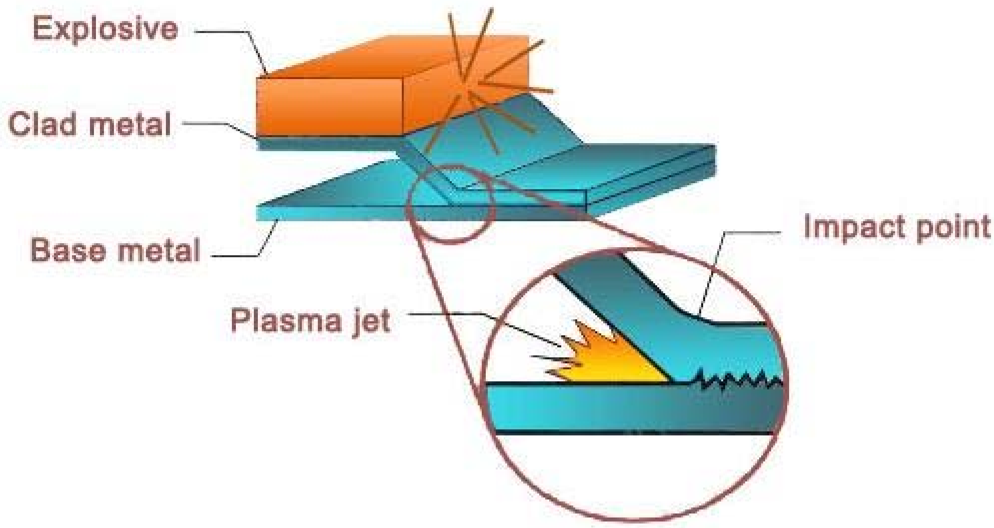


Figure 6.9-1 - Explosion Welding

Figure 6.9-2 - Magnified Explosion Weld

Due to their use of steel and aluminium superstructures, explosion welding is often found on large passenger ships.

6.10 Friction Stir Welding

Friction stir welding is a relatively new welding method, having been invented in1991, and not yet commonly applied in shipbuilding. Friction stir welding in shipbuilding can be found in the welding of aluminium structures, typically for lightweight, high speed and passenger vessels.

With friction stir welding, a rotating tool is introduced into the gap between the two metal plates to be joined. The friction between the rotating tool and the plates creates heat, which reduces the yield stress of the materials and allows them to be ‘stirred’ together at a temperature below their melting point. The plates to be joined must be tightly clamped into position to prevent them moving during the operation. There should be no gap between the plates during the process, allowing the weld to be created without the need of filler material.

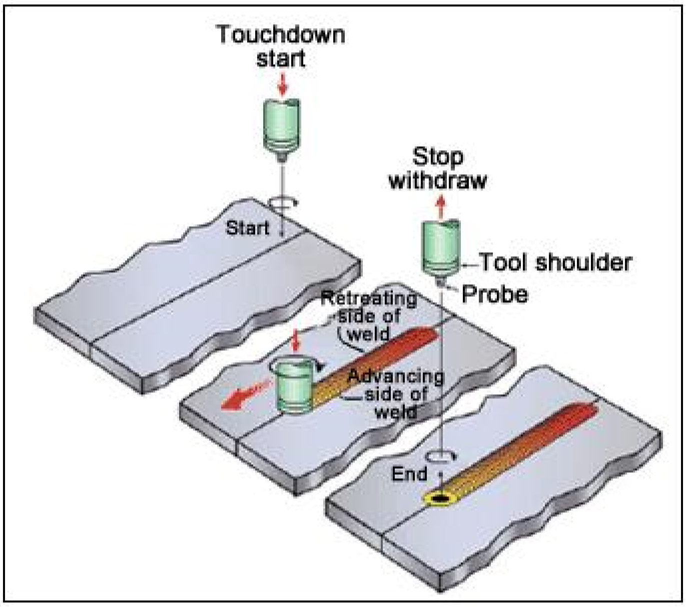


Figure 6.10-1 - Friction Stir Welding, Courtesy of TWI Ltd.

The rotating tool is pressed down into the gap between the two plates, the probe part of the tool first touches the plates, creating friction and thus heat, reducing the yield stress of the plates and thus allowing the probe to be pressed down into the gap between the plates. The tool shoulder then reaches the surface of the plates providing additional heating and preventing material flowing away from the fusing gap. The tool then traverses along the gap heating the plates and stirring them together, thus creating the 'weld'.

The advantages of friction stir welding include:

a) Low distortion and shrinkage due to low energy being input into the weld.
b) Excellent mechanical properties in fatigue, tensile and bend tests
c) No arc or fumes
d) No porosity
e) No spatter
f) Can operate in all positions
g) Energy efficient
h) One tool can typically be used for up to 1000m of weld length in 6XXX series aluminium alloys
i) No filler wire required
j) No gas shielding for welding aluminium
k) Some tolerance to imperfect weld preparations - thin oxide layers can be accepted
l) No grinding, brushing or pickling required in mass production

There are some disadvantages of friction stir welding the main ones for shipbuilding being the relatively inflexible operation as the process is only applicable to butt welds and requires the plates to be heavily clamped. In addition, when the tool is withdrawn at the end of the weld the probe will leave a small hole in the gap between the plates.

6.11 Laser and Laser-Hybrid Welding

Laser welding uses a focused laser beam to produce partial penetration welds with lower heat input and therefore lower distortion. However, it requires very small gaps between the plates to be joined and is therefore difficult to adopt in shipbuilding.

Laser hybrid welding is currently being trialed by major European shipyard building passenger ships, e.g. Meyer Werft, Fincantieri. The process uses a combination of a laser and an arc welding process (such as MAG) within the same weld pool to produce a butt weld with reduced distortion, due to lower heat input from laser welding, and an increased gap between the plates to be joined, due to the filler metal being provided by the arc welding process. However the gap between the plates to be joined is still limited (circa 1mm) and thus the process is currently limited to the panel line.

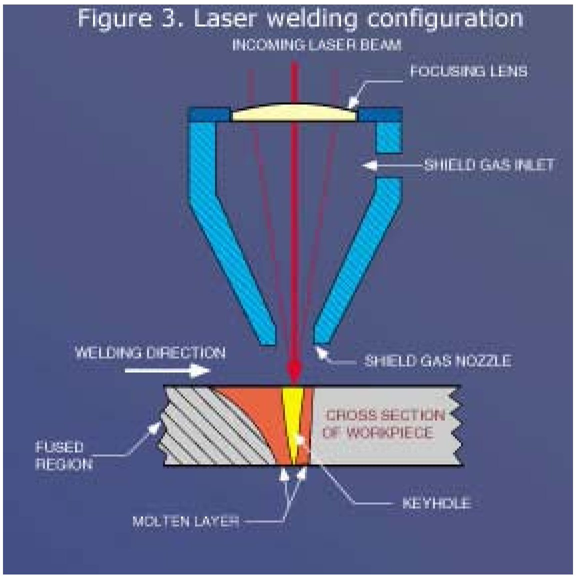


Figure 6.11-1 - Laser Welding

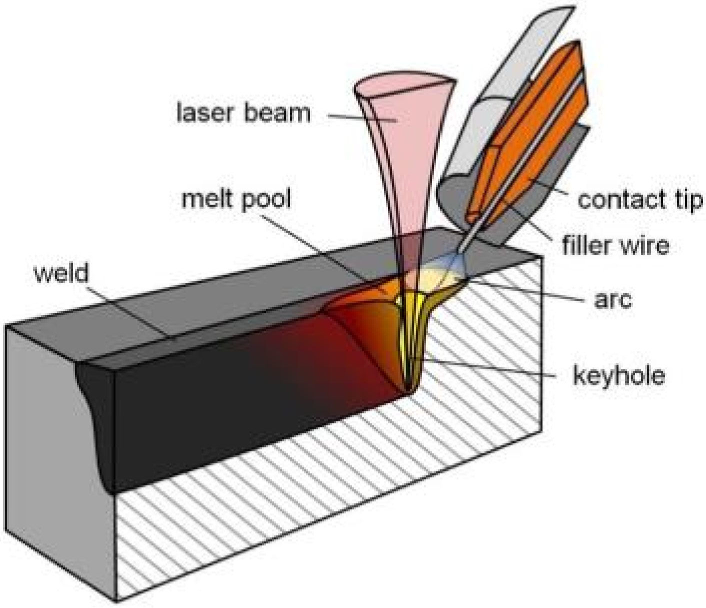


Figure 6.11-2 - Laser Hybrid Welding

6.12 Resistance Spot (stud) and Seam Welding

Resistance welding works when two metals are brought into contact and a current passed between two attached electrodes. The interface between the metals will create resistance to the current flow and the energy expended overcoming this resistance is converted into heat, localized at the interface. If the current is high enough and provided long enough this heat will cause the metals to melt and create a weld pool between them. When the current is then removed the weld pool cools and the metals become welded together.

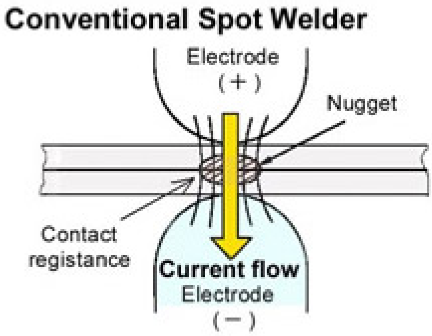


Figure 6.12-1 - Spot Welding

In shipbuilding resistance welding can be found as both spot welding and seam welding. Spot welding is found in the form of stud welding, where typically threaded studs are welded to a metal panel to provide an anchor for linings, insulation, containment systems etc.

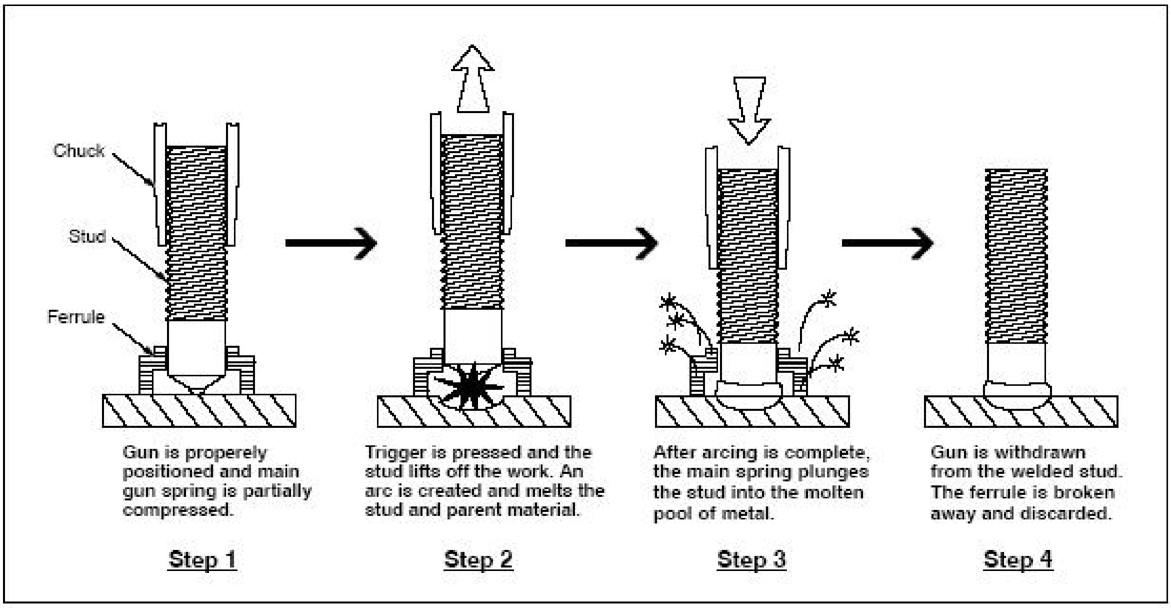
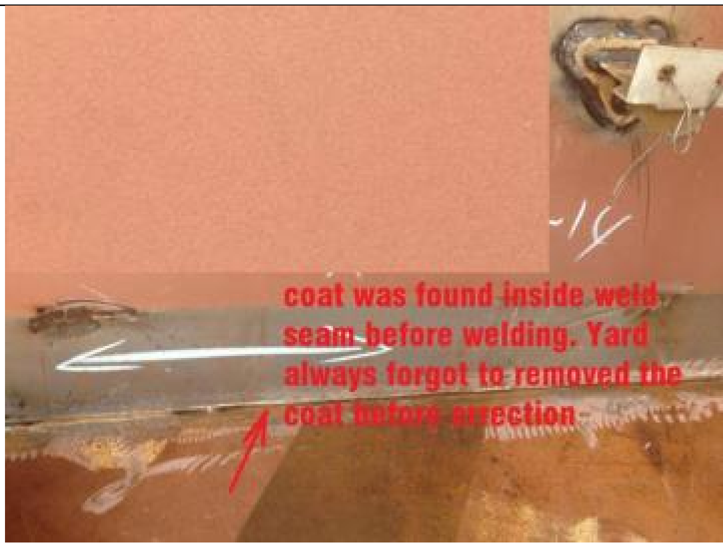


Figure 6.12-2 - Stud Welding Technique

Figure 6.12-3 - Stud Welding Gun, courtesy of Nelson Stud Welding

Appendix 1
Welding Experience

<table>
<tr><td colspan="3">Case 1: Paint in way of welding seam</td></tr>
<tr><td>Ship-Type</td><td>Product tanker</td><td>Capacity:50000</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessels age when damage found: New building</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2">Maindeck, deck house</td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2">


</td></tr>
<tr><td>Description of defect/damage</td><td colspan="2">- Poor weld quality.
- Material – AH36 in deck.
- Type of weld – fillet weld.
- Welding method, MIG.
- Plate thickness 12.5mm</td></tr>
<tr><td>How discovered</td><td colspan="2">- Visual</td></tr>
</table>

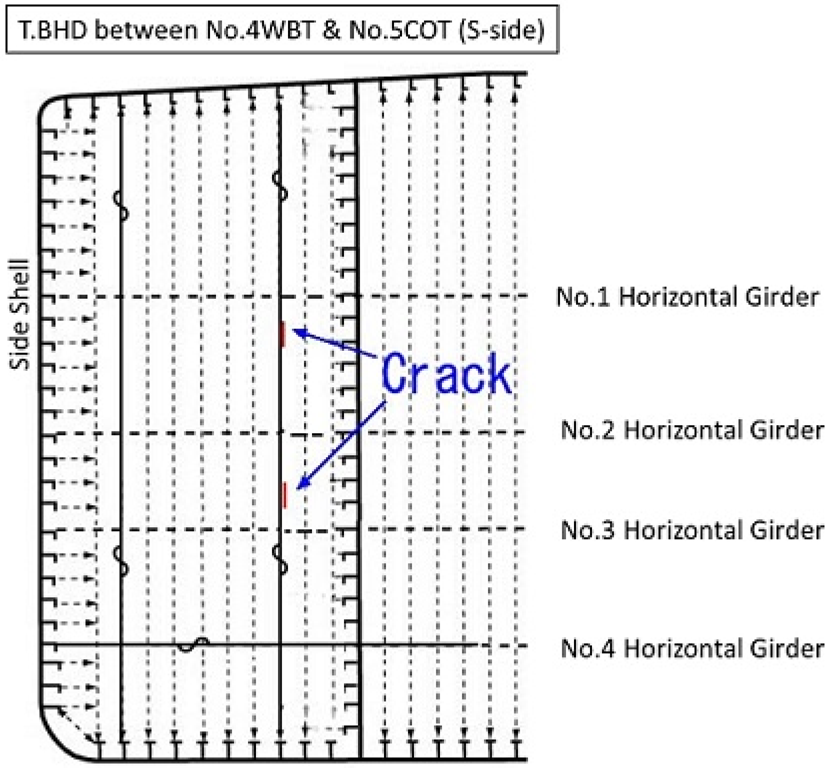
Probable cause of Damage	- Poor workmanship and lack of preparation
Description of Repair	- Remove plate and remove paint below
Preventative action/lessons learned	- Enforce proper preparation before erection

Case 2: Crack in inner bottom plate seam		
Ship-Type	Product tanker	Capacity:50000
Year of build	Vessels age when damage found: New building	
Location of damage:	Inner bottom, transverse in way of insert/suction well	
Photo/Sketch of defect/damage	 	
Description of defect/damage	- Crack in inner bottom plate seam - Material – AH36. - Type of weld – Full penetration butt weld. - Welding method, MIG. - Plate thickness 14.5 mm	

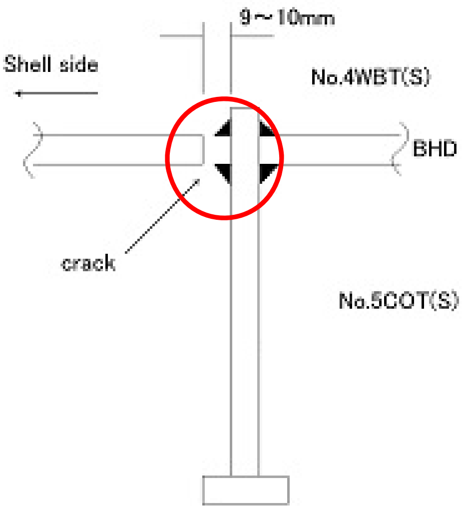
How discovered	- Visual, during fit-up inspection
Probable cause of Damage	- The transverse plate weld was partly completed during block fabrication. - The crack has appeared due to heat shrinkage or possibly handling of the block.
Description of Repair	- Gouge out the crack, clean and check with MTI/DPI and complete the transverse weld. Then continue with the insert plate, longitudinal weld. Check completed welds by UT/RT
Preventative action/lessons learned	- In this case the transverse weld should have been completed before moving the block or completing block erection welds. - In general, the root should be checked with MTI/DPI prior to welding the opposite side. - Education of worker, QC/QA, use MPI/DPI after gouging. - If the crack had been over welded it is likely that there would have been an internal defect/crack that would have propagated due to the longitudinal hull girder loads.

Case 3: Porosity in plate seam, vertical transverse weld		
Ship-Type	Product tanker	Capacity:50000
Year of build	Vessels age when damage found: New building	
Location of damage:	Side shell, vertical block or normal plate seam	
Photo/Sketch of defect/damage	 	
Description of defect/damage	- Weld porosity. - Type of weld – Full penetration butt weld. - Welding method, MIG or SMAW. - Plate thickness 14mm, A grade mild steel	

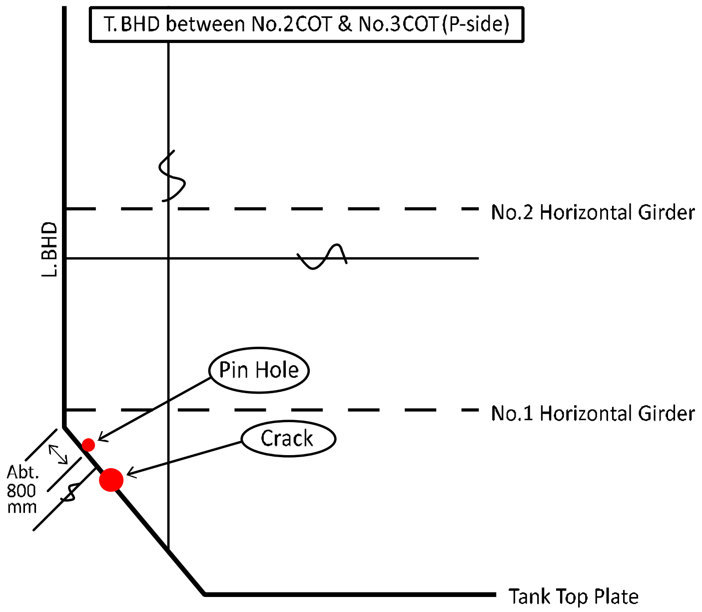
How discovered	- Visual, during fit-up inspection
Probable cause of Damage	- The plate weld. Has been carried out without run-off tabs, possibly with poor control of welding parameters or in windy condition, lack of shield gas.
Description of Repair	- Gouge out the vertical welds until defect free, check with UT/RT further along the weld (100%) to ensure that no more porosity exists. Re-weld the vertical plate seam, then continue with the erection seam.
Preventative action/lessons learned	- Use run-off tabs, large enough to avoid defects like this in the remaining weld. - Enhance inspection routines for prefabrication parts, sub inspections.

<table>
<tr><td colspan="3">Case 4: Crack due to excessive gap</td></tr>
<tr><td>Ship-Type</td><td>VLCC</td><td>Capacity: abt. 261,000 dwt</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessel’s age when damage found: 11 years old</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2">- Erection fillet weld joint of T.BHD

</td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2">- Cracks at erection fillet weld joint of T.BHD in way of vertical stiffener

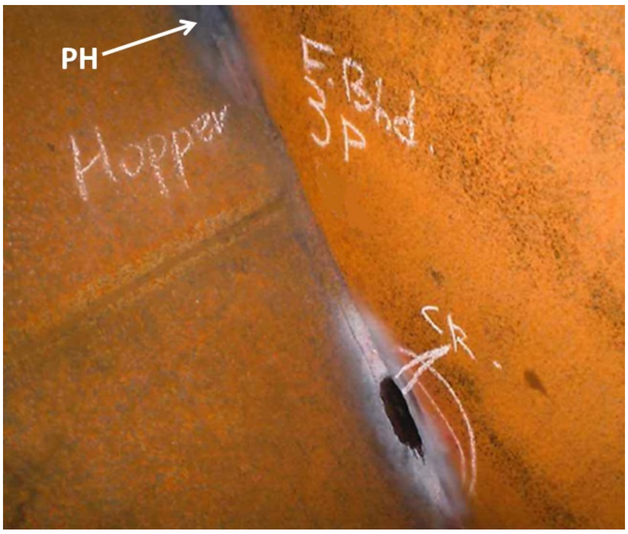
</td></tr>
<tr><td>Description of defect/damage</td><td colspan="2">- Crack in fillet weld due to excessive gap.
- Material – AH32
- Type of weld – Fillet weld
- Welding method – semi-automatic with CO_2 shielding</td></tr>
</table>

	- NDT applied – Unknown - Plate thickness – T. BHD: 14.0mm and 16.5mm – V. Stiffener: 10.5mm and 12.0mm
How discovered	- Alleged oil leakage from COT to WBT through oil-tight bulkhead was reported. - Leak test was used to identify the extent of the cracks.
Probable cause of Damage	- Excessive gap (about 9mm to 10 mm) between T. BHD and vertical stiffener on the occasion of erection fillet welding.   
Description of Repair	- Affected T. BHD and vertical stiffener were partly cropped and renewed. The concerned fillet weld was gouged out and re-welded with full penetration weld.
Preventative action/lessons learned	- Excessive gap shall be avoided on the occasion of erection welding. - Highlights the importance of good fit-up inspection and following the WPS.

<table>
<tr><td colspan="3">Case 5: Pinhole and crack</td></tr>
<tr><td>Ship-Type</td><td>VLCC</td><td>Capacity: abt. 284,000 dwt</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessel’s age when damage found: 5 years old</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2">- Fillet weld joint between T. BHD and bilge hopper plate

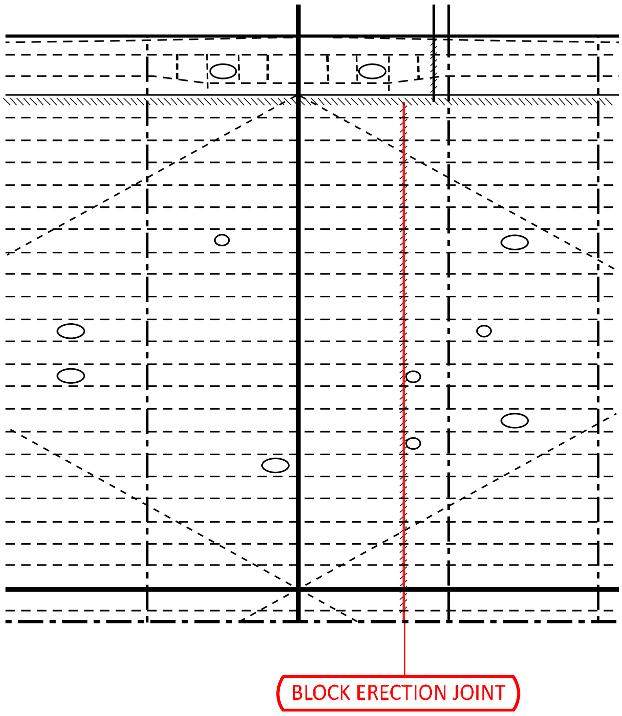


</td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2">



</td></tr>
<tr><td>Description of defect/damage</td><td colspan="2">- Pin hole and cracks in the fillet weld joint between T. BHD and bilge hopper plate
- Type of weld – Fillet weld
- Welding method – CO_2 welding
- Plate thickness - T. BHD: 18mm AH36
- Hopper Plate: 30mm and 20mm AH36
.</td></tr>
<tr><td>How discovered</td><td colspan="2">- Oil mark was found on the occasion of the internal examination at class</td></tr>
</table>

	periodical survey. - PT was used to identify the extent of the defects.
Probable cause of Damage	- Presumably welding conditions of the approved Welding Procedure Specifications (WPS) were not observed and/or environmental condition of welding work was not appropriate.
Description of Repair	- Pin hole and cracks were permanently repaired by gouging and re-welding.
Preventative action/lessons learned	- Welding shall be conducted in accordance with the approved WPS. - Moisture, grease, rust, etc. shall be removed from the intended weld part properly.

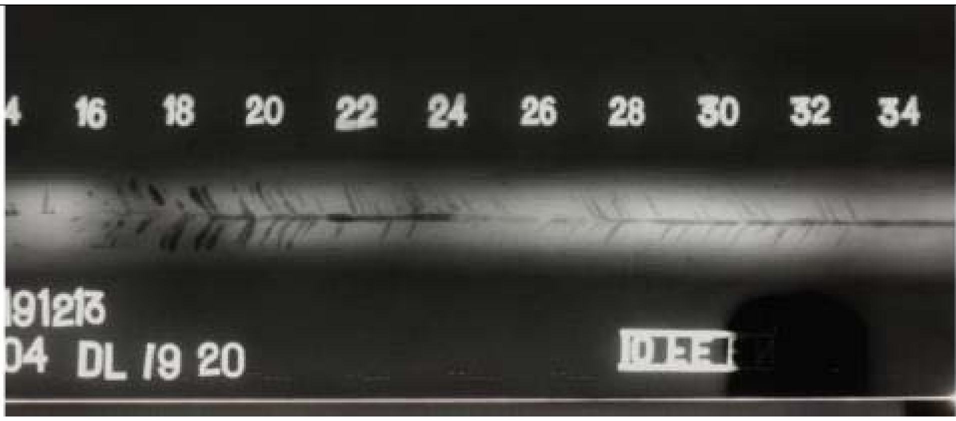
<table>
<tr><td colspan="3">Case 6: Welding wire defect</td></tr>
<tr><td>Ship-Type</td><td>Aframax Oil Tanker</td><td>Capacity:105,000 deadweight</td></tr>
<tr><td>Year of build: 2003</td><td colspan="2">Vessels age when damage found: 5 years old</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2">Transverse erection weld on the main deck.

</td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2">
The defect was found when inert gas was seen to be bubbling through water on the main deck in way of an erection butt weld located close to the deck store vertical stiffeners.</td></tr>
</table>

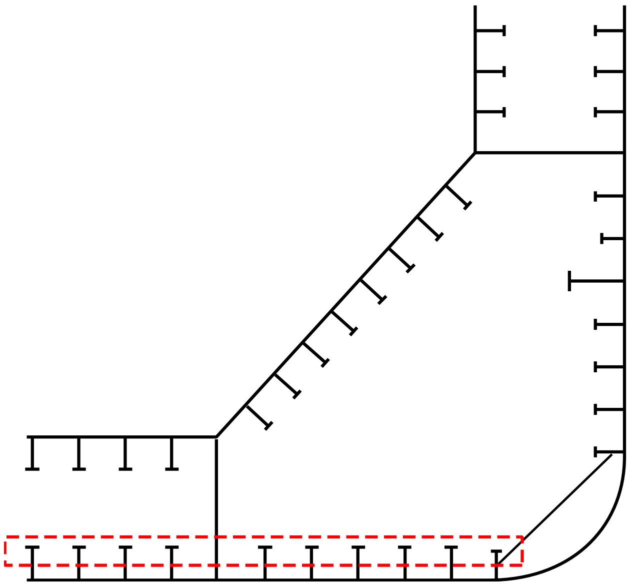
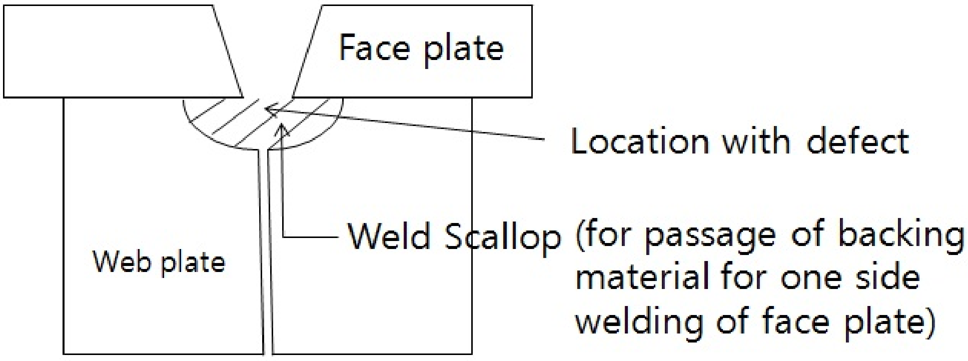
	 MPI of Weld indicating extent of the crack
Description of damage	- Through-thickness crack found in deck weld by visual inspection by crew member. MPI and UT subsequently used to determine the extent of the defects. - Examination of the defective weld indicated lack of sidewall and inter-run fusion. - Material – deck plating, 17mm thick AH32 - Type of weld – Full penetration butt weld - Welding method – Submerged arc welding using two electrodes and embedded wire.  Macro of Defective Weld Showing Void of Un-Fused Embedded Wire

	 Piece of Weld Showing Un-Fused Embedded Wire at Centre of Weld Thickness
How discovered	- Inert gas was seen to be bubbling up through water on the main deck in way of an erection weld located close to the vertical stiffeners of a deck store bulkhead. - MPI was used to identify the extent of the defect. Subsequent gouging and further MPI ensured the true extent of the defect was found.
Probable cause of Damage	Inspection of the weld revealed that a weld procedure had been used whereby, after a root run is applied, specially prepared welding wire is placed into the weld gap. An automatic weld is then made using two electrodes; the first electrode melts the embedded wire in the gap and the second provides a capping run of weld. - It appears that the approved weld procedure was not followed resulting in the embedded wire not melting completely.
Description of Repair	- All main deck plating welds were examined with UT to identify lack of inter-run fusion and sidewall fusion. - All defective areas were gouged and re-welded
Preventative action/lessons learned	- Newbuild specifications now require that all weld procedures are submitted to the Buyer.

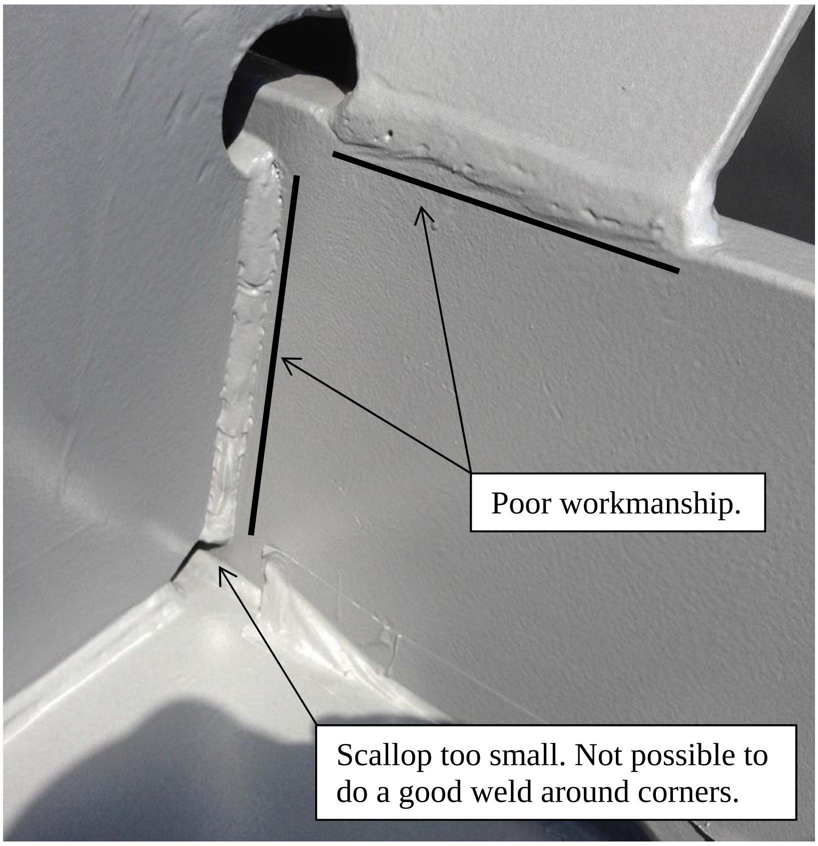
<table>
<tr><td colspan="3">Case 7: Main deck erection weld porosity</td></tr>
<tr><td>Ship-Type</td><td>Handysize Product Tanker</td><td>Capacity: 47,000 DWT</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessels age when damage found: 7.5 Years</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2">Main Deck: Erection welds in way of No. 4 & No.5 COT/WBT’s</td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2">
Wormhole porosity in root run after blasting

Herringbone pattern caused by surface breaking porosity (wormholes)</td></tr>
</table>

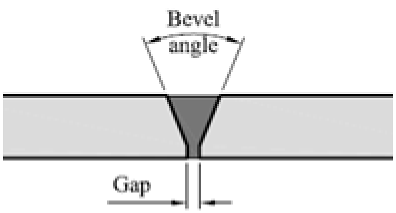
	
Description of defect/damage	- Porosity in the root run, with long pores causing wormholes. - Material –Grade ‘A‘ Mild Steel, - Type of weld – Full penetration butt weld - erection welds - Welding method - Likely, FCAW with gas shielding, using backing strip, although unconfirmed - NDT applied - UT and RT - Plate thickness - 12mm
How discovered	- Initial discovery from surface visual defect under corrosion. Further investigation undertaken with UT and RT
Probable cause of Damage	- Analysis carried out - Visual Inspection, UT, Radiography, Macrostructure examination and Hardness profiling. - Root cause of defect - Poor welding control. Probably moisture either in the backing strip or on weld preparation. - Environmental conditions - high humidity, rain and high wind speeds may have been contributing factors.
Description of Repair	- Gouge and re-weld root of the affected welds. - 100% UT after repair to confirm complete removal of defect.
Preventative action/lessons learned	- Audit of welding practice and ensure WPS is being followed. - Increased level of owner inspection and patrolling, ensuring correct weld practice. - Increased number of NDE locations at new build.

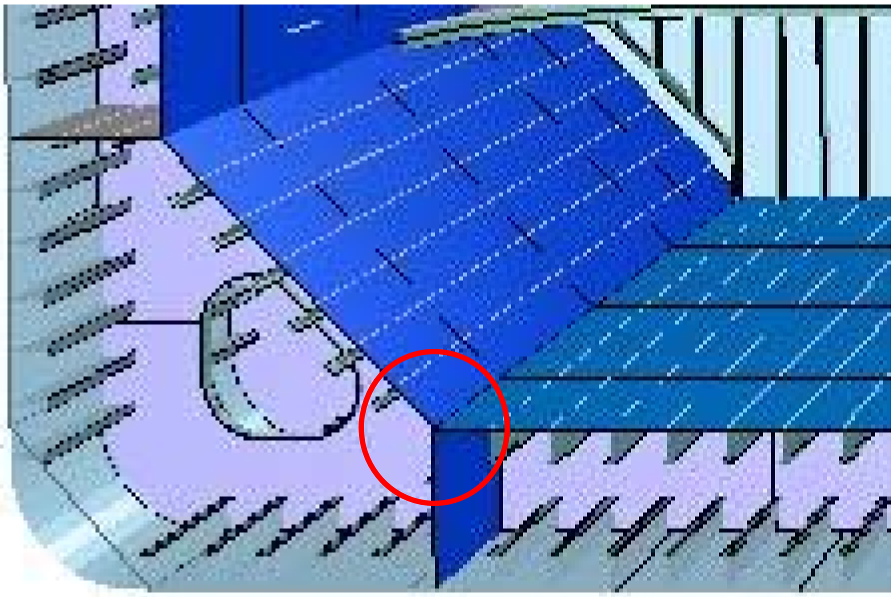
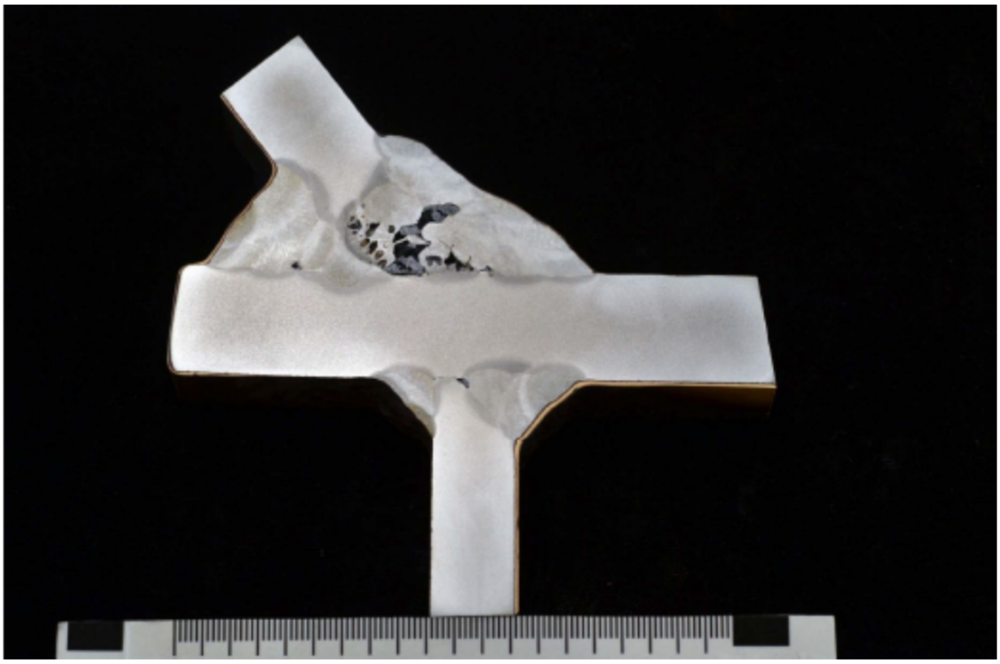
<table>
<tr><td colspan="3">Case 8: Weld scallop</td></tr>
<tr><td>Ship-Type</td><td>VLCC</td><td>Capacity: 300,000 DWT</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessels age when damage found: during construction</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2">
 
</td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2">Structural discontinuity is shown in below figure.

</td></tr>
</table>

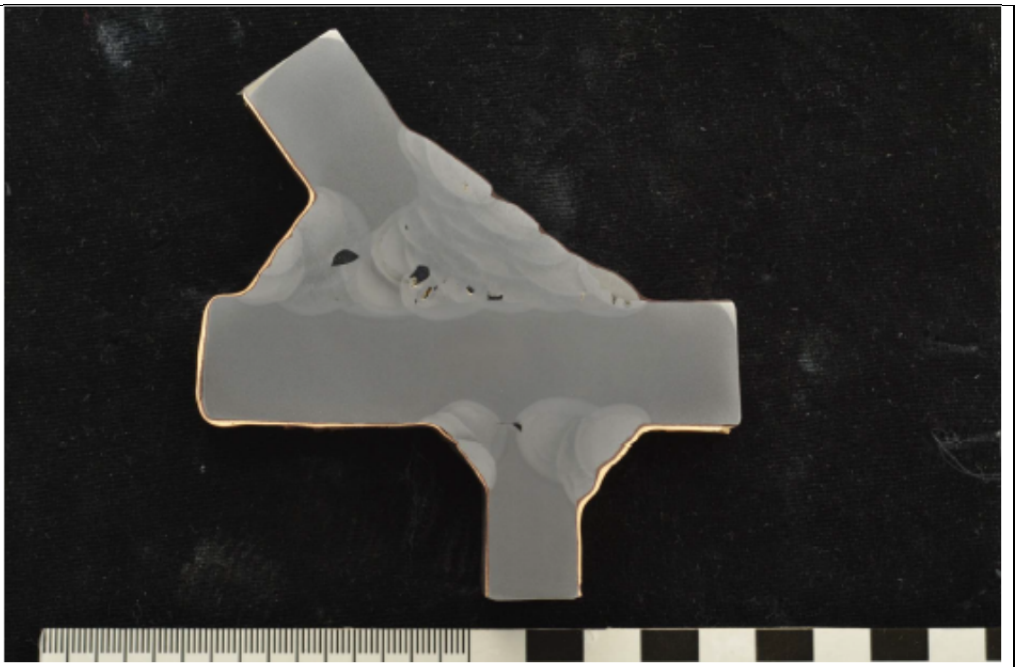
	
Description of defect/damage	Slag inclusion, porosity, lack of fusion, lack of penetration at build up welding of scallop.
How discovered	UT or RT according to NDT plan for new construction
Probable cause of Damage/defect	Welding is done at overhead position. Due to the height of T bar being small, welding to build up the scallop becomes difficult. Therefore, weld zone of scallop has more possibility of defect.
Description of Repair	Gouge/ Reweld
Preventative action/lessons learned	Extensive NDT at this location. Consider changing the detail to something easier to construct, i.e. a larger scallop closed with a collar plate.

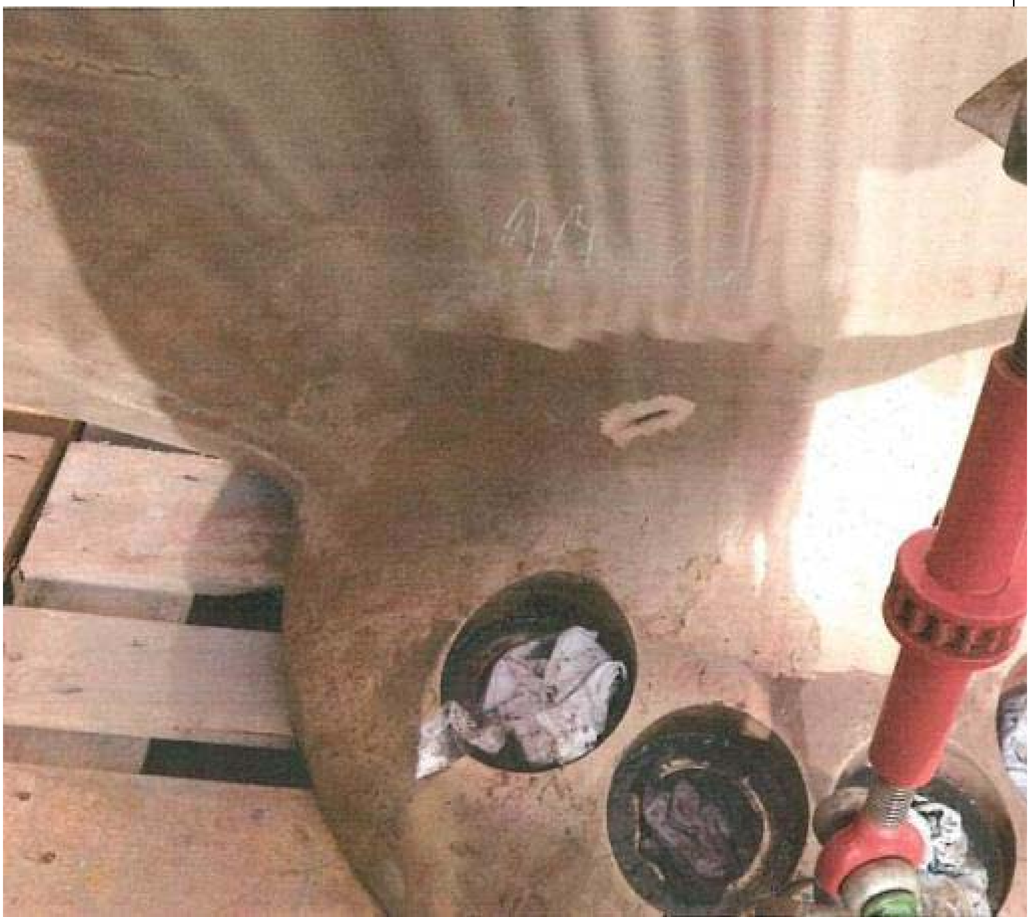
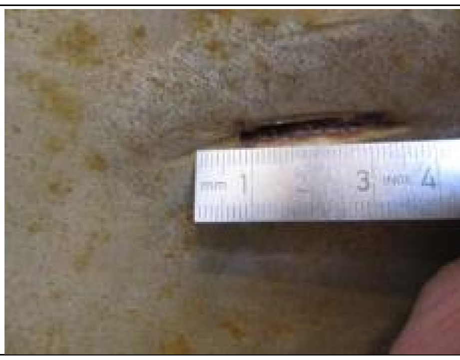
Case 9: Poor design – small scallop		
Ship-Type	MR tanker	Capacity:
Year of build	Vessels age when damage found: New building	
Location of damage:	Bottom plate/stiffener	
Photo/Sketch of defect/damage		
Description of defect/damage	Generally poor and uneven welding with pores. Scallop at bottom is insufficient to achieve round welding and good corrosion protection	
How discovered	- Visual	
Probable cause of Damage	- Poor workmanship - Design mistake w.r.t. size of scallop	
Description of Repair	- Unknown, likely left as is.	
Preventative action/lessons learned	- Ensure good access for welding.	

Case 10: Poor fit-up and workmanship		
Ship-Type	MR Tanker	Capacity:
Year of build	Vessels age when damage found: New building	
Location of damage:	Bottom shell	
Photo/Sketch of defect/damage		
Description of defect/damage	- Excessive gap and uneven edge - Too small scallop for good round welding and corrosion protection	
Probable cause of Damage	- Poor workmanship and design	
Description of Repair	- Unknown. Should be repaired by insert or building up edges with weld ("buttering") - Note the small scallop which will make welding difficult	
Preventative action/lessons learned	- Importance of a good fit-up inspection	

Case 11: Poor edge preparation and fit-up		
Ship-Type	MR tanker	Capacity:
Year of build	Vessels age when damage found: New building	
Location of damage:	Side shell	
Photo/Sketch of defect/damage	 	
Description of defect/damage	– Poor edge preparation and fit-up – Inadequate tack welding – Thickness 12mm	
How discovered	- Visual	
Probable cause of Damage	- Poor workmanship (beveling, fit-up, surface preparation)	
Description of Repair		
Preventative action/lessons learned	- The yard/workshop should have a standard for fit-up, tack welding, etc. which should be followed. - Bevel to ensure full penetration. 	

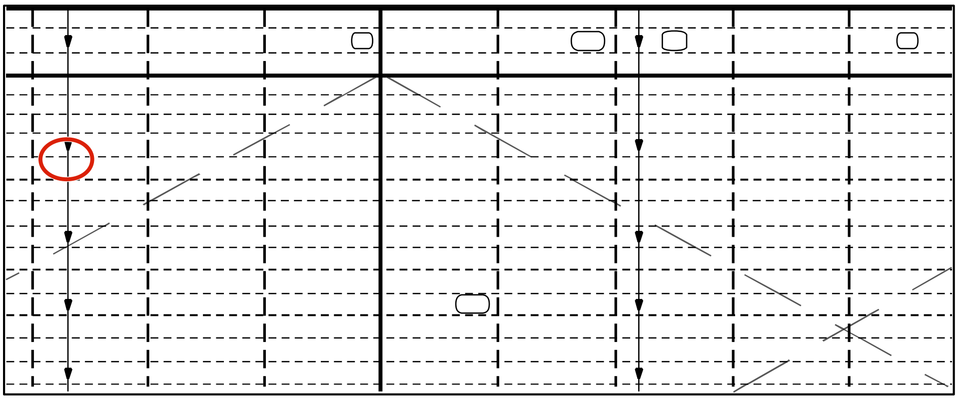
<table>
<tr><td colspan="3">Case 12: Poor hopper knuckle weld</td></tr>
<tr><td>Ship-Type</td><td>VLCC</td><td>Capacity: 320,000 DWT</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessels age when damage found: < 5 years</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of damage:</td><td colspan="2"></td></tr>
<tr><td>Photo/Sketch of defect/damage</td><td colspan="2"></td></tr>
</table>

	
Description of defect/damage	Welding defect in hopper corner. Voids and slag inclusions. Intermittent defects along entire length of hopper corner. Material HTS 32.
How discovered	Discovered due to cargo oil leakage into ballast tank after short time in service.
Probable cause of Damage	Poor fit-up – gap too large. Poor welding with insufficient back-gouging/cleaning between welding passes, likely that WPS not followed.
Description of Repair	Gouge/reweld. Due to poor fit up (see macro section) inserts were also required.
Preventative action/lessons learned	Fit-up inspection before welding commencement would have detected the poor fit-up. This could have been corrected by inserts or possibly building up the edge of the sloping plate ("buttering"). The defects could have been picked up at an early stage of production by a competent NDT operator. The owner may consider requiring full penetration welds at this joint to ease NDT. With a partial penetration weld UT will detect the gap at the root and results may be unclear.

Case 13: Weld repair of propeller blade		
Ship-Type		Capacity:
Year of build	Vessels age when damage found:	
Location of damage:	This relates to a crack on a CU3 propeller blade which developed during service. 	
Photo/Sketch of defect/damage	 	

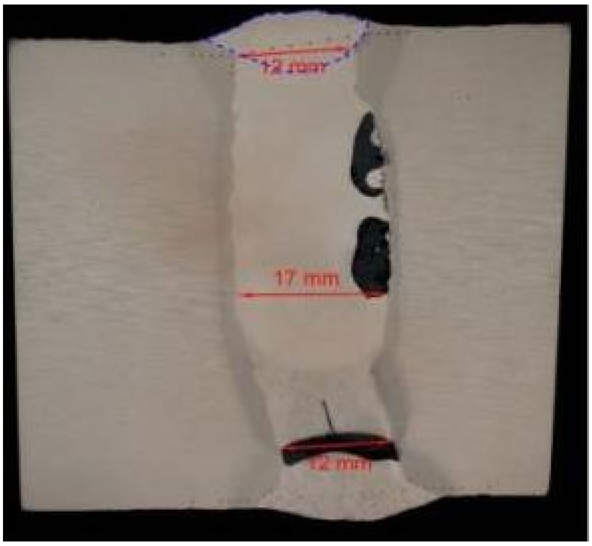
Case 13: Weld repair of propeller blade	
	
Description of defect/damage	See pictures above
How discovered	This relates to a crack on a CU3 propeller blade which developed during service.
Probable cause of Damage	Most likely the crack could have initiated due to a sudden impact.
Description of Repair	The requirements for weld repair of copper alloy propellers are given in Class Rules for Materials. Although the defect falls in Zone A for this repair, we do not envisage or recommend any condition of Class or memorandum provided that the repair is carried out in accordance with the Class requirements.
Preventative action/lessons learned	

Case 14: Rudder stock crack		
Ship-Type		Capacity:
Year of build	Vessels age when damage found:	
Location of damage:		
Photo/Sketch of defect/damage		
Description of defect/damage	During rudder inspection it was found that a horizontal crack has developed on the rudder stock (please see the pictures attached) on about ¾ of total perimeter. Crack depth was measured with UT and it varied from15 mm to 20 mm. Rudder stock diameter at the cracked area is 524 mm. The material is forging with carbon content less than 0.23.	
How discovered	During rudder inspection in a dry dock.	
Probable cause of Damage		
Description of Repair	Considering long delivery time of a new rudder stock, the shipyard proposes to repair it by welding.	
Preventative action/lessons learned		

<table>
<tr><td colspan="3">Case 15: Deck Longitudinal Block Joint Welds</td></tr>
<tr><td>Ship-Type</td><td>Tanker</td><td>Capacity: 125,000 DWT T</td></tr>
<tr><td>Year of build</td><td colspan="2">Vessels age when damage found: 7 years</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Location of defect:</td><td colspan="2">Fracture noted in a transverse erection weld in the main deck plating.

</td></tr>
<tr><td>Photo/Sketch of defect</td><td colspan="2">
Internal inspection of the defect 1</td></tr>
</table>

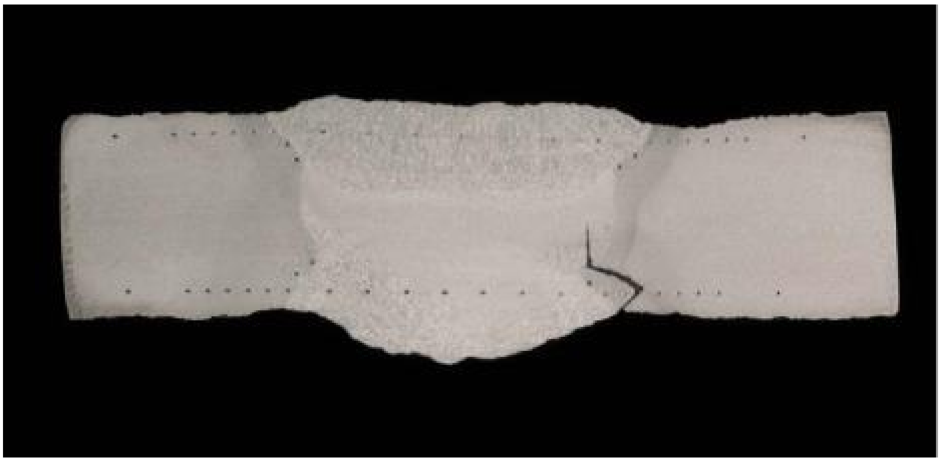
	 Internal inspection of the defect 2  Internal Inspection of the defect 3 The defect was first detected from the crack on the main deck, however following the internal inspection it was noted to have propagated from the construction weld of the bulb profile.
Description of damage	- Through thickness crack found in the deck erection weld during visual inspection by ships staff. Further visual inspection and MPI/ UT carried out to confirm extent of the defects. - Type of weld – Butt erection weld - Plate thickness – Deck 21mm A 36, Bulb Profile 300x12mm A 36
Probable cause of defect	- Samples of the butt weld in deck longitudinals were sent to the Classification Society for further analysis including x-ray, macros and microstructure examination. Examples of the results shown below:

Close up of the weld cap showing defects in the weld caps.



Macrograph showing slag inclusion in the weld root area.

Micrograph of the cavity in the weld root area. A crack was observed from the cavity to the outer surface.

	 A slice through the web of the bulb flat deck longitudinal - The root cause of was found to be a combination of factors originating from poor workmanship. - From the macros it was clear that edge preparation was not in accordance with the WPS. - Due to narrow gap it was not possible to weld properly, resulting in large slag inclusions.
Description of Repair	- Defective welds were gouged and re-welded with suitable edge preparation. Insert repairs carried out where defects had propagated to the base material. - Following completion of repairs MPI and UT carried out.
Preventative action/lessons learned	- Increased level of owner inspection and random inspection to ensure the correct edge preparation and welding practice is implemented. - Increased scope for NDT at new build.

Case 16: Poor piping welds		
Ship-Type	N/A	Capacity:
Year of build	Vessels age when damage found:	
Location of damage:	Piping	
Photo//Sketch of defect/damage	 Fabricated pipe bend – many pieces, many poor welds. 	
Description of defect/damage	- Lack of penetration - Lack of fusion - Pin holes	

	- Poor weld profile
How discovered	- Visual
Probable cause of Damage	- Poor workmanship - Poor design of pipe bend
Description of Repair	- Unknown, but the work has to be re-done. Either gouge and re-weld or new pieces.
Preventative action/lessons learned	- Change in welding procedure. - Training and qualification of welders to be checked. - Design of welded bend to be modified.

Appendix 2
Sample WPS, WPQR, WQTR

ANNEX N AWS D1.1/D1.1M:2010

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☐
PREQUALIFIED __________ QUALIFIED BY TESTING __________
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐

Identification # __________
Revision ______ Date ________ By ________
Authorized by ________ Date ________
Type—Manual ☐ Semiautomatic ☐
Mechanized ☐ Automatic ☐

Company Name __________
Welding Process(es) __________
Supporting PQR No.(s) __________

JOINT DESIGN USED
Type:
Single ☐ Double Weld ☐
Backing: Yes ☐ No ☐
Backing Material:
Root Opening ______ Root Face Dimension ______
Groove Angle: ______ Radius (J–U) ______
Back Gouging: Yes ☐ No ☐ Method ______

POSITION
Position of Groove: ______ Fillet: ______
Vertical Progression: Up ☐ Down ☐

ELECTRICAL CHARACTERISTICS

Transfer Mode (GMAW) Short-Circuiting ☐
Globular ☐ Spray ☐
Current: AC ☐ DCEP ☐ DCEN ☐ Pulsed ☐
Power Source: CC ☐ CV ☐
Other __________
Tungsten Electrode (GTAW)
Size: ______
Type: ______

BASE METALS
Material Spec. __________
Type or Grade __________
Thickness: Groove ______ Fillet ______
Diameter (Pipe) __________

FILLER METALS
AWS Specification __________
AWS Classification __________

TECHNIQUE
Stringer or Weave Bead: __________
Multi-pass or Single Pass (per side) __________
Number of Electrodes __________
Electrode Spacing Longitudinal ______
Lateral ______
Angle ______
Contact Tube to Work Distance __________
Peening __________
Interpass Cleaning: __________

SHIELDING
Flux ______ Gas ______
Composition ______
Electrode-Flux (Class) ______ Flow Rate ______
______ Gas Cup Size ______

PREHEAT
Preheat Temp., Min. __________
Interpass Temp., Min. ______ Max. ______

POSTWELD HEAT TREATMENT
Temp. __________
Time __________

WELDING PROCEDURE

Pass or Weld Layer(s)	Process	Filler Metals		Current		Volts	Travel Speed	Joint Details
		Class	Diam.	Type & Polarity	Amps or Wire Feed Speed			

Form N-1 (Front)

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ANNEX N AWS D1.1/D1.1M:2010

Procedure Qualification Record (PQR) # __________
Test Results

TENSILE TEST

Specimen No.	Width	Thickness	Area	Ultimate Tensile Load, lb	Ultimate Unit Stress, psi	Character of Failure and Location

GUIDED BEND TEST

Specimen No.	Type of Bend	Result	Remarks

VISUAL INSPECTION
Appearance ____________________
Undercut ____________________
Piping porosity ____________________
Convexity ____________________
Test date ____________________
Witnessed by ____________________

Radiographic-ultrasonic examination
RT report no.: __________ Result __________
UT report no.: __________ Result __________

FILLET WELD TEST RESULTS
Minimum size multiple pass Maximum size single pass
Macroetch Macroetch
1. _______ 3. _______ 1. _______ 3. _______
2. _______ 2. _______

Other Tests

All-weld-metal tension test
Tensile strength, psi ____________________
Yield point/strength, psi ____________________
Elongation in 2 in, % ____________________
Laboratory test no. ____________________

Welder's name ____________________ Clock no. __________ Stamp no. __________

Tests conducted by ____________________ Laboratory

Test number ____________________

Per ____________________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in conformance with the requirements of Clause 4 of AWS D1.1/D1.1M, (__________) *Structural Welding Code—Steel.*
(year)

Signed ____________________
Manufacturer or Contractor
By ____________________
Title ____________________
Date ____________________

Form N-1 (Back)

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ANNEX N AWS D1.1/D1.1M:2010

WPS QUALIFICATION TEST RECORD FOR ELECTROSLAG AND ELECTROGAS WELDING

PROCEDURE SPECIFICATION

Material specification ____________
Welding process ____________
Position of welding ____________
Filler metal specification ____________
Filler metal classification ____________
Filler metal ____________
Flux ____________
Shielding gas ______ Flow rate ______
Gas dew point ____________
Thickness range this test qualifies ____________
Single or multiple pass ____________
Single or multiple arc ____________
Welding current ____________
Preheat temperature ____________
Postheat temperature ____________
Welder's name ____________
Guide tube flex ____________
Guide tube composition ____________
Guide tube diameter ____________
Vertical rise speed ____________
Traverse length ____________
Traverse speed ____________
Dwell ____________
Type of molding shoe ____________

TEST RESULTS

Reduced-section tensile test

Tensile strength, psi
1. ____________
2. ____________

All-weld-metal tension test

Tensile strength, psi ____________
Yield point/strength, psi ____________
Elongation in 2 in, % ____________

Side-bend tests

1. ______ 3. ______
2. ______ 4. ______

Radiographic-ultrasonic examination

RT report no. ____________
UT report no. ____________

VISUAL INSPECTION (Table 6.1, Cyclically loaded limitations)

Appearance ____________
Undercut ____________
Piping porosity ____________
Test date ____________
Witnessed by ____________

Impact tests

Size of specimen ______ Test temp ______
Ft·lb: 1. ______ 2. ______ 3. ______ 4. ______
5. ______ 6. ______ Avg. ______
High ______ Low ______
Laboratory test no. ____________

WELDING PROCEDURE

Pass No.	Electrode Size	Welding Current		Joint Detail
		Amperes	Volts	

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in conformance with the requirements of Clause 4 of AWS D1.1/D1.1M, (________) *Structural Welding Code—Steel.*
(year)

Procedure no. ____________ Manufacturer or Contractor ____________

Revision no. ____________ Authorized by ____________

Form N-3 Date ____________

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WELDER, WELDING OPERATOR, OR TACK WELDER QUALIFICATION TEST RECORD

Type of Welder ____________

Name ____________ Identification No. ____________

Welding Procedure Specification No. ____________ Rev ____________ Date ____________

Variables	Record Actual Values Used in Qualification	Qualification Range
Process/Type [Table 4.12, Item (1)]		
Electrode (single or multiple) [Table 4.12, Item (7)]		
Current/Polarity		
Position [Table 4.12, Item (4)]		
Weld Progression [Table 4.12, Item (5)]		
Backing (YES or NO) [Table 4.12, Item (6)]		
Material/Spec.	to	
Base Metal		
Thickness: (Plate)		
Groove		
Fillet		
Thickness: (Pipe/tube)		
Groove		
Fillet		
Diameter: (Pipe)		
Groove		
Fillet		
Filler Metal (Table 4.12)		
Spec. No.		
Class		
F-No. [Table 4.12, Item (2)]		
Gas/Flux Type (Table 4.12)		
Other		

VISUAL INSPECTION (4.9.1)

Acceptable YES or NO _____

Guided Bend Test Results (4.31.5)

Type	Result	Type	Result

Fillet Test Results (4.31.2.3 and 4.31.4.1)

Appearance ____________ Fillet Size ____________

Fracture Test Root Penetration ____________ Macroetch ____________

(Describe the location, nature, and size of any crack or tearing of the specimen.)

Inspected by ____________ Test Number ____________

Organization ____________ Date ____________

RADIOGRAPHIC TEST RESULTS (4.31.3.2)

Film Identification Number	Results	Remarks	Film Identification Number	Results	Remarks

Interpreted by ____________ Test Number ____________

Organization ____________ Date ____________

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in conformance with the requirements of Clause 4 of AWS D1.1/D1.1M, (__________) *Structural Welding Code—Steel.*
(year)

Manufacturer or Contractor ____________ Authorized By ____________

Form N-4 Date ____________

Appendix 3
References

1. “The Welding Handbook for maritime welders”, UNITOR/Wilhelmsen Ships Services, 11th edition, Revision 0.

2. “Rec. No. 47 Shipbuilding and Repair Quality Standard”, IACS, Rev.7, June 2013.

3. “NDT Course Material”, Force Technology, Nesbru, Norway

4. “Lloyd’s Register Rules for the Classification of Ships”, January 2016.

5. www.twi-global.com. 2006. *wet welding repairs*. Available online at: http://www.twi-global.com/technical-knowledge/published-papers/wet-welding-repairs-may-2006/

6. www.twi-global.com. 2009. Friction Stir Welding of Aluminium Alloys. Available online at: http://www.twi-global.com/technical-knowledge/published-papers/friction-stir-welding-of-aluminium-alloys/

7. “The International Safety Guide for Oil Tankers & Terminals” (ISGOTT), Fifth edition, Witherby & Co., Ltd., 2006.

8. DNV GL Class Guideline CG-0051, “Non-destructive testing”, December 2015.

9. DNV GL Rules for the Classification of Ships, Part 2 “Materials and Welding”, January 2016.

10. Course Material - CSWIP Visual Welding Inspector Level 1, TWI Training and Examination Service, Cambridge, United Kingdom.