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FEASIBILITY STUDIES OF THE WELDABILITY OF STRUCTURAL STEELS USED IN THE OFFSHORE ENVIRONMENT

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Abstract

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The rising demand for oil and gas has made it very necessary for the oil and gas industries to explore the offshore. There is a huge resources which is available in the offshore. The search for oil and gas is faced with greater challenges because of the nature of the marine environment as it poses difficult and harsh conditions for the construction of offshore structures. The major problem of the construction of offshore structure is the ability to produce a sound weld that gives the whole structure the structural integrity needed to withstand the harsh environmental conditions. This research work presents the performance of typical offshore steels with improved weldability. The ability of reducing the carbon content of thermo-mechanically rolled steels down to 0.08% makes it possible to achieve good weldability, toughness and strength for high strength steels used in offshore applications. Importantly, the ideal welding procedure should be strictly followed as recommended. The fabrication process is as important as the welding procedure in achieving a sound weld which is free of weld defects such as hydrogen induced cracking, lamellar tearing and solidification cracking. This research work also considers the corrosion as it affects offshore structure and necessary measures to mitigate the problem caused by corrosion.

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Finally I say I dedicate this thesis to my lovely beautiful little daughter Beulah Elohor Omajene. Daddy is saying I love you, you are the joy that keeps me going.

Joshua Emuejevoke Omajene

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List of symbols and abbreviations

σ_{ref}	Reference Stress Level
α	Ferrite
γ	Austenite
A	Elongation
A_{c1}	Lower Critical Temperature
A_{c3}	Upper Critical Temperature
A_{cm}	Upper Critical Temperature
AISI	America Iron and Steel Institute
Al	Aluminum
API	American Petroleum Institute
AWS	American Welding Society
B	Boron
C	Carbon
CALM	Catenary Anchor Leg Mooring
CE	Carbon Equivalent
$C0_2$	Carbon dioxide
Cr	Chromium
Cu	Copper
DIN	German Institute for Standardization

EN	European Standards
FPSO	Floating Production Storage and Offloading
Fe_3C	Cementite
FCAW	Flux Cored Arc Welding
GBS	Gravity Based Structure
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
H	Hydrogen
HAZ	Heat Affected Zone
HD	Hydrogen Content
HHI	Hyundai Heavy Industries Company
I	Welding Current (Amps)
IIW	International Institute of Welding
ISO	International Organization for Standardization
J2	Impact Energy at Testing Temperature of 20 degree Celcius
L	Liquid
MIG	Metal Inert Gas
M_f	Martensite Finish
MMA	Manual Metal Arc
Mn	Manganese
Mo	Molybdenum

M_S	Martensite Start
N	Nitrogen
Nb	Niobium
Ni	Nickel
NL	Normalized
P	Phosphorus
PAW	Plasma Arc Welding
P_{cm}	Carbon Equivalent According to Ito Bessyo
Q	Quenched
Q (kJ/mm)	Heat Input
RA	Roughness Value
S	Sulphur
SAW	Submerged Arc Welding
SC	Subcommittee
SMAW	Shielded Metal Arc Welding
T_{ref}	Reference Temperature (^oC)
t	Thickness
TC	Technical Committee
Ti	Titanium
TIG	Tungsten Inert Gas
TS	Tensile Strength

UNE	Una Norma Espanola (A Spanish Standard)
V	Vanadium
V	Welding Voltage (Volts)
YS	Yield Strength
Z	Plastic Section Modulus (mm^3)

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1 Introduction

The constructions carried out in the offshore are done in the marine environment. The offshore includes warm marine environment and arctic environment. There are several industries which carry out their production in the offshore. Companies such as the oil and gas, shipbuilding, energy companies are those found in the offshore. For the energy companies, construction such as the wind turbine is installed in the offshore. The oil and gas industries have installation such as the oil platform, drilling rig and jack-up. Activities in the offshore are dangerous and so some of the constructions which are to be installed in the offshore are done onshore and installed in the offshore. Some of the activities of the construction both in the offshore and onshore include fabrication and welding. The materials used in the offshore face some problems such as corrosion and ability to weld under water. The fabrication and construction of structures used in the offshore, proper material selection needs to be carried out to achieve proper function and low cost.

The chapter two of this thesis will be discussing the different types of offshore structures and their functions and factors to consider when designing them. The different structural steel grades used for offshore application will be looked into in this chapter also. This Master's thesis will be looking into the welding procedures, the effect of different welding parameters and heat treatment of structural steels in the chapter three of this report. Chapter four of this report will be reviewing consumable used for welding of offshore structural steels. In this chapter, the selection of a proper filler material based on Schaeffler's diagram will be looked into. Chapter five of this report will discuss the various chemical reactions involved in welding processes and the phase transformation of steel. In the chapter six the weldability of structural steel will be analyzed and the factors that affect the weldability of structural steels for offshore application. Finally chapter seven will introduce underwater welding and the challenges faced. The conclusion and summary is discussed in chapter eight of the report.

1.1 The aim of the research work

The research work is aimed at identifying weldable structural steels which are used for welding of offshore construction. The welding processes suitable for welding offshore structural steel steels, and precautions taken to achieve a sound weld at lower production cost.

1.2 Delimitations

This work will focus on the weldability of offshore structures as applicable to oil and gas production. The offshore applications in wind turbines, bridges and ship building are not a major focus of the research work. This work will focus on warm marine environment.

1.3 History of offshore oil and gas exploration

The search for more oil to meet the demands of the world`s consumption of oil led to the offshore drilling in 1896 off the coast of Summerfield in California United States. Just about fifty years later, Kerr-McGee oil industries started their first productive drilling off the coast of Louisiana in water depth of about 6 meter. At this time, steel drilling structures were used as against the wooden drilling structures used in Summerfield. This change in material from wood to steel helped improved the structural integrity for rigs and at lower costs as compared to the life of the well. Companies such as Shell and Texaco were the first to use barge drilling, which is towing small mobile platforms to locations where there is oil drilling prospect.

In the 1980s there was a shift in the oil industries which led deeper water exploration from the shallow water exploration. This was due to the fact that shallow water exploration posed some challenges like seismic limitations and highly gas prone shelf which were not economically viable for shallow water drilling. The first deep water drilling by Shell Oil Company in 1975 was at a water depth of 305 meter or more. Towards the end of the 1980s deep water production was twice that of shallow water and even ultra-deep water production of about 1524 meters is now possible [1].

The Fig. 1 below shows the federal offshore oil production in the Gulf of Mexico from 1984 to 2009.

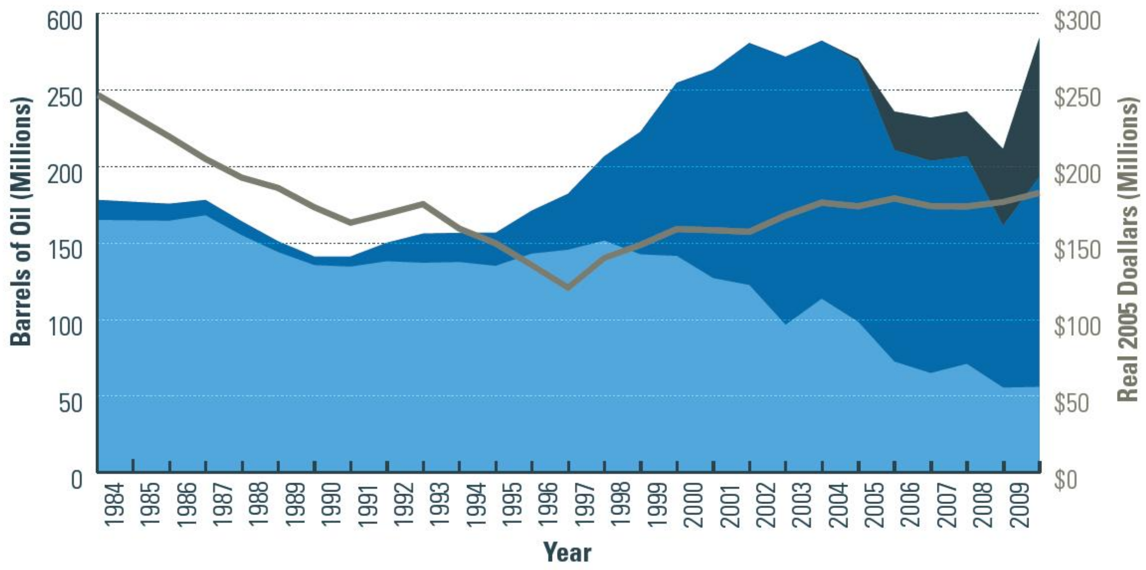


Fig. 1 Federal Offshore Oil production in the Gulf of Mexico [1].

The Table 1 below illustrates the increased production of oil with increased water depth of offshore production. The various colors represent the water depth of the offshore. The black, dark blue and blue colors represent ultra-deep, deep and shallow water depth respectively.

Table 1 Oil production with increased water depth [1].

	Offshore type	Depth of water (meter)	Maximum Barrels of oil (millions)
• (Black)	Ultra Deep	1524 + meter	450
• (Dark blue)	Deep	305-1523 meter	425
• (Blue)	Shallow	0-304 meter	180

2 Offshore structures

Offshore structures are classified into fixed structures and movable structures as shown in Fig. 2 below. Fixed structures are those structures which remain at the location for a long period of time throughout the service life of the structure. The movable structures can be moved from one location to another. The jacket is the most critical structure among the offshore structures because it carries production platform with high payload.

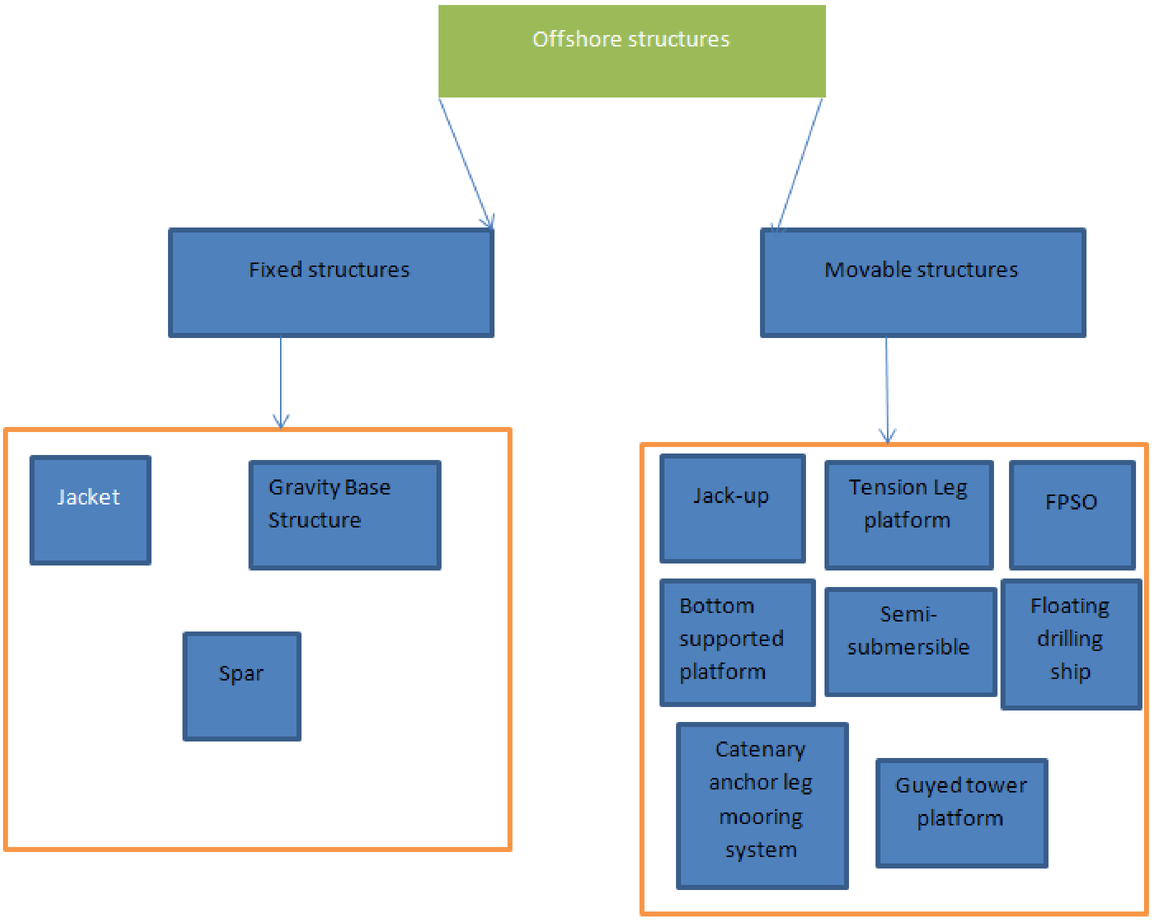


Fig. 2 Classification of offshore structures [2, 3].

The Fig. 3 list the different offshore structures and their functions.

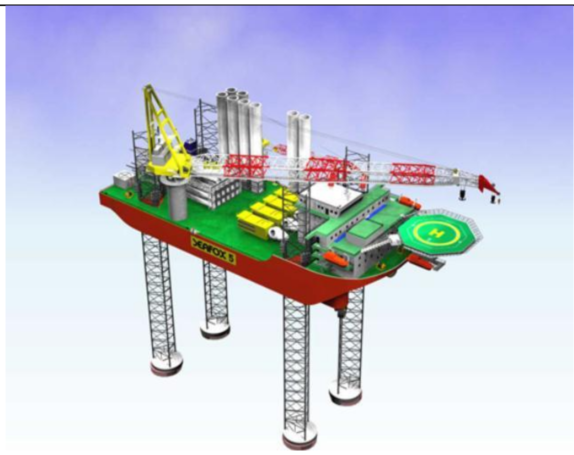
Fig. 3 Offshore structures and functions [4, 5, 6, 7, 8].

Offshore structures	Function	Structures
CALM Buoy	Importation and exportation of oil. Offloading crude oil from FPSOs.	 There are two types of buoy, turntable and turret buoy.
FPSO	Floating production unit for shallow and deep water.	 Can stand in critical environmental conditions.

GBS	It is a base which supports several vertical columns which supports a deck carrying production facilities.	 It is easy to adapt for oil storage since the base is large.
Jacket	It is a stable platform for oil and gas production facilities.	 Can withstand extreme harsh weather conditions. High tensile strength tubular steels with 350-500 MPa. Thickness of tube between 40-90 mm and over 100 mm for large jacket.
Jack-up	They are used mainly as drilling units.	

		They are dynamic sensitive structures when compared to fixed structures. The service loading is due to wave and wind action with variable amplitude and frequency.
Semi-submersible	Used as crane vessels. Used as drilling vessels. Used as production platform and accommodation facilities. The lower hull provides buoyancy for the whole rig. The column gives the rig stability during drilling operations.	 Consist of lower hulls, column, braces, decks and derricks.
Spar	It is a vertical floating platform which supports drilling and production activities simultaneously.	 The family of spar consists of cylindrical, truss and cell spar.

TLP (tension Leg platform)	It is a floating platform that is connected to the seabed by vertical tendons.	 The structure is fully buoyant, and it is restricted below the floating line by mooring elements that are attached in tension to gravity anchors, piles or sea floor.
Drilling vessels	Carries a drilling rig and station keeping equipment.	 It is kept stationary for a long period of time. They carry large pay load than semi-submersible.

Installation vessels	Used for installing equipment such as anchors and subsea structures.	 They bring the equipment on their deck and install it.

2.1 Properties/Requirements

The fatigue life of offshore steel fixed platform structures are affected by some factors such as wind, water wave, ice and snow, seismicity, tides and storm surges, air and sea temperatures, currents, salinity, submarine slide, and marine growth [2].

The requirements for structural steels that are necessary to fulfill offshore applications are as shown in the Table 2 below.

Table 2 Structural steel properties and reasons for these properties [9, 10].

Properties	Reason
Light weight	Having high strength
Durability	Cost reduction because of longer service life
Ductility	Ability to deform after yielding
Shear strength	Prevents sudden fracture
Weldability	Easy to weld and achieve good welds
Young modulus	High resistance to deformation
Impact strength	Low temperature toughness
Toughness	Charpy V-Notch impact energy

The requirements for offshore structures are based on the ISO 19900 prepared by the technical committee ISO/TC 67, petroleum and natural gas industries, subcommittee SC 7, for offshore structure. The ISO requirements are design requirements and assessments of all structures used by petroleum and gas industries. These standards specify the principles which are involved in the fabrication, transportation and installation phase of the construction work of the offshore structures. This standard is applicable to the design of complete structures which include substructures such as topsides structures, vessels hulls, foundations and mooring systems [3, 4].

Environmental Conditions

Offshore structures respond to actions caused by the environmental conditions and this need to be considered in the design phase. These environmental conditions are explained below.

<u>Wind</u>: The actions caused by wind which is characterized by the mean value of its velocity over a period of time based on the elevation above the mean water level is considered in the design phase of the structure [4].

<u>Waves</u>: The characteristics of the sea as a function of the wave height, the period of the wave, the length of time the wave happens and the direction of the wave is considered in the design of the offshore structure [4].

<u>Water depth and sea level variations</u>: The water depth, the size of the low and high tides, the negative and positive storm surges are important factors to determine when designing offshore structures [4].

<u>Currents</u>: Current is determined in terms of the magnitude and direction of their velocity. It is also determined by the variation of water depth and how often it varies [4].

<u>Marine growth</u>: The marine growth should be considered so as to device cleaning means during the platform life. The marine growth is defined by their thickness, density and roughness [4].

Ice and snow: Regions with ice and snow should have consideration of the accumulation of snow on horizontal and vertical surfaces thickness and density [4].

Temperature: Temperatures are important to the design of offshore structures because the air and sea temperatures affect the characteristic properties of the material. The maximum, average and minimum air and sea temperature at the location is considered.

2.2 Structural steel type/ grades used in offshore

The offshore industries are concerned about materials applications which are suitable for offshore structures with high weldability. This affects the structural integrity of the structure during the service life of the structures. A proper selection of materials with characteristics that can fulfill the requirements for offshore application of great importance to the offshore industries. Failure of structures can occur as a result of using materials which cannot fulfill these requirements. The steel types for offshore applications are listed in Table 3 below.

Table 3 Steel type for offshore application.

Steel type	UNE-EN Standard	Grade	Type
Non-alloyed, hot rolled steel	UNE-EN 10025-2	JR, JO, J2, K2	S235, S275, S355
Weldable fine-grained steel in normalized condition	UNE-EN 10025-3	N, NL	S275, S355, S420, S460
Thermo-mechanical rolled, weldable fine-grained steel	UNE-EN 10025-4	M, ML	S275, S355, S420, S460
Steel with improved atmospheric corrosion resistance (weathery steel)	UNE-EN 10025-5	JO, J2, K2	S235, S355
Steel of high yield strength, in quenched and tempered condition	UNE-EN10025-6:2007+A7	Q, QL, QL1	S460

Where

J and K represent impact strength for structural steels corresponding to 27 and 40 Joules.

R, 0, and 2 are testing temperatures.

L is the specified minimum Charpy V-notch values at test temperature not lower than -50^{o}C.

The letter G is followed by a maximum of two digits characterizing and indicating the steel grade within the groups 1, 2 or 3 as per table 4 of EN 10225 for G1-G10. For G11 and upwards is the steel grade within the groups 1, 2, or 3 as per table 7 of EN 10225. Where G1-G6 within the EN 10225, this steels are designated as a group 1 steels. These steels are substantially modified and have enhanced through thickness ductility and impact values at -40^{o}C. The G7 are designated as group 2 steels. While the G8-G10 are designated as group 3 steels.

2.2.1 S355G7 offshore steel plate

This steel has good tensile and yield strength properties. It can be supplied in the normalized (N) or thermo-mechanically (M) rolled form. The weldability of this steel is good. The Tables 4 and 5 show the chemical compositions and mechanical properties respectively of S355G7 steel in the thermo-mechanically rolled condition.

Table 4 Chemical properties of S355G7+M steel [5].

S355G7+M Chemical composition							
Grade	The element maximum (%)						
	C	Si	Mn	P	S	Al	N
S355G7+M	0.14	0.15-0.55	1.0-0.01	0.02	0.01	0.0055	0.01
	Nb	V	Ti	Cu	Cr	Ni	Mo
	0.04	0.06	0.025	0.3	0.25	0.5	0.08

Table 5 Mechanical properties of S355G7+M steel [5].

S355G7+M Mechanical properties							
Grade		Mechanical property			Charpy V impact test		
	Thickness	Yield	Tensile	Elongation	Degree	Energy 1	Energy 2
S355G7+M	mm	Min MPa	MPa	Min %	-40	J	J
	t≤50	355	470-630	22%		50	50
	50<t≤63	355	470-630	22%		50	50
	63<t≤100	325	490-630	22%		50	50
Note: Energy 1 is transverse impact test, Energy 2 is longitudinal impact test							

2.2.2 S420G1 offshore steel plate

The steel can be delivered quenched (Q) or thermo-mechanically (M) rolled. This steel has good yield and tensile strength and is used for offshore platforms and oil rigs. This steel has improved weldability. The chemical composition and mechanical properties of S420G1 steel are shown in Tables 6 and 7 respectively.

Table 6 Chemical properties of S420G1 steel plate [6].

S420G1 Chemical composition								
Grade								
	C	Si	Mn	P	S	Al	N	
S420G1	0.14	0.15-0.55	1.65	0.02	0.01	0.015-0.055	0.01	
	Nb	V	Ti	Cu	Cr	Ni	Mo	Nb+V
	0.04	0.08	0.025	0.3	0.25	0.5	0.08	0.09

Table 7 Mechanical properties of S420G1 steel plate [6].

Grade	Mechanical properties (min) unless stated							
	Tensile strength		Yield strength					Elongation
	Thickness (mm)		Thickness (mm)					A
	≤40	40<t≤100	≤16	16<t≤40	40<t≤63	63<t≤80	80<t≤100	%
S420G1+M	500/660	480/640	420	400	390	380	380	19
S420G1+Q	500/660	480/640	420	400	390	380	380	19

2.2.2 S460G1 offshore steel plate

The delivery conditions for this steel can be in the quenched (Q) or thermo-mechanically (M) rolling. This steel has high yield and tensile strength and good weldability.

Used in fixed offshore structures such as

- Oil rigs
- Service platforms

The chemical composition and mechanical properties of S460G1 are shown in Tables 8 and 9 respectively.

Table 8 Chemical composition of S460G1 [7].

S460G1 Chemical composition								
Grade								
	C	Si	Mn	P	S	Al	N	
S460G1	0.14	0.15-0.55	1.65	0.02	0.01	0.015-0.055	0.01	
	Nb	V	Ti	Cu	Cr	Ni	Mo	Nb+V
	0.04	0.08	0.025	0.3	0.25	0.7	0.25	0.09

Table 9 Mechanical properties of S460G1 [7].

SG460G1 Mechanical properties						
Thickness for all grades (mm)	≤16	>16≤25	>25≤40	>40≤63	>63≤80	>80≤100
Yield strength MPa	460	440	420	415	405	400
Tensile strength MPa	540/700	530/690	520/680	515/675	505/665	500/660
Elongation A (%)	17					
Impact energy	60 J at -40^{o}C					

2.2.4 S355G8 offshore steel plate

This steel has good tensile and yield strength and can be delivered in the following conditions.

- Normalized (N) condition
- Thermo-mechanically rolled (M) condition

It is used in the construction of structures and platforms. This steel has good weldability. The Tables 10 and 11 shows the chemical composition and mechanical properties respectively of S355G8 steel.

Table 10 Chemical composition of S355G8 [8].

S355G8 Chemical composition								
Grade								
	C	Si	Mn	P	S	Al	N	
S355G8	0.14	0.15-0.55	1.0-1.65	0.02	0.007	0.015-0.055	0.01	
	Nb	V	Ti	Cu	Cr	Ni	Mo	Nb+V
	0.04	0.06	0.025	0.3	0.25	0.5	0.08	0.06

Table 11 Mechanical properties of S355G8 [8].

Grade	Mechanical properties (min) unless stated								
	Tensile strength		Yield strength						Elongation A
	Thickness (mm)		Thickness (mm)						
	≤100	>100	≤16	16<t≤25	25<t≤40	40<t≤63	63<t≤100	100<t≤150	%
S355G8+M	470/630	-	355	355	345	355	325	-	22
S355G8+N	470/630	460/620	355	355	345	335	325	320	22

2.2.5 European Standard EN 10225:S355 Grades

This standard specifies the requirements for weldable structural steels which are used for the fabrication of fixed offshore structures. The steels are in the form of plates, sections, and open sections [9]**.** The Tables 12 and 13 show the chemical composition and mechanical properties of the S355 steel grades respectively.

Table 12 Chemical Composition of EN 10225:S355 grades [9].

S355G1	Chemical composition, CE=0.43						
Grade							
	C	Si	Mn	P	S	Al	N
S355G1	0.20	0.50	0.9-1.65	0.035	0.030	0.02	0.030
	Nb	V	Ti	Cu	Cr	Ni	Mo
	0.05	0.12	0.030	0.35	0.30	0.50	0.10
S355G4	Chemical composition, CE=0.43						
Grade							
	C	Si	Mn	P	S	Al	N
S355G4	0.16	0.50	1.60	0.035	0.030	0.02	0.015
	Nb	V	Ti	Cu	Cr	Ni	Mo
	0.05	0.10	0.050	0.35	-	0.30	0.20

S355G11 Chemical composition, CE=0.43

Delivered also in the thermo-mechanical rolled condition and normalized condition as open sections

Grade							
	C	Si	Mn	P	S	Al	N
S355G11	0.14	0.55	1.65	0.025	0.015	0.015-0.055	0.012
	Nb	V	Ti	Cu	Cr	Ni	Mo
	0.04	0.06	0.025	0.025	0.015	0.50	0.08

S355G12 Chemical composition, CE=0.43

Delivered also in the thermo-mechanical rolled condition and normalized condition as open sections

Grade							
	C	Si	Mn	P	S	Al	N
S355G12	0.14	0.55	1.65	0.02	0.007	0.01-0.055	0.012
	Nb	V	Ti	Cu	Cr	Ni	Mo
	0.04	0.06	0.025	0.3	0.25	0.50	0.08

Table 13 Mechanical properties of EN 10225:S355 Grades [9].

Grades	Minimum yield strength (MPa)				TS (MPa) YS/TS	Max YS:TS ratio	Min Elong (5.65 sqrt s_o (%)	Min ave Charpy V (J)			Z properties	
	≤ 16 mm	>16≤20mm	>20≤40mm	>40≤63mm				Orienta-tion	-20°C	-40°C	Min ave RA (%)	Min Ts (MPa)
S355G1	355	345	345[1]	-	470/630	0.87	22	long	50	-	-	-
S355G4 S355G4+M	355	345	345[1]	-	450/610	0.87	22	Long	50	-	-	-
S355G11 S355G11+M	355	345	345	335	460/620	0.87	22	Long	-	50[2]	-	-
S355G12 S355G12+M	355	345	345	335	460/620	0.87	22	long	- -	50[2] 50[2]	35[4]	368[4]

Where

Z is the plastic section modulus which is an essential property for steel design. It is used for materials where plastic behavior is dominant.

1. $\leq$ 25 mm.
2. $\leq$ 25 mm, test at -20^{o}C.
3. Transverse impact optional.
4. Through thickness tensile testing optional.

3 Welding procedures

3.1 Effect of welding parameters

The main welding parameters such as welding current, welding speed and welding voltage are explained as follows.

Welding current**:** It is a function in the arc welding process which determines the rate at which the electrode burns off, the fusion depth and geometry of the weld [10].

Welding speed**:** This is the rate at which the electrode travels along the seam. Maximum penetration is achieved at an optimum speed. High welding speed and constant voltage and current will lead to a reduced bead width [10].

Welding voltage**:** A higher welding voltage will result in a flat, low penetrating and wider weld. The welding voltage is a function of the potential difference between the surface of the molten pool and the tip of the welding wire [10].

3.2 Pre- heating

The base metal to be welded is heated up either fully or at the area around the joint to a specific temperature. This process may be continued during the welding process, however the preheat temperature is sufficient to maintain the required temperature throughout the welding process [11]. The Table 14 below shows a general application guide for the pre heating requirements for different situations and in many cases it is recommended that the interpass temperature should be maintained below 250^{0}C [12]. The assumptions for using the guide in the Table 14 below are

- The weld is a fillet weld with combined joint thickness of 3t which is $t_1+t_2+t_3$

  as shown in the Fig. 4 below.

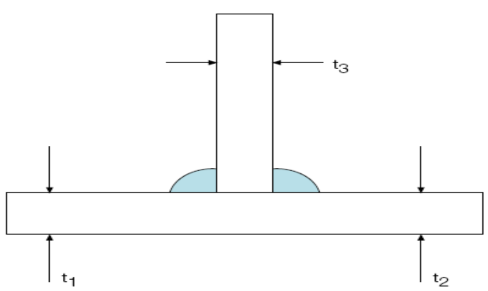


Fig. 4 Combined joint thickness $t_1+t_2+t_3$

- Consumable hydrogen level is 5 ml/100g

Table 14 Preheat recommendation for the avoidance of HAZ cracking [12].

			Heat input (kJ/mm)						
Grade	t(mm)	CE/wt%	0.8	1.0	1.5	2.0	2.5	3.5	5.0
	t≤20	0.32	30						
	20<t≤65	0.35	50	35	Room temperature				
S355N	t≤40	0.39	75	65	35	Room temperature		This heat input range is not applicable	
	40<t≤120	0.39	75	65	35				
S420Q/S450Q/S460 Q	6≤t<16	0.38	55	40	Room temperature				
	16≤t<30	0.34	45	30					
	30≤t<60	0.37	60	45					
	40≤t<60	0.38	60	45					
	60≤t≤100	0.40	70	55	25				

The importance of preheating to make the parent metal suitable for welding operation are as follows [13].

- Slowing the cooling rate
- Increasing weld metal fusion
- Removal of moisture
- Reduction of weld distortion and shrinkage stresses

3.3 Heat input

The heat supplied by the welding process which affects the cooling rate and the weld metal microstructure is the heat input. The heat input affects the toughness of the weld metal as well as the weld bead size. An increase in the weld bead size leads to a corresponding increase in the heat input and slower cooling rate [22, 23].

The heat input Q can be calculated with the formulae Eq. 1 below [14].

$$Q=\frac{k\times U\times I\times 60}{v\times 1000} \qquad \text{(Eq. 1)}$$

Where

U= Voltage (V)

I= Current (A)

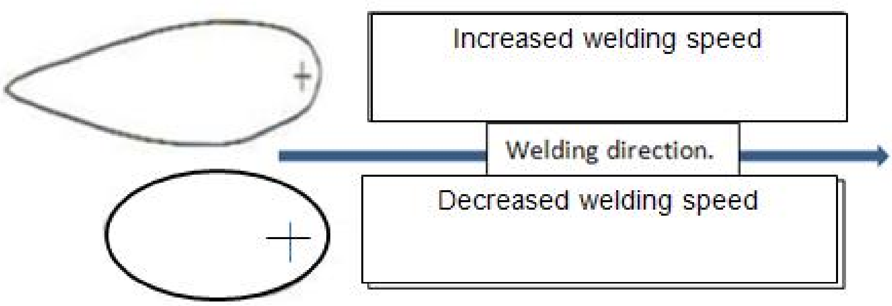
v= Welding speed (mm/min)

k= Thermal efficiency

The thermal efficiency for different welding processes are [14].

SMAW	0.8
GMAW, all types	0.8
SAW	1.0
GTAW	0.6

The shape and size of the weld pool is significantly affected by the the welding speed. The figure 5 below illustrates the effect of and welding speed.



I

Fig. 5 Effect of welding speed.

The Fig. 6 below shows the effect of heat input on a weld joint.

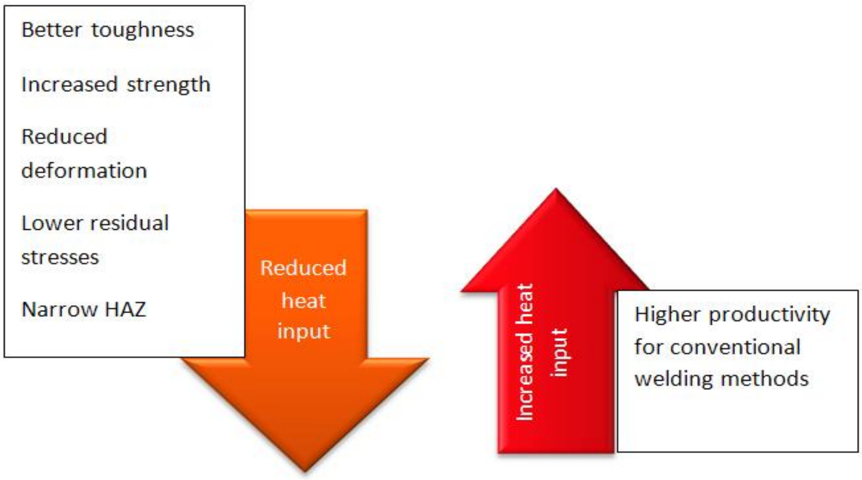


Fig. 6 Effect of heat input on a weld joint [14].

The recommended upper limit of heat input is shown in the Table 15 below.

Table 15 Recommended upper limit of heat input [12].

Delivery condition	Maximum recommended heat input (kJ/mm)
Normalised	3.5
Thermomechanically rolled	5.0
Quenched and tempered	3.5

Offshore structural steels have a wider working range comparing with traditional steels and this can be seen from the Fig. 7 below.

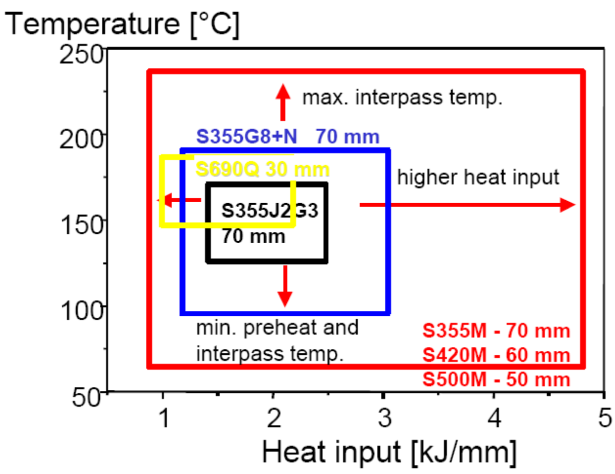


Fig. 7 Heat input range of offshore steels [15].

3.4 Heat treatment processes

Steels can be heat treated to alter the microstructure and properties. This is done by heating and cooling phase transformation of the microstructure of a solid state. The process of heat treatment is either thermal or thermo-mechanical which alters the structure alone or structure and shape respectively. Quenching at a fast cooling rate in water or in oil producing non equilibrium structures.

Heating process involve subjecting the steel to a time-temperature cycle in which the following stages such as heating, holding at a certain temperature also called soaking and finally cooling [16].

The Fig. 8 below shows the temperature range for the heat treatment of carbon steel for different range of carbon content.

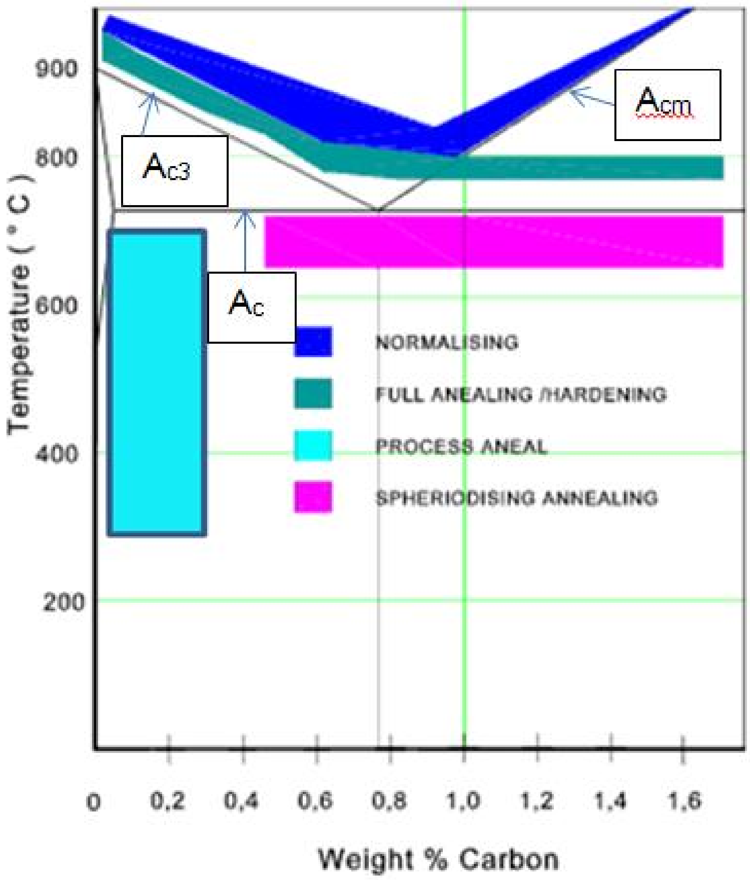


Fig. 8 Temperature range for the heat treatment of carbon steel [17].

Hardening

Steels are hardened by heating them above the A_{c3} transformation temperature and holding it for a sufficient long time to achieve uniform temperature and solution of carbon in the austenite and subsequently fast cooled. The austenite is transformed to martensite on cooling through the M_s to M_f range. The maximum hardness that can be achieved depends on the carbon content [16].

Annealing

Annealing is aimed at producing softening, alter the mechanical or physical property and produce a desirable microstructure. Annealing is slow cooling rate in air or in furnace producing equilibrium structures. Annealing is divided into full annealing and process annealing. Full annealing is a process of softening steel by heating it above the A_{c3} and then subsequent cooling below the Ac_1 temperature. Higher carbon content can be fully annealed at a lower temperature than lower carbon content. Process annealing which is also known as stress relieving is the process applied to low carbon steel up to 0.25% carbon content. This is done to soften the steel for further cold working. The steel is heated below the A_{c1} temperature and this type of annealing will cause recrystallization and softening of the cold worked ferrite grain but does not affect the cold pearlite grain [16].

Tempering

This is also called drawing which is the reheating of hardened martensitic or normalized steel to a temperature below the critical Ac_1 temperature. Steels need to be tempered after hardening to avoid cracks. Carbon steels and alloy steels should be tempered as soon as they cool down to 40 ^{o}C-60 ^{o}C. The steels should be tempered before they reach this temperature because some steels martensite formation temperature is quite low and there may be presence of untransformed austenite [16].

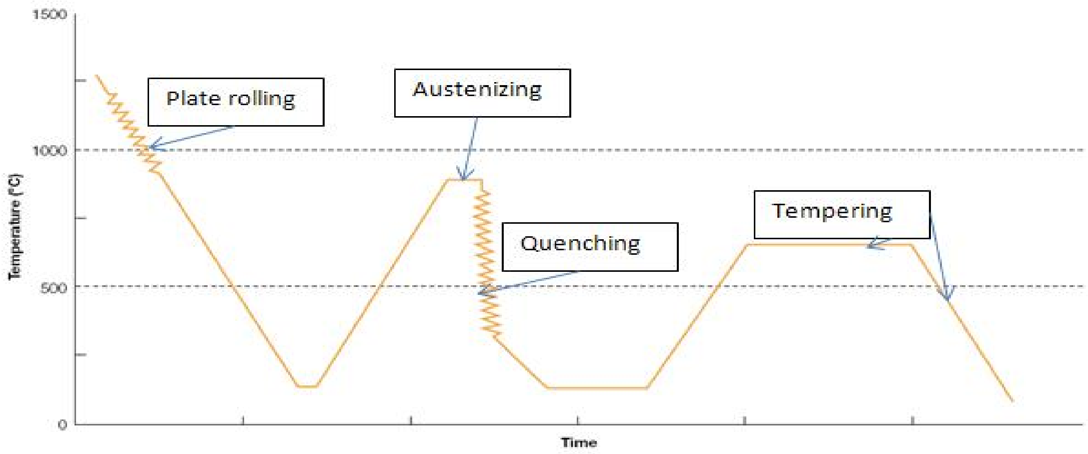


Fig. 9 Time-temperature curve for tempering [12].

Normalizing

Normalizing improves the toughness and yield strength because of the small grain size formed. The steel alloy is soaked at a temperature between 30 ^{o}C -50 ^{o}C above the Ac_3 or Acm in the austenite range depending on the carbon content. It is then cooled in the air after soaking. During normalizing, the grain is refined and there is a transformation of γ to α upon heating [16].

Spherodizing

The heating and cooling of steels to produce a round or globular carbide in a matrix of ferrite. This is done by a long heating below the Ac1 temperature. The initial structure affects the rate of spherodizing. A finer pearlite achieves spherodization more easier. This heat treatment process is usually applied to steels with high carbon content up to 0.6% and more. Spherodizing is done to improve machinability [16].

4 Filler materials used for offshore structural steels

Some problems associated with the weld metal can be solved by changing the electrode or other consumables. It is common to use filler metal in fusion welding processes [18]. A proper selection of filler metal or electrode is essential in achieving a sound weld. And this are based on the consideration if the weld metal can be free from defect or the weld metal is compatible with the base metal and the properties are good [19]. The characteristics to consider are as follows

- Chemical composition of the electrode.
- Dilution of the base metal.
- Protection method, either flux or shielding gas.
- Solidification of weld pool, cooling rate and transformation.

The selection of proper filler metal is based on matching the base metal and weld metal service properties. The use of a filler metal with almost or same chemical characteristics as the base metal is not a guarantee to have a desired result because the microstructure of the weld metal are different from the base metal. The use of a filler metal with identical chemical composition as the base metal in fusion welding for most carbon and alloy steels will result in a weld metal with higher strength and lower toughness than the base metal. The final chemical composition of the base metal and the filler metal can be determined by the dilution formulae which depend on the amount of melted base metal and amount of added filler metal [19]. The dilution formulae Eq. 2 is stated below as

$$\text{Dilution, \%} = \left(\frac{\text{Weight of parent metal melted}}{\text{Total weight of fused metal}}\right) \times 100 \qquad \text{(Eq. 2)}$$

Studies have been conducted to determine the effect of combining alloy additions and the most recognized amongst these studies is by Schaeffler in 1960`s. The Schaeffler diagram is used to predict the weld metal composition. It can be used to determine the most suitable electrode for welding depending on the base metal constituent. To determine the weld metal composition, the chromium and nickel equivalents expected for a particular weld joint is calculated. The weld is a mixture of the base metal and the weld electrode. The percentage of dilution of a particular welding process is a parameter to determine the percentage of the weld metal. For example 30% dilution is expected using SMAW process of joining A312 TP 304L austenitic stainless steel pipe to A106 Gr. B carbon steel pipe. In this case the weld metal is 70% of the electrode composition with 15% A312 TP 304L composition and 15% A106 Gr. B as can be seen in the Fig.10 below [20].

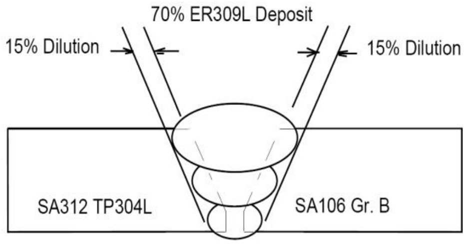


Fig. 10 Dillution effect [20].

In this case, the choice of chosing either E308L or E309L can be determined as thus

Table 16 Chemical composition of electrode and steel pipe [20].

Material	Cr (%)	Ni (%)	C (%)	Mo (%)	Mn (%)	Si (%)
E309L (electrode)	24	12	0.04	0.7	3	0.7
E308L (electrode)	19	9	0.04	0.7	2	0.7
Tp 304L (steel pipe)	19	8	0.04	-	1	-
A106-B (steel pipe)	0.03	0.02	0.15	0.01	1	0.4

The selection of the electrode can be made by reading from the Schaeffler diagram if the Chromium equivalent and Nickel equivalents of the choice electrode are known. The formulae for calculating the chromium equivalent and Nickel equivalent is shown in Eq. 3 and 4 below.

For E308L electrode

Cr equivalent = % Cr + % Mo + 1.5×%Si + 0.5×%Nb (Eq. 3)

70% electrode composition = 0.7(% Cr + % Mo + 1.5×%Si + 0.5×%Nb)

15% Tp 304L pipe composition=0.15(% Cr + % Mo + 1.5×%Si + 0.5×%Nb)

15% A106-B pipe composition=0.15(% Cr + % Mo + 1.5×%Si + 0.5×%Nb)

Where Nb = 0

Cr equivalent for E308L = 0.7(% Cr + % Mo + 1.5×%Si + 0.5×%Nb) + 0.15(% Cr + % Mo + 1.5×%Si + 0.5×%Nb) + 0.15(% Cr + % Mo + 1.5×%Si + 0.5×%Nb)

Ni equivalent = %Ni +30×%C +0.5× %Mn (Eq. 4)

70% electrode composition = 0.7(%Ni +30×%C +0.5× %Mn)

15% Tp 304L pipe composition=0.15(%Ni +30×%C +0.5× %Mn)

15% A106-B pipe composition=0.15(%Ni +30×%C +0.5× %Mn)

Ni equivalent for E308L = 0.7(%Ni +30×%C +0.5× %Mn) + 0.15(%Ni +30×%C +0.5× %Mn) + 0.15(%Ni +30×%C +0.5× %Mn)

The same calculation is done for the E309L electrode and the result is shown in Table 17 below

Table 17 Chromium and Nickel equivalents for 70% electrode chemistry and 15% each for base metal chemistry [20].

Electrode	Cr	Ni
E308L	17.1	9.9
E309L	20.6	12.1

From the Schaeffler diagram is shown in Fig. 11 below. The weld deposit structure for the E308L electrode is austenite, martensite and 2% ferrite. The weld deposit structure for the E309L electrode is austenite and 7% delta ferrite. The choice of electrode therefore will be the E309L electrode because the martensite in the E308L electrode will have a cracking tendency [20].

The Schaeffler diagram is shown Fig. 11 below.

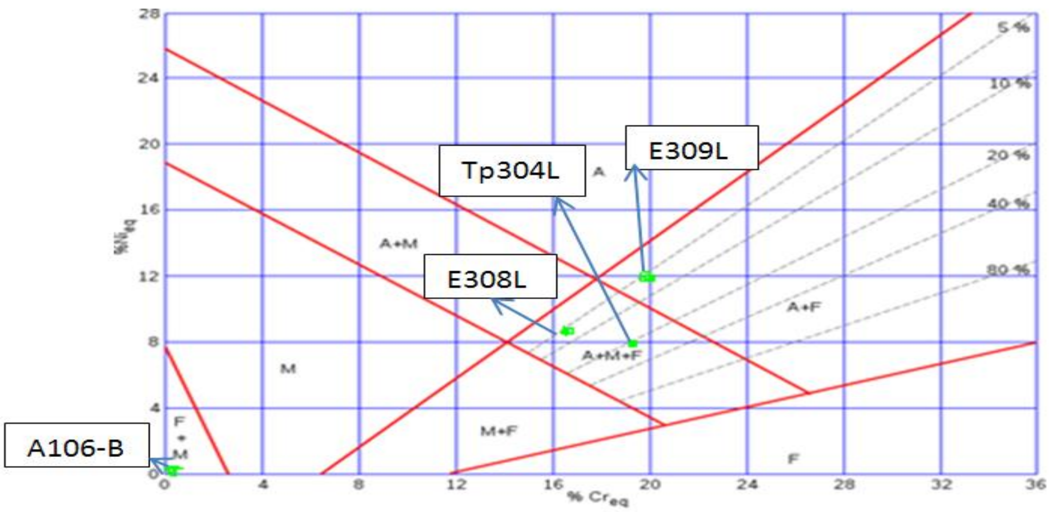


Fig. 11 Schaeffler Diagram **[20]**.

Welding Consumables for offshore application

The solutions to offshore application in terms of welding consumable have received a great attention for example from BÖHLER WELDING which includes welding consumable for welding mild steels, high strength low alloy steels, nickel based steels, duplex and super duplex steels, standard and super austenitic stainless steels, nickels and titanium alloys and copper base steels. These welding consumables are suitable for welding pipelines, subsea templates, manifolds and all other offshore installation from wellhead to topside [21]. Based on the chemical composition and mechanical properties of electrodes, proper electrode selection can be made depending on the welding process to be used and the material to be welded. Some of the consumables available for mild steels, API pipe steels and high strength steels for offshore application are shown in the Tables 18, 19, 20, and 21 below.

Table 18 BÖHLER selection guide for offshore welding consumables [21].

	Base metal UNS/ASTM AISI/API	SMAW	FCAW	GTAW	GMAW	SAW
Mild steel Re < 380MPa	A106Gr.B	FOX EV 50	HL 51-FD	EML	-	EMS 2 + BB 400
API Pipe steels	API 5L-X52	FOX EV pipe FOX BVD 85		EML 5	SG 3-P	EMS 2 +BB 400
	API X56-X65	FOX BVD 85 FOX BVD 90 M	Ti 60-FD	I 52 Ni	SG 3-P(max. X60) K-Nova Ni	EMS 2 +BB 400
	API X60-X65	FOX EV 60 pipe FOX BVD 85		I 52 Ni	K-Nova Ni	
	API X70	FOX EV 70 pipe FOX BVD 90			K-Nova Ni	
High strength steels Re > 380 MPa	S420-S460	FOX EV 60	Ti 60-FD	EML 5	K-Nova Ni	3NiMo1-UP+BB420TTR
	S500	FOX EV 65		I 52 Ni	K-Nova Ni	
	AISI 4130	FOX NiMo 100			NiMo 1-IG	3NiMo1-UP+BB420TTR

	S690Q	FOX EV 85		I 52 Ni (root pass only)	NiCrMo2.5-1G	3NiMo1-UP+BB420TTR 3NiCrMo2.5-UP+BB420TTR BB420TTRC

Table 19 BÖHLER consumables for Mild steels [21].

BÖHLER Standard AWS EN	Welding process	chemical composition (%)	Mechanical properties	Size (mm)	Characteristics and applications
FOX EV 50 E7018-1 H4R E42 5 B 42 H5	SMAW	C 0.07 Si 0.5 Mn 1.1	Re 490MPa Rm 560 MPa A5 27% Cv 190J/+20 ^{o}C 100J/-50 ^{o}C	2 2.5 3.2 4 5 6	Good impact strength at low temperature. Basic coated electrode are used for high quality welds for all position but not used for vertical down position. The electrode coating has good resistance to moisture. It has low hydrogen content approximately less than or equal to 5 ml/100g.

EML 5 ER 70 S-3 W 46 5 W2Si	GTAW	C 0.1 Si 0.6 Mn 1.2	Re 500MPa Rm 600 MPa A5 26% Cv 220J/+20 ^{o}C ≥47J/-50 ^{o}C	1.6 2.0 2.4 3.0	It is used for GTAW welding of rod with high requirement for impact strength down to -50 ^{o}C. Used for components that will be galvanized after welding. It is used for high quality welds.
HL 51-FD E70 C-6M H4 T46 4 MM 2 H5	FCAW	C 0.07 Si 0.7 Mn 1.5	Re 490MPa Rm 610 MPa A5 27% Cv 130J/+20 ^{o}C 70J/-46^{0}C (80% Ar/20% $C0_2$)	1.2 1.6	It induces a steady spray arc droplet transfer with a minimum spatter being formed. Used for automatic and semi-automatic welding of mild and fine grained constructional steels. There is no need for interlayer cleaning because of the formation of little oxide layer. The hydrogen content is less than or equal to 5 ml/100g. It is good for fillet welds.

EMS 2 +BB 400 F7A4-EM12K S 42 4 AB S2Si	SAW	C 0.07 Si 0.35 Mn 1.5	Re 420MPa Rm 500 MPa A5 22% Cv 100J/+20 ^oC ≥47J/-40 ^oC	2 2.5 3 3.2 4	It is a wire/flux combination used for welding general purpose structural, fine grained and pipe steels. It has a low Si and moderate Mn pickup. It is suitable on AC and DC.

Table 20 BÖHLER consumables for high strength steels [21].

BÖHLER Standard AWS EN	Welding process	Chemical composition (%)	Mechanical properties	Size (mm)	Characteristics and applications
FOX EV 60 E8018-C3 H4 R E46 6 1 Ni B 42 H5	SMAW	C 0.07 Si 0.4 Mn 1.15 Ni 0.9	Re 510MPa Rm 610 MPa A5 27% Cv 180J/+20 ^oC 110J/-60^0C	2.5 3.2 4 5	It is a Ni-alloyed basic coated electrode with low hydrogen content of ≤ 5 ml/100g. It has a good operating characteristic in all welding positions except vertical down position. It has high toughness properties as low as -60^{0}C.

FOX EV 65 E8018-G H4 R E55 6 1 Ni B 4 2 H5	SMAW	C 0.06 Si 0.3 Mn 1.2 Ni 0.8 Mo 0.35	Re 600MPa Rm 650 MPa A5 25% Cv 180J/+20 ^{o}C 80J/-60^{0}C	2 2.5 3.2 4 5	It is a NiMo-alloyed basic coated electrode with low hydrogen content of ≤ 5 ml/100g used for welding high tensile strength steels.
EML 5 ER 70 S-3 W 46 5 W2Si	GTAW	C 0.1 Si 0.6 Mn 1.2	Re 500MPa Rm 600 MPa A5 26% Cv 220J/+20 ^{o}C ≥47J/-50^{0}C	1.6 2.0 2.4 3.0	It is used for GTAW welding of rod with high requirement for impact strength down to -50^{0}C. Used for components that will be galvanized after welding. It is used for high quality welds.
NiCrMo2.5-IG ER110 S-G G69 6 M Mn3Ni2.5CrMo	GMAW	C 0.08 Si 0.6 Mn 1.4 Cr 0.3 Mo 0.4 Ni 2.5	Re 810MPa Rm 910 MPa A5 18% Cv 130J/+20 ^{o}C ≥47J/-60^{0}C (80% Ar/20% $C0_2$)	1 1.2	It is a medium alloyed GMAW wire. It is used for welding high strength fine grained constructional steels that have requirements of low temperature toughness as low as -60^{0}C.

Table 21 BÖHLER consumables for API pipe steels [21].

BÖHLER Standard AWS EN	Welding process	Chemical composition (%)	Mechanical properties	Size (mm)	Characteristics and applications
FOX EV pipe E 7016-1 H4 R E 42 6 4 B 12 H5	SMAW	C 0.06 Si 0.6 Mn 0.9 Ni 0.17	Re 470MPa Rm 560 MPa A5 29% Cv 170J/+20 ^{o}C 55J/-46^{0}C	2.0 2.5 3.2 4	It is a basic coated electrode suitable for vertical up welding of root passes. It uses a D.C negative polarity. It has a low hydrogen content of $\leq$ 5 ml/100g. It is suitable for filler and cover passes for pipes, tubes and plates using D.C. positive polarity. It has good impact properties for as low as -46^{0}C.
FOX EV 60 pipe E8016-G H4 R E 50 4 1 Ni B 1 2 H5	SMAW	C 0.07 Si 0.6 Mn 1.2 Ni 0.9	Re 550MPa Rm 590 MPa A5 26% Cv 170J/+20 ^{o}C 110J/-46^{0}C	2.5 3.2 4	It is a basic coated electrode suitable for vertical up welding of root passes using D.C. negative polarity. It is suitable for filler and cover passes for pipes, tubes and plates using D.C.

					positive polarity and also A.C. It has a low hydrogen content of ≤ 5 ml/100g. It has good impact properties for as low as -46^{0}C.
EML 5 ER 70 S-3 W 46 5 W2Si	GTAW	C 0.1 Si 0.6 Mn 1.2	Re 500MPa Rm 600 MPa A5 26% Cv 220J/+20 ^{o}C ≥47J/-50^{0}C	1.6 2.0 2.4 3.0	It is used for GTAW welding of rod with high requirement for impact strength down to -50^{0}C. Used for components that will be galvanized after welding. It is used for high quality welds.
I 52 Ni ER 80S-Ni1 W 3Ni1	GTAW	C 0.07 Si 0.7 Mn 1.6 Ni 0.9	Re 500MPa Rm 600 MPa A5 25% Cv 150J/+20 ^{o}C 90J/-50^{0}C	1.6 2.0 2.4	It is a Ni-alloyed GTAW rod used for welding offshore pipe. It is used for high integrity work applications. It has a high impact toughness as down to -50^{0}C

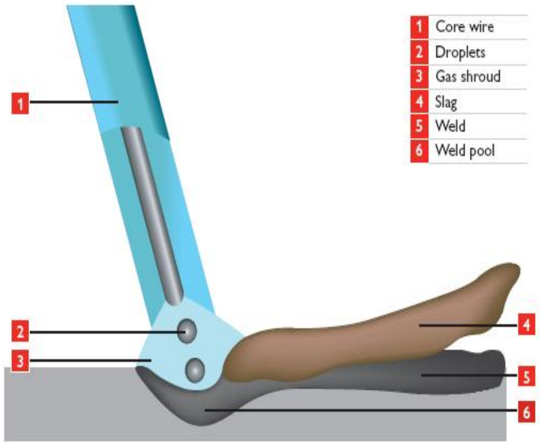
EMS 2 +BB 400 F7A4-EM12K S 42 4 AB S2Si	SAW	C 0.07 Si 0.35 Mn 1.5	Re 420MPa Rm 500 MPa A5 22% Cv 100J/+20 ^{o}C ≥47J/-40^{0}C	2 2.5 3 3.2 4	It is a wire orflux combination used for welding general purpose structural, fine grained and pipe steels. It has a low Si and moderate Mn pickup. It is suitable on AC and DC.

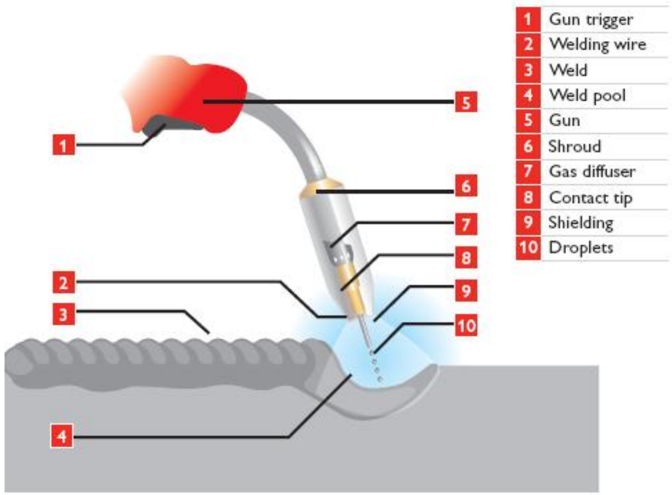
5 Welding processes

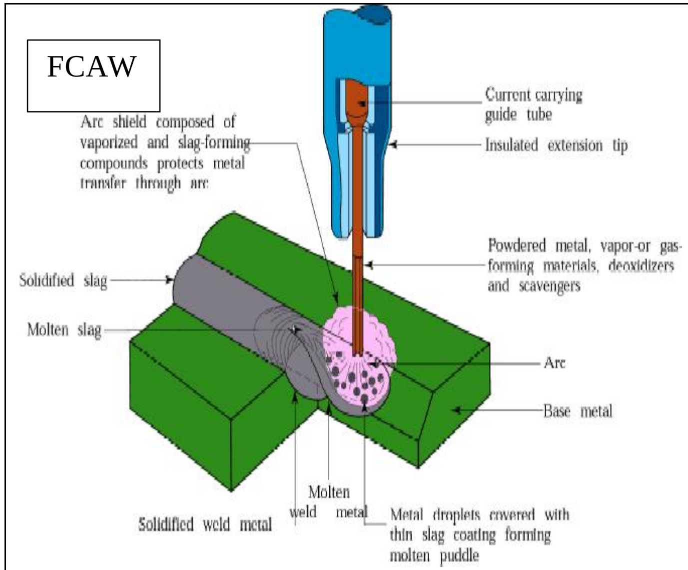
Structural steels for offshore application can be welded by the following welding processes, SMAW, GMAW, FCAW, GTAW, and SAW [22].

The Fig. 12 below describes the different welding processes.

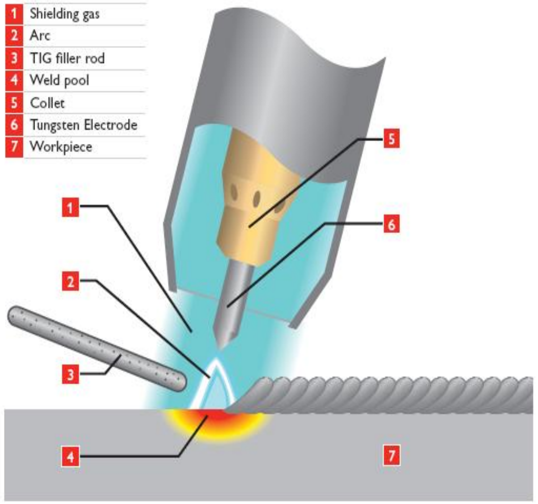
Fig. 12 Welding processes [23, 24].

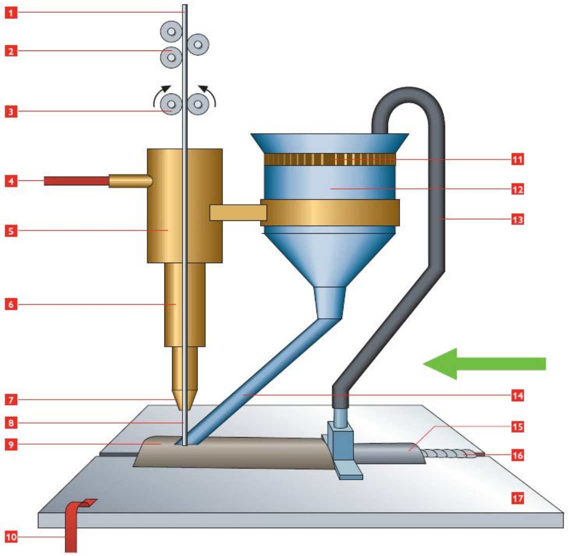
Welding process	Material	Application	Welding equipment
SMAW  Schematic of SMAW process Operation: It is a fusion welding process that uses the heat generated by an electric arc to fuse metal together in the joint area. An arc is truck between the tip of the electrode and the workpiece and the core wire beings to melt.	Most steels Stainless steels Cast irons Nickel alloys Copper alloys Aluminum alloys	General fabrication Structural steelwork Power plant Process plant Pressure vessels Cryogenic plant Pipelines Shipbuilding Bridge building Offshore fabrication Repair and maintenance in a wide variety of industries	Power source Electrode cable Electrode holder Electrode Work clamp Return cable

The coating of the core wire provides a protecting gas to shield the weld pool from the surrounding air.			
GMAW  Operation: It is done semi-automatic by a handheld gun. It uses shielding gas such as argon, carbon dioxide, argon and carbon dioxide mixture, argon mixture with oxygen or helium. It uses electrode.	Stainless steel. Mild carbon steel. Aluminium. Copper and its alloy. Nickel and its alloy. Magnesium. Titanium. Zirconium.	Railways. Earth moving equipment. Automobiles. Steel furniture manufacture. Shipbuilding. Bridges. Rocket and missile launchers.	Power source. Work clamp. Electrode. Shielding gas source. Wire feeder. Wire reel. Welding gun.

<table>
<tr>
<td>FCAW


Operation:
It uses heat generated by a DC electric arc to join metals together.
The arc is struck between a continuously fed consumable filler wire and the workpiece.
The filler wire and workpiece are both melted in the process.</td>
<td>Carbon steel.
Stainless steel.
Aluminium.</td>
<td>Structural fabrication of boiler.
Bridges.
Ship building.</td>
<td>Power source.
Shielding gas source.
Electrode.
Welding gun.</td>
</tr>
<tr>
<td>GTAW</td>
<td>Used to weld any metal or alloy.
Stainless steels.
Aluminum alloys.</td>
<td>High quality fabrication of stainless steel.
Orbital GTAW is used in nuclear,</td>
<td>Direct or alternating current power source with constant current.
Welding torch.
Tungsten electrode.</td>
</tr>
</table>

 *Schematic of the TIG welding process* Operation: It uses the heat generated by an electric arc. The arc is struck between a non-consumable tungsten electrode and the workpiece to join them together. The process may be operated without filler wire or the filler wire is added by a consumable wire rod to the weld pool.	Copper alloys. Nickel alloys. Reactive and refractive metals such as titanium, tantalum and zirconium.	pharmaceutical, semi-conductor and food industries for installation of pipework where high quality standards are required.	Leads and connectors. Gas supply system. Arc and re-ignition system.
SAW	Carbon. Carbon manganese.	Longitudinal and spiral welded pipes. Shipbuilding.	DC or AC power source.

 Operation: It uses arc struck between a continuously fed electrode and the workpiece. The metal is melted in the process and an additional filler metal is provided by a granular flux. The arc is submerge under the molten flux and it provides protection to molten metal against the atmosphere.	Stainless steels. Nickel based alloys.	Structural steel welding application.	1 Submerged arc wire 2 Straightening rollers 3 Feed rollers 4 Power lead 5 Contact tube 6 Extension tube 7 Electrode guide 8 Electrode 9 Flux bed 10 Lead to earth 11 Slag sieve 12 Flux hopper 13 Excess flux recovery syster 14 Flux delivery tube 15 Slag 16 Weld bead 17 Work piece

In the selection of welding processes, the following criteria must be considered. The weld cost, productivity, weld positions, weld materials, and the welder skill. These factors affect the quality of the weld and the cost of the process [23]. The Table 22 below compares the different welding processes.

Table 22 Welding process comparisons [23].

GMAW (MIG) to SMAW	GTAW(TIG) to SMAW	FCAW to SMAW	FCAW to GMAW(MIG)	GTAW(TIG) to GMAW (MIG)
SMAW has low productivity. SMAW is mostly manual while GMAW can be manual, automatic or robotized. SMAW requires no shielding gas. SMAW is suitable for outdoor work, while GMAW suffers from draught affecting the gas shield. The wastage of consumable	SMAW is mostly manual, but GMAW is used manually and automatic orbital welding of pipe. SMAW needs no shielding. SMAW is suitable for outdoor work, while GMAW suffers from draught affecting the gas shield. SMAW creates slags and should be removed, GMAW does not create slag. SMAW welding speed is	SMAW is mostly manual while GMAW can be manual, automatic or robotized. SMAW needs no shielding, but some type of FCAW needs shielding but others don't need shielding. Suitable for outdoor work. SMAW consumable wastage is high compared to FCAW	GMAW and FCAW can be done manually, automatically and robotically. Position welding is easier with FCAW than GMAW. GMAW needs shielding gas but some type of FCAW needs shielding gas but others don't	They can be both done manually or automatically. GTAW requires a higher skill level than GMAW. GTAW has less defect level than GMAW. Weld cost per unit length is higher in GTAW than GMAW. GMAW welding speed is about two times that of GMAW with exception of hot-wire GTAW.

is high in SMAW. SMAW creates slags and should be removed, GMAW does not create slag. About 65% of consumable weight for SMAW is converted to weld metal as against 98% for GMAW GMAW welding speed is higher.	higher but needs clean up compared to GTAW	FCAW has higher welding speed. About 65% of consumable weight for MMA is converted to weld metal as against 80% for FCAW.	need. GMAW is mostly for workshop application. The welding speed for both GMAW and FCAW are similar. GMAW does not create slag but FCAW creates slag. Weld cost per unit length is higher with FCAW than GMAW.	

Offshore structures use high grades of steel and as such their welding procedures are more strictly controlled. The jacket sustains the platform and it makes it a very critical structure. It is fabricated with brace tubular legs. This tubular construction is welded by full penetration which gives it a sound weld that can withstand the environmental conditions and stresses that may arise. Large diameter, thick section pipes are produced by the following steps shown in Fig. 13 below.

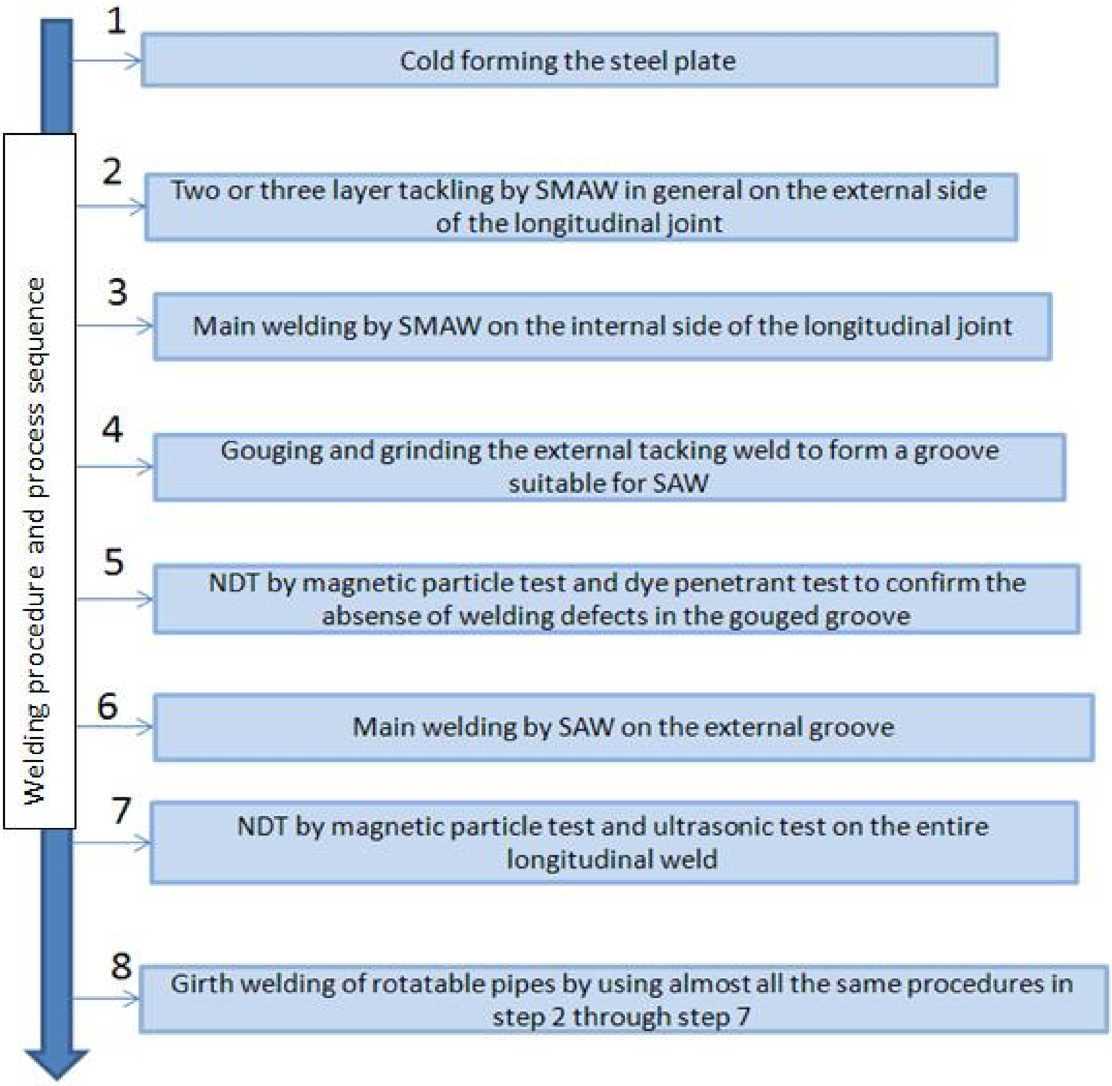


Fig. 13 Thick pipe welding by full penetration [25].

The node joint Fig. 14 of a jacket is where components are crossed forming T-, Y-, and K-connections. This joint has a high stress concentration and it is known as hot spot. This node joint changes its groove angle as out of position welding progresses along the joint. The legs of a jack-up rig consist of a rack, chord and brace as shown in Fig. 14 below and the rack to rack joint of a jack-up is shown in Fig. 15 below [25].

Fig. 14 Node joint of a jacket [25].

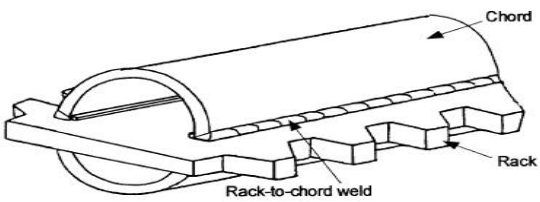


Fig. 15 Rack-to-rack joints of a jack-up [25].

5.1 Chemical reactions in welding

Gases such as nitrogen, oxygen and hydrogen are dissolvable in weld metal during welding. The sources of such gases are from air, shielding gas, flux and presence of moisture on the surface of the workpiece. The presence of these metals on the weld is of great significance as it affects the quality of the weld [26]. The different gases present in welding chemical reactions is shown in Table 23 below.

Table 23 Summary of the different gases present in welding and their effects [26].

Gases	Effect
Nitrogen: Used as shielding gas for Cu and Ni. Fe, Ti, Mn, and Cr weld metal should be protected from nitrogen. Nitrogen acts as austenite stabilizers for austenitic stainless steels. Increased nitrogen in weld can decrease ferrite content and increase the risk of solidification cracking. The source: Air Dissolvable metal (favourable): Fe, Ti, Mn, Cr Non dissolvable metals (unfavourable): Cu, Ni	Presence of nitrogen in the weld metal can act as a site for crack initiation. The effect of nitrogen on steel is that it increases strength but reduces toughness.

Oxygen: Addition of oxygen or $C0_2$ to argon used in GMAW helps to stabilize the arc, reduce spatter and helps the filler metal to flow in the fusion line. The source: Air, use of $C0_2$ containing shielding gas, decomposition of oxide in the flux and slag metal reaction in the weld pool. Dissolvable metal (favourable): In GMAW of steels. Non dissolvable metals (unfavourable): Al and Mn alloys	Oxygen can oxidize carbon and other alloying element and reducing hardenability and also form inclusions. Oxygen reduces the toughness of steel but toughness is improved if acicular ferrite is promoted.
Hydrogen: Low hydrogen consumables should be used. The source: Decomposition of cellulose electrode, wet workpiece or electrode, moisture in the flux and shielding gas.	Hydrogen induced cracking. Hydrogen can cause porosity in aluminum weld.

Argon: Used as shielding gas for GTAW, plasma arc welding and other welding processes. It has a greater oxide cleaning action than helium. It provides good arc starting due to its low ionization.	Provides stable arc and good penetration for carbon steels. It has good gap bridging ability for carbon steels.
Helium: Helium is used for welding thicker sections because of higher voltage drop. It is suitable for welding application with increased heat input.	It produces a hotter and broader arc which improves the depth of penetration and bead width. Helium may improve travel speed.

The Table 24 below shows the different protection techniques for different fusion welding processes.

Table 24 Protection techniques in common welding processes [26]

Fusion welding process	Protection technique
GTAW, GMAW, PAW	Gas
SAW, Electroslag	Slag
SMAW, FCAW	Gas and slag
EB	Vacuum
Self-shield arc	Self-protection
Laser welding	Gas

Several arc welding have different level of oxygen and nitrogen which are common to these different arc welding processes. The GMAW has some amount of carbon-dioxide and argon content present in the process. The Fig. 16 below illustrates this.

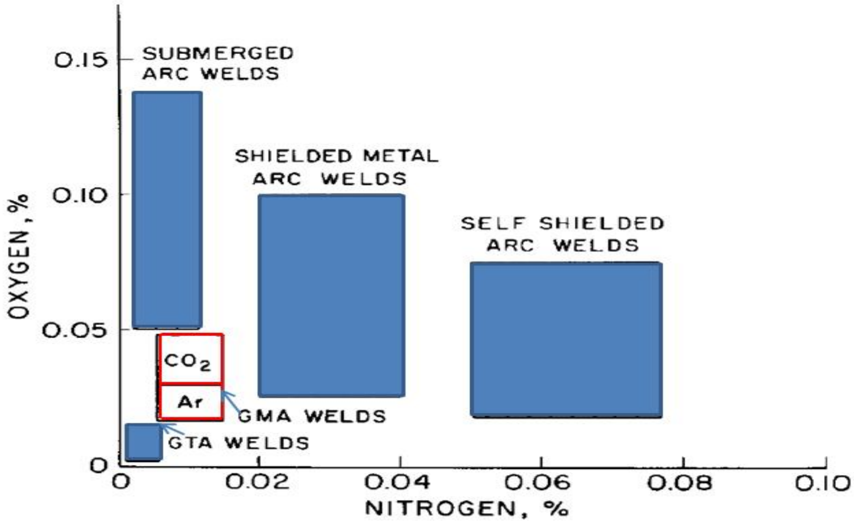


Fig. 16 Oxygen and nitrogen levels expected from several arc welding processes [26].

5.2 Phase Transformation in the Heat affected Zone of C-Mn Steel Welds

The HAZ undergoes solid-state phase transformations such as grain growth, phase transitions, annealing, tempering and recrystallization. As a result of this transformation, the HAZ has coarse grained, fine grained and partially transformed microstructural sub-regions [27].

The Table 25 below shows the chemical composition of a typical C-Mn steels grade AISI 1005.

Table 25 Chemical composition of AISI 1005 steel [28].

element	C	Mn	Si	Ni	P	Cu	S	Al	Nb	Mo	Ti	V	Cr
Wt. %	0.05	0.31	0.18	0.11	0.009	0.008	0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.10

The phase transformation for pure iron and C-Mn AISI 1005 steel is different because of the alloying elements contained in AISI 1005. For example pure iron exists in BCC as well as FCC crystal form. In pure iron, the α-Fe transforms to γ-Fe at 910^0C. The γ-Fe transforms back to δ-Fe at 1390^0C. The δ-Fe remains stable up to 1536^0C. However the microstructure of AISI 1005 contains carbide phase at lower temperature [29].

The Fig. 17 below shows the phase transformation diagram of AISI 1005 steel.

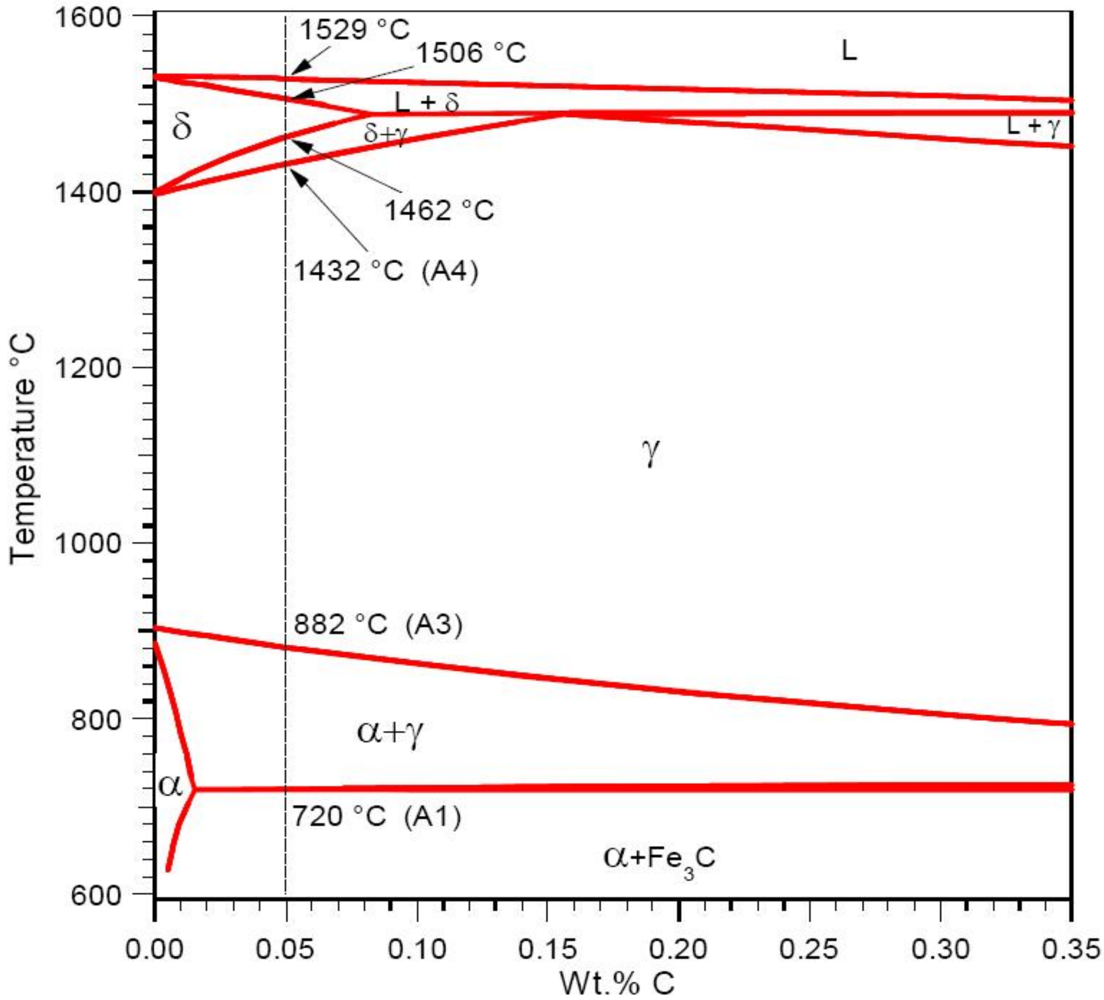


Fig. 17 Fe-C phase diagram for the AISI 1005 steel [37, 38].

The Table 26 below summarizes the phase transformation temperature for the AISI 1005 C-Mn steel calculated from thermodynamic relationship. This calculation is done using the thermocalc software.

Table 26 Calculated phase transformation temperature for the AISI 1005 C-Mn steel [28].

Transformation events on heating	Transformation	Temperature (^{0}C)
Cementite disappears	Fe_3C à (α+γ)	720
α-ferrite disappears	(α+γ) à γ	882
δ-ferrite disappears	γ à (γ+ δ)	1432
Austenite disappears	(γ+ δ) à δ	1462
Liquid appears	δ à (δ +L)	1506
Ferrite disappears (Liquidus)	(δ +L) à L	1529

The base metal and the HAZ microstructure after polishing the surface of the weld and etched with nitric acid and alcohol is revealed and it is shown in the Fig. 18 below with the HAZ having a coarse grained microstructure.

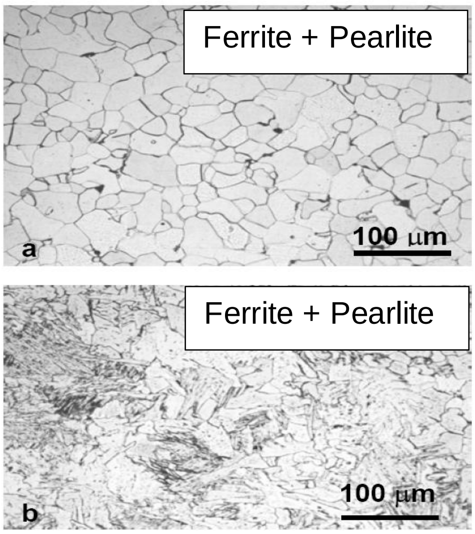


Fig. 18 Optical micrographs of AISI 1005 steel fusion weld for (a) base metal, and (b) coarse region of the HAZ.

6 Weldability

According to DIN 8528 Part 1, weldability of a material is determined by three outer variables which are the material to be welded, the influence of the manufacturing process and the design of the material to be welded. Every welding criterion in the DIN 8528-1 is of equal importance and must be put into consideration [30].

Steels are said to be weldable if it has good strength properties and toughness in the service life. Materials which have high tendency to form hard and brittle areas in the HAZ using fusion welding with the susceptibility of forming defects such as hydrogen induced cold cracks, lamellar tearing, stress relieve cracks and solidification cracks are said to have poor weldability [15].

A good weld preparation and avoidance of defects which are likely caused by the welding operator such as lack of penetration or fusion can lead to sound weld for all common structural steels. However other steels may need special treatments to be able to get quality and sound welds. Some of the difficulties in achieving good welds in some steels are as a result of extremes in heating, cooling and strains which come as a result of the welding process. Microstructural changes and environmental effects during welding are also a problem associated with the quality of the welded joint. Joint cracking are likely to occur in structural steels with these effects place. Some of the different cracking which are present are discussed below.

The Fig. 18 below illustrates the variable that determines weldability of a material.

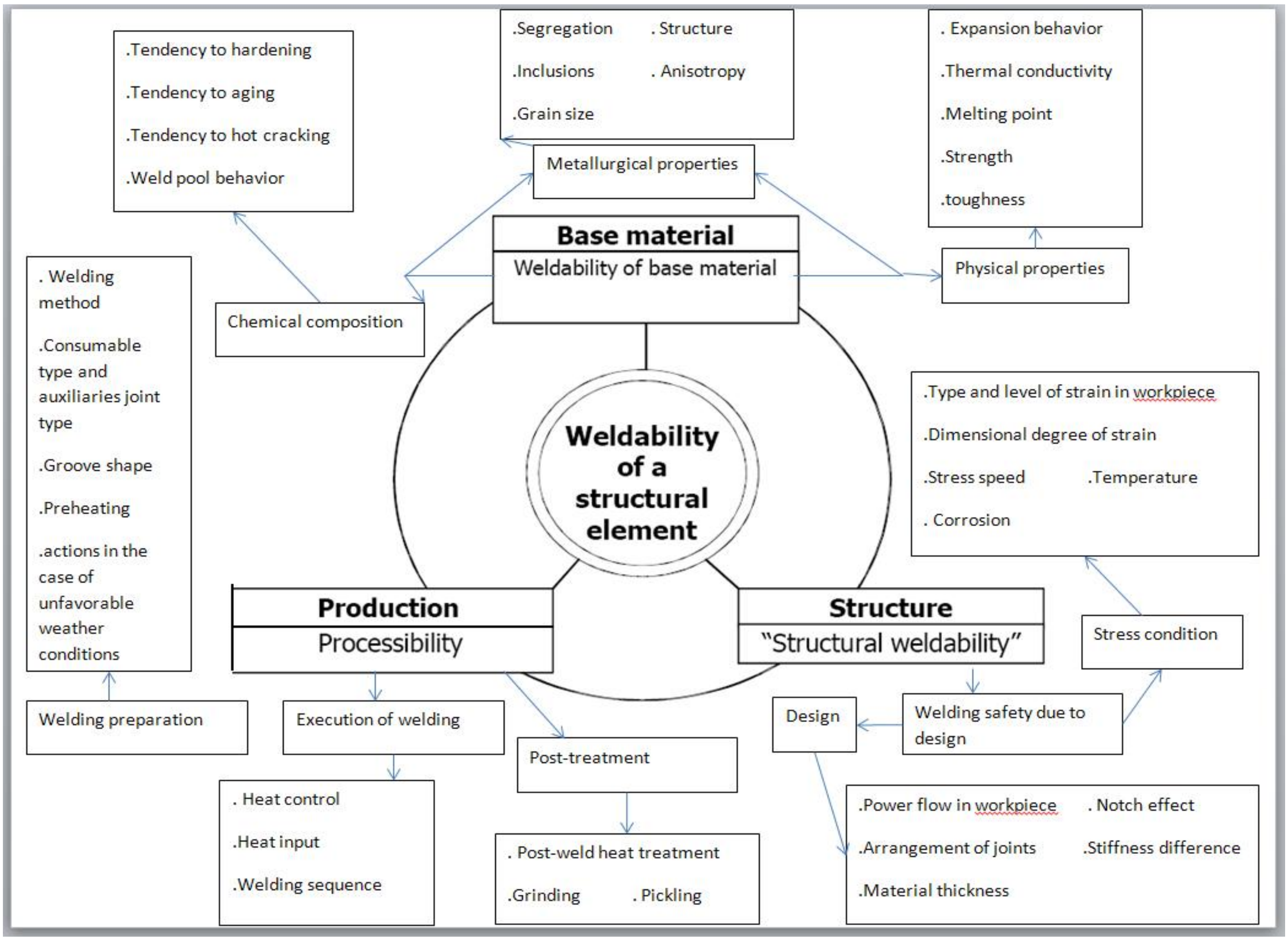


Figure 19 Influencing Factors on Weldability according to DIN 8528 Part 1 [30].

Problems associated with weld metal can be solved by changing the electrode and changing the base metal for problems associated with the HAZ or changing the heat input. However these are expensive to do. In calculating the weldability of a base material, the IIW has come out with an equation which is called the carbon equivalent (CE). In Japan, the Ito-Bessyo composition characterizing parameter (P_{cm}) is also used. The carbon equivalent were initially used to characterize the hydrogen cracking tendency for steels but are now also used to assess the hardenability of the steel based on their alloying element [31].

$$CE = C + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5} \qquad \text{Eq. 5}$$

$$\mathbf{P_{cm}} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + \mathbf{5B} \qquad \text{Eq. 6}$$

The Table 27 shows the effect of CE on weldability and the procedure to carry out to improve the weldability of steel at different CE range.

Table 27 Effect of CE range on weldability[41].

CE	Weldability	Procedure
<0.4	Excellent	Preheat to remove moisture
0.41-0.45	Good	Preheat + low H electrode
0.46-0.52	Fair	Preheat + low H electrode + interpass temperature control
>0.52	Poor	Preheat + low H electrode + interpass temperature control + post weld heat treatment

Table 28 shows different alloying elements and their effects on steel.

Table 28 Effects of alloying elements on steel [41, 42].

Elements	Solid solubility		Influence upon ferrite	Influence upon austenite (hardenability)	Influence exerted through carbide		Functions of element
	In ɣ-Fe	In α-Fe			Carbide forming tendency	Action during temperature	
Al	1.1% rise by carbon	36% +-	Hardens by solid solution.	Hardenability increases slowly if dissolved in austenite.	Graphitizes	-	Used as deoxidizer. Restrict grain growth. Alloying element in nitriding steel.
Cr	12.8%(in 0.5%C steels 20%)	Unlimited	Slight increase in hardness. Corrosion resistance increases.	Moderate increase of hardenability.	Greater than Mn	Resist softening mildly.	Increases corrosion and oxidation resistance. Increases hardenability. Increases strength at high temperature. With high carbon it resist wear and abrasion.

Mn	Unlimited	3%	Increase hardness Decreased ductility	Hardenability increases slightly. High carbon retains austenite.	Greater than Fe , less than Cr	Very little in usual percentage	Opposes brittleness from slphur. Increases hardenability cheaply. High Mn and high C gives steels resistance to wear and abrasion.
Mo	3%(with 0.5%C steels 8%)	37.5%(less with lowered temperature)	Age-hardening system in high Mo-fe alloys	High increase in hardenability.	Strong, greater than Cr	Opposes softening by secondary hardening	Raises grain coarsening temperature of austenite. Increases depth of hardening. Increases corrosion resistance of stainless steels. For abrasion resistant particles.
Ni	unlimited	10% independent of carbon content	Increased strength and toughness by solid solution	Hardenability increases slightly High carbon retains austenite.	Graphitizes less than Fe	Very little in small percentage.	Strengthen unquenched and annealed steels. Increases toughness of pearlitic-ferritic steels especially in low temperature.

P	0.5%	2.8% independent of carbon content	Increased hardness by solid solution Decreased ductility	Slight increase in hardenability	Nil	-	Strengthen low carbon steels. Increases resistance to atmospheric corrosion. Improves machinability in free cutting steel.
Si	Approximately 2% (with 0.35C approx.. 9%)	18.5%(effect of carbon is minimal)	Increased hardness Decreased ductility	Hardenability increases more than Ni	Negative graphitizes	Hardness is sustained by solid solution	Used as deoxidizers. Alloy for electrical and magnetic sheet metals. Improves oxidation resistance. Strengthens low alloy steel.
Ti	0.75%(with 0.2%C steels approximately 1%)	Approximately 0.6%(less with lowered temperature)	Gives age-hardening in high Fe-Ti alloy	Its carbide reduces hardenability	Highest known(2% Ti makes 0.5% C steel unhardened)	Secondary hardening present	Reduces martensitic hardness and hardenability in medium Cr steels. Prevents formation of austenite in high Cr steels. Prevents localized depletion of Cr in stainless steels during long heating periods.

V	Approximately 1% (with 0.2%C steels 4%)	33%(less with lowered temperature)	Moderate hardness in solid solution	Hardenability increases highly as dissolved.	Very strong.	Maximum for secondary hardening.	Promotes fine grain-elevates coarsening temperature. Increases hardenability when dissolved.
C			Increases hardness. Decreases ductility.	Strong former and promotes austenite structure.	Very strong		Essential in the formation of cementite, pearlite, spherodite, bainite and iron-carbon martensite.
Cu	0.35 % at room temperature.	3.5 % dissolves in ferrite.	Corrosion resistance improves.	Stabilizes austenite.			Improves resistance to atmospheric corrosion.
B	0.001-0.005 wt%			Finer austenite grain increases hardenability.			Increases hardenability.

The Table 29 below shows the effect of carbon content, manganese content and grain size on the weldability of structural steels.

Table 29 Effect of C, Mn and grain size on weldability of structural steels [32].

Condition	Resistance to brittle fracture	Weldability	Strength
Increased % C	Decreases	Decreases	Increases
Increased % Mn	Increases	Decreases	Increases
Decreased grain size	Increases	Depends	Increases

The Table 30 below explains the differences in improving the parameters of steels to achieve better weldability for high strength steels compared to traditional steels.

Table 30 Changes in steel chemistry [32].

Parameter	Traditional	High Strength
% C	0.2-0.25	0.06-0.15
% Mn	0.8-1.2	1.2-1.5
Micro alloy addition	Nb, V, Ti, Mo, B (0.05-0.15%)	Nb,V (< 1%)
Grain size	6	12
CE	0.38(0.33-0.45)	0.33 (0.26-0.40)

Hardenability

The ease of steel to harden to a certain depth is an important property of steel which defines the strength, toughness and fatigue properties. Hardenability is improved by the addition of alloying elements. The cooling of steel at a rate which is equal or greater than the critical cooling rates is able to form a fully martensitic structure. This is however for thin sections and thick sections cool more slowly in the interior section than the surface. But however through thickness hardness can be achieved in thick sections if the steels are modified and the critical cooling rate is lower. The steel austenite grain size and composition are functions of the hardenability of steel. Hardenability is measures by the Jominy end quench using the critical cooling rate and it is measured in terms of the depth of full hardening , diameter of the bar [43, 44].

Hardness

Full martensite is formed after the austenization of steel and quenching it. This gives no room for the diffusion of carbon out of the martensite grains and thereby forming carbide phase. Hardness is a measure of the resistance to penetration or indentation. It is measured using the Brinell, Rockwell or Vicker hardness test [43, 44]. The hardness of steel is a function of its carbon content.

The Fig. 20 below illustrates the relationship between carbon content, hardenability on the weldability of steel. This figure shows that an increase in carbon content or hardenability will lead to a decrease in weldability.

Fig. 20 Relationship between carbon content, hardenability and weldability of steel.

6.1 Weld defects

The major challenge faced in welding is the ability of producing welded joints that are free from weld defects. The soundness of a weld is determined on the defect level that are present in welds. Defects are classified into two major classes: defects formed during the manufacturing process such as welding and defects which are already present in the material as a result of the steel making process, the chemical composition and mechanical properties of the metal. The defects which result during the welding process are grouped into external and internal weld defects. The defects as a result of the material itself are grouped into hot cracks, cold cracks and cavities with weld metal. The classifications of the different defects which are major problems that affect the weldability of structural steels are explained below.

The Fig. 21 below shows the classification of the different types of defects in a weld.

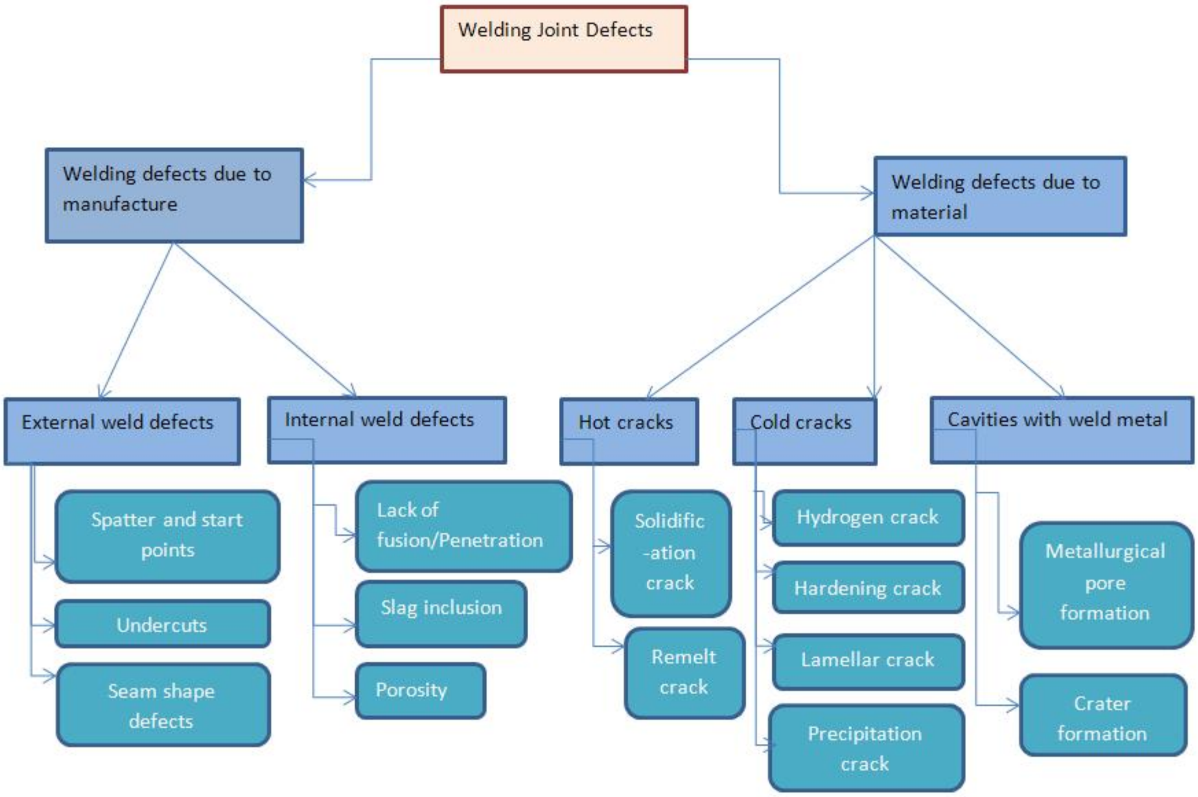


Fig. 21 Weld defect classification.

Lamellar tearing

The tearing close to the weld or outside the HAZ is caused by the presence of high localized stresses and low ductility of the base metal in the direction of the through-thickness. This influenced by nonmetallic inclusions lying parallel to the surface of the plate. However hydrogen, electrode strength and preheating are also factors which affect how susceptible steel is to lamellar tearing. Although preheating if the hydrogen content is high helps to reduce the susceptibility of lamellar tearing but this is not the case if the joint in service are restrained. The hydrogen, present for example when a cellulosic electrode such as E7010 causes embrittlement [33]. The inclusions present are produced in the steel making process e.g. sulphates and silicates which are formed as spheres, small angular particles as the steel ingot cools down after casting and grain boundary films. The form of the inclusion, the density and distribution of these inclusions determine the through thickness ductility in a rolled plate.

The Fig. 22 below shows the lamellar tearing under a T butt weld of a structural steel.

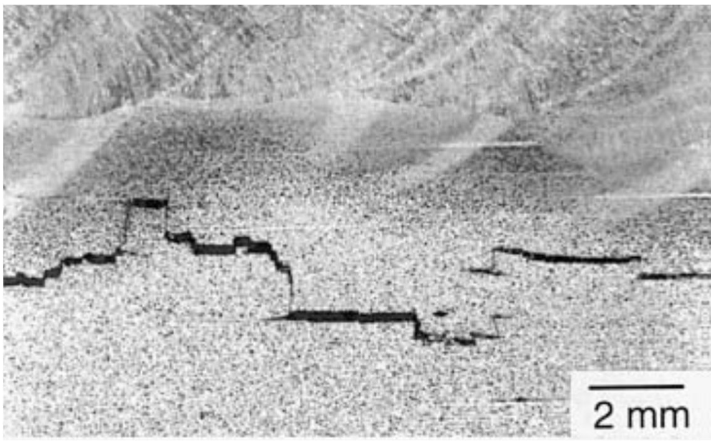


Fig. 22 Lamellar tearing near a C-Mn steel weld [33].

Some of the ways to remedy lamellar tearing are as follows.

- Improved joint design to avoid contraction stresses in the through thickness direction of the plate [33].
- The use of steel with low nonmetallic inclusions and sufficient through thickness ductility [33].

Solidification Cracking

Fractures at the intergranular and interdentritics weld metal boundaries during the solidification process of fusion welding when the molten weld is having impurities such as S and P. Coarse columnar grains are more susceptible to solidification cracking than equiaxed grains. Solidification cracking occurs more frequently in sub-arc welding, less in GMAW and FCAW and it hardly occurs in SMAW welding [31,46, 47]. A brittle metal is prone to solidification crack and if the base metal is attached to a fixed part and creates tensile stresses. Solidification crack can be minimized by choice of parent metal composition, process parameter and joint design.

Stress relieve cracking

Post weld heat treatment is performed to improve toughness and reduce residual stresses by subjecting the weld metal to thermal stress relief. Weld metal with Cr, Mo, V are highly susceptible to crack. Carbide precipitation strengthens the grain interior and the joint reaches a range of temperature where creep can occur and the residual stresses are relieved by plastic deformation. A weld or HAZ with less ductility are prone to cracking during this process since they can no carry the strain associated with residual stress relief [34].

Hydrogen induced cracking

This is also known as HAZ cracking, underbead or cold cracking. The cracks can form within minutes or it is delayed for several days after welding. The risk of cold cracking is a function of the chemical composition of the metal and also the steel making process. An increase in the level of hydrogen present in the weld metal increases the risk of cold cracking. For hydrogen induced cracking to occur, four factors must occur at the same time, these factors are.

- Hydrogen in the weld metal introduced into the molten weld pool during welding
- High stresses as a result of the rigidity of the weld assembly during cooling by solidification shrinkage and thermal contraction
- Presence of brittle martensitic microstructure
- Low temperature between -100^{0}C and 200^{0}C since the martensite formation temperature is relatively low

In order to avoid cold cracking, heat treatment is needed to lower the cooling speed and allow the removal of hydrogen from the weld before it is cold to the ambient temperature.

The Fig. 23 below shows how hydrogen is diffused from the weld metal to the HAZ during welding. From the figure T_F is the transformation of the weld metal from austenite into ferrite and pearlite while T_B is the transformation from austenite to martensite. Hydrogen in the T_F phase is rejected and moved to the T_B phase because austenite cannot absorb more hydrogen and hydrogen is soluble in ferrite. The base metal has higher carbon content than the weld metal because the filler metal usually has lower carbon content. And in that case, the HAZ is transformed from austenite into martensite after the weld metal has transformed from austenite into ferrite and pearlite [15, 33].

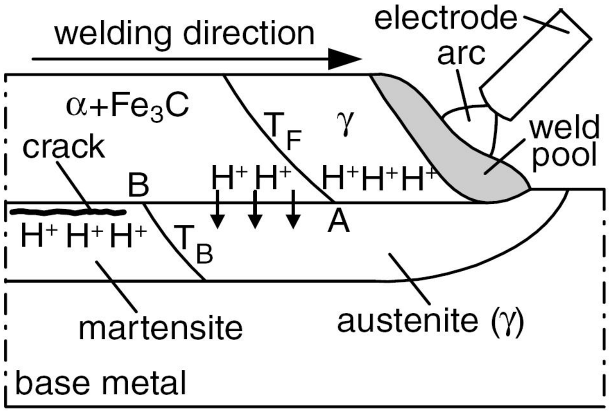


Fig. 23 Diffusion of hydrogen from weld metal to HAZ during welding [33].

Causes and remedy for cracking

Depending on the CE, different measures should be taken to avoid cracks in the weld and achieve a sound weld. Low carbon content will lead to hardness below critical level. High carbon content will lead to hardness above critical level. If the carbon content is medium, and the steel is slow cooled during the heat treatment, it will lead to hardness below the critical level and if it is fast cooled, it will lead to hardness above the critical level. A low hardness will in most cases have low cracking tendency. While hardness above critical level have a high cracking tendency if there is no preheat and if there is high presence of hydrogen content. However if preheated in the presence of low hydrogen content, we can achieve low risk of cracking.

The Fig. 24 below shows the factors affecting cracking tendency in the HAZ.

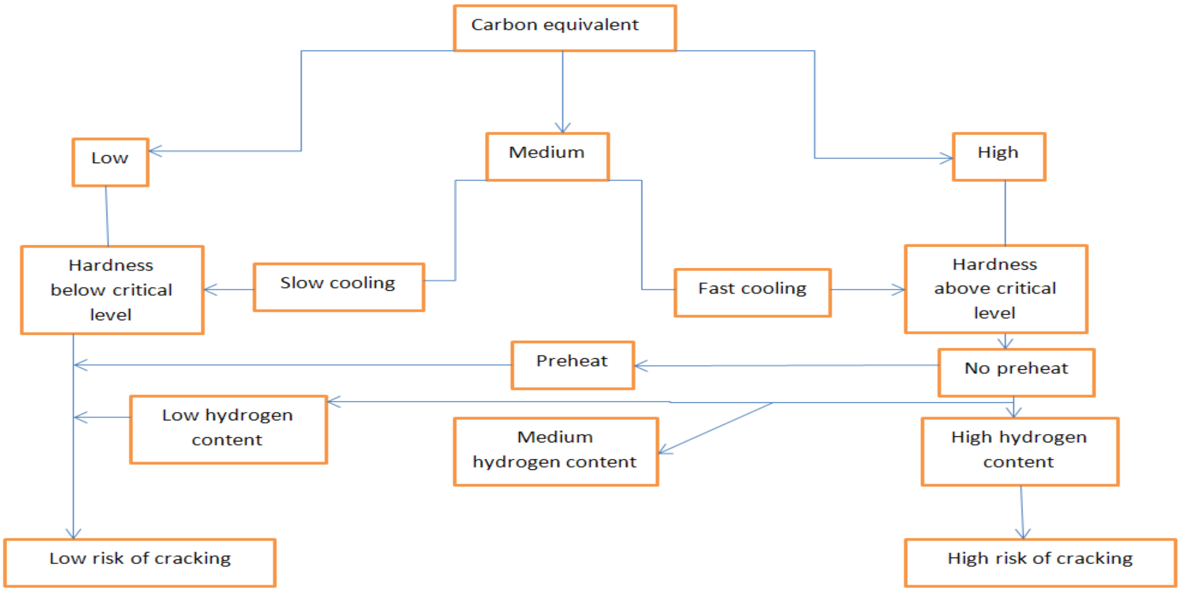


Fig. 24 Principle factors affecting the cracking tendency of HAZ.

6.2 Typical weldable offshore steels- Weldability test requirements

The desire to produce sound and reliable joint has made fabricators to use normalized offshore steels instead of conventional steels. The carbon content for such normalized offshore steels are reduced from typically 0.12% to 0.18% and the trace and microalloying ements are reduced. Impurities such as oxygen, nitrogen, and sulphur have been reduced and this gives a good HAZ and base material properties especially toughness [15]. The use of thermo-mechanically rolled steels makes it possible to reduce the carbon content up to 0.08% as a result of the grain refinement of such steels [15]. Examples of steels with carbon content of 0.08% are S355G8+M and S460G2+M with CE of 0.35 and 0.40 respectively. The weldability of these steels have been improved and are suitable for offshore application because of their improved weldability and toughness. The transformation characteristics and the material properties of a steel grade can be determined from the HAZ hardness measurement. The application of different heat input leads to different cooling rates. According to the welding society, the cooling time is $t_{8/5}$ which is the cooling duration from 800^{0}C to 500^{0}C. The hardness characteristics for low heat input welding such as FCAW and laser welding which have short cooling time, the difference in hardness is a fuction of carbon content which is important in martensite formation. However for high heat input welding, the hardness characteristics is influenced by the alloying content as in the case of high alloyed steels such as S460N and S690Q. However due to the chemical composition of S460G2+M, the hardness can be kept almost 100 HV lower compared to the S460N [15]. The Fig. 25 below shows the comparison of hardness versus $t_{8/5}$ cooling time for different grades of offshore steels.

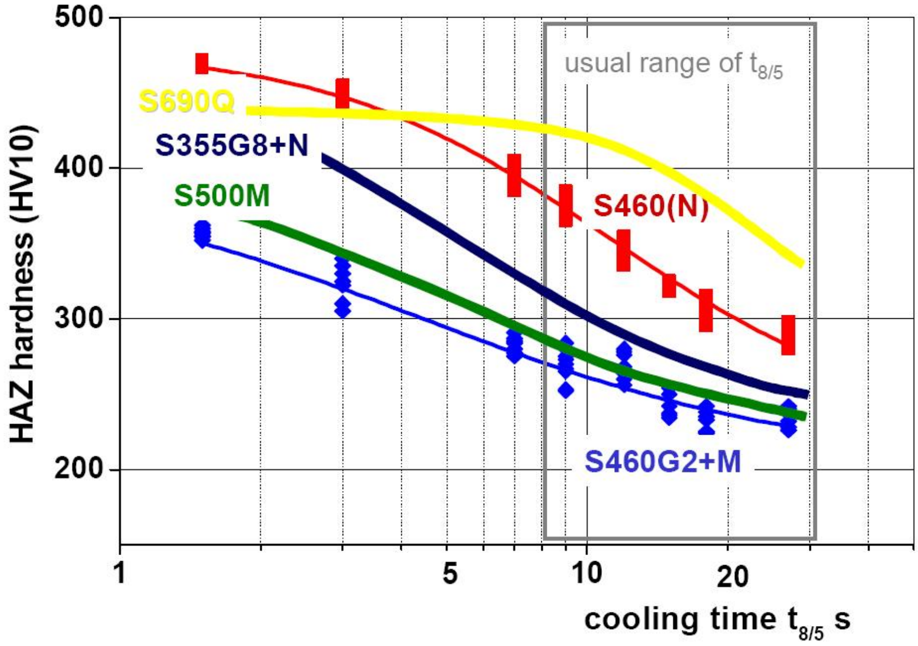


Fig. 25 Bead on plate HAZ hardness for various steels as a function of weld cooling time measured in the as welded condition [15].

In an attempt to avoid weld defect such as hydrogen induced cold cracking, preheating and minimum interpass temperature is needed. However this is an expensive, difficult to control on the yard and time consuming process. A steel such as S355G8+M and S460G2+M with lower carbon contents have a less brittle and less hard HAZ. A preheat temperature of 70^0C is needed for each 0.01% increase in carbon content if the preheat for thermomechanically rolled steel having carbon content of 0.08% is compared to a normalized steel having carbon content of 0.18% according to CET (DIN EN 1011) formulae as shown in Eq. 7 below.

$$\mathrm{CET}=\mathrm{C}+\frac{\mathbf{Mn+Mo}}{\mathbf{10}}+\frac{\mathbf{Cu+Cr}}{\mathbf{20}}+\frac{\mathbf{Ni}}{\mathbf{40}} \qquad \text{(Eq. 7)}$$

CET is carbon equivalent that is commonly used to characterize the susceptibility of steel to cold cracking. From the formula, the can see that carbon is detrimental for cold cracking. The lower the carbon content, the less hard is the HAZ and less brittle.

where

T = 700 CET + 160tanh (t/35) + 62 HD exp 0.35 + (53 CET – 32) Q +330 (Eq. 8)

T is preheating temperature. Preheating involves heating the base metal either entirely or just around the joint to a specific temperature.

t = plate thickness (mm)

HD = hydrogen (ml/100g -ISO 3690)

Q = heat input (kJ/mm)

The comparison of calculated preheat as a function of plate thickness for combined heat input and hydrogen level for different steel grades is show in the Fig. 26 below. Practical examples of thermomechanically rolled steel plates welded without preheating and good weld joint were achieved can be seen in the S355M plate of 120 mm thickness used for huge storm barrier in Maaslant Kering close to Rotterdam and S420M and S460M plates up to 50 mm welded with FCAW process . This is achievable because of the optimized chemical composition of the thermomechanically rolled plate and also having a clean and dry surface [15].

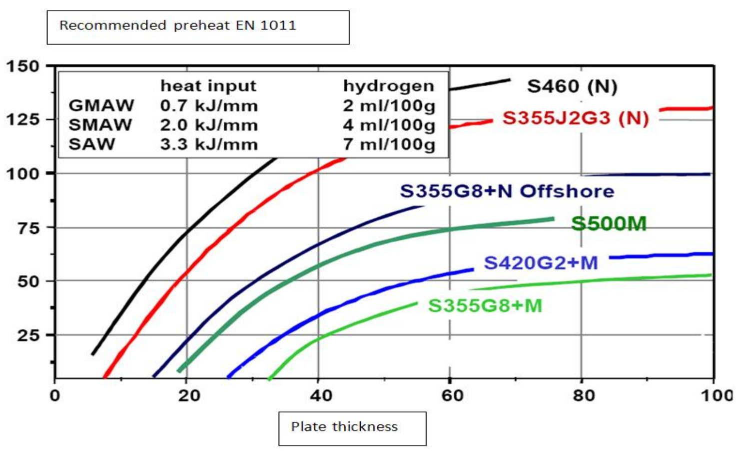


Fig. 26 Calculated preheat temperature as a function of plate thickness [15].

The offshore steels are required to have high toughness in the HAZ. Low sulphur content and absence of large inclusions is essential for toughness in the HAZ. Traditional S355 steels with high sulphur content are not able to 27 J impact strength. However, the S355N steel with low sulphur content can achieve a 50 J at -40^{0}C while a lower sulphur and carbon content in the S355M can reach 200 J at -40^{0}C as shown in the Fig. 27 below.

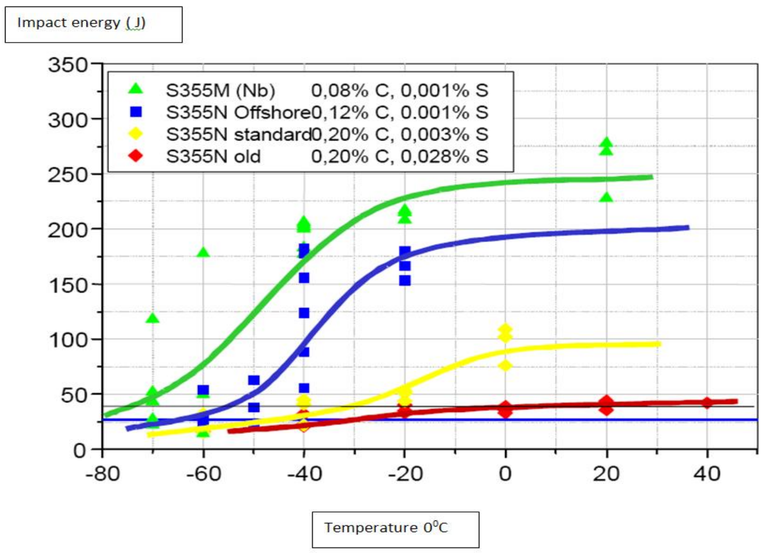


Fig. 27 Impact toughness in the HAZ of 3.5 kJ/mm SMAW on 20 mm thick plates of 355 MPa yield strength [15].

The Table 31, 32, and 33 below shows the weldability test requirement for butt welds on plates, sections and seamless hollow sections. The test piece thickness is the maximum material thickness. The welding direction for plate is parallel to the rolling direction of the plate. The welding direction for sections is the rolling direction of the section. The width of the welded test piece is 500 mm or more or 10 times the thickness. The test piece condition is As welded, post weld heat treated. The minimum preheat and maximum interpass temperatures for the test piece is 125^{0}C and 250^{0}C respectively [35].

Table 31 Weldability test requirements for butt welds on plates **[35]**.

Grade	Quality	Test piece condition	Nominal heat input (kJ/mm)		
			FCAW[a] 0.7+-0.2	SAW[b] 5.0+-0.2	SAW[b] 3.5+-0.2
			Min. preheat temperature = $125^{0}C$ [c] Max. interpass temperature $=250^{0}C$ [c]		
S355	G8+N G10+N G8+M G10+M	As welded	x	x	X[d]
		Post weld heat treatment	x	X	X[d]
S420	G2+Q G2+M	As welded	x	x	X[e]
		Post weld heat treatment	-	x	X[e]
S460	G2+Q G2+M	As welded	x	X[f]	x
		Post weld heat treatment	-	X[f]	x

Where

X testing is required

-testing not required

a FCAW for t< 50 mm only when demanded by the buyer

b SMAW may be used instead of SAW if agreed between buyer and supplier

c Alternative preheat/interpass temperatures can be used if agreed between buyer and supplier and it should be on the basis of maximum carbon content and material thickness

d if test results at 5.0 kJ/mm go below the buyers acceptance criteria, S355G8 (+N and +M) and S355G10 (+N and +M) may require test at 3.5 kJ/mm.

e S420G2 (+Q and +M) test may be needed if the buyers acceptance criteria of 5.0 kJ/mm is not met.

f S460G2 (+Q and +M) shall not be welded beyond 3.5 kJ/mm.

Table 32 Weldability test requirements for butt welds on sections [35].

Grade	Quality	Test piece condition	Nominal heat input (kJ/mm)			
			FCAW[a] 0.7+-0.2	SAW[b] 3.0+-0.2	SAW[b] 5.0+-0.2	SAW[b] 3.5+-0.2
			Min. preheat temperature = 125^{0}C[c] Max. interpass temperature = 250^{0}C[c]			
S355	G12+N G11+N G12+M	As welded	x	X[d]	X[e]	x
S420	G4+N G4+M	As welded	-	X[d]	X[e]	x
S460	G4+N G4+M	As welded	-	X[d]	X[d]	x

Where

X -testing is required

- testing not required

a FCAW

b SMAW may be used instead of SAW if agreed between buyer and supplier

c Alternative preheat/interpass temperatures can be used if agreed between buyer and supplier and it should be on the basis of maximum carbon content and material thickness

d if test results at 3.5 kJ/mm go below the buyers acceptance criteria, for all grades may require test at 3.0 kJ/mm.

e If specified by purchaser.

Table 33 Weldability test requirements for butt welds on seamless hollow sections [35].

Grade	Quality	Test piece condition	Nominal heat input (kJ/mm)			
			FCAW[a] 0.7+-0.2	SAW[b] 3.0+-0.2	SAW[b] 5.0+-0.2	SAW[b] 3.5+-0.2
			Min. preheat temperature = 125^0C[c] Max. interpass temperature = 250^0C[c]			
S355	G15+N G15+Q	As welded	x	X[d]	_	x
S420	G6+Q	As welded	-	X[d]	_	x
S460	G6+Q	As welded	-	X[d]	_	x

Where

X testing is required

- testing not required

a FCAW

b SMAW may be used instead of SAW if agreed between buyer and supplier

c Alternative preheat/interpass temperatures can be used if agreed between buyer and supplier and it should be on the basis of maximum carbon content and material thickness

d if test results at 3.5 kJ/mm go below the buyers acceptance criteria, for all grades may require test at 3.0 kJ/mm.

6.3 Fracture toughness test

Fracture toughness which is defined in terms of notch impact value is the resistance of steel to brittle fracture. The brittle fracture is the energy absorbed in the standard Charpy probe shock bending test. The impact test to determine the steel impact toughness is done by measuring the work needed to fracture a test specimen under impact. This test is important to predict the behaviour of materials under impact stress or dynamic loading [36]. At the lowest service temperature, the steel material should have sufficient fracture toughness to resist brittle fracture during the tension or bending test.

To carry out the Charpy impact test, the uniform rectangular prismatic Charpy specimen with one notch per specimen which gives room for rupture. The Charpy testing machine Fig. 28 below has a hammer with a striking head which is attached to an almost frictionless pendulum with a known potential energy [36].

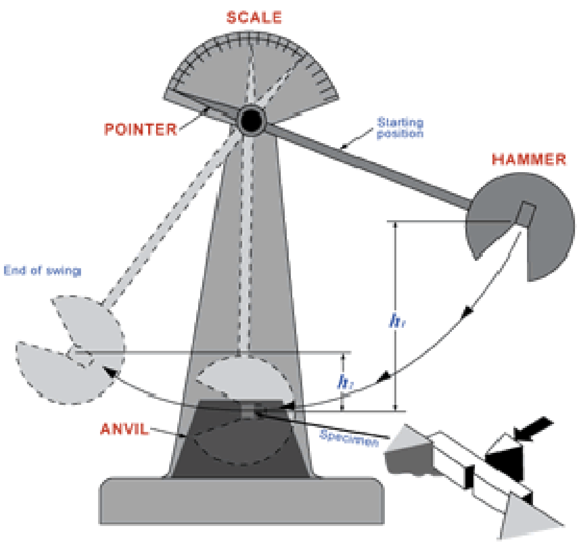


Fig. 28 Charpy- V impact testing machine [37].

The Fig. 29 below shows the transition temperature curve for a test specimen.

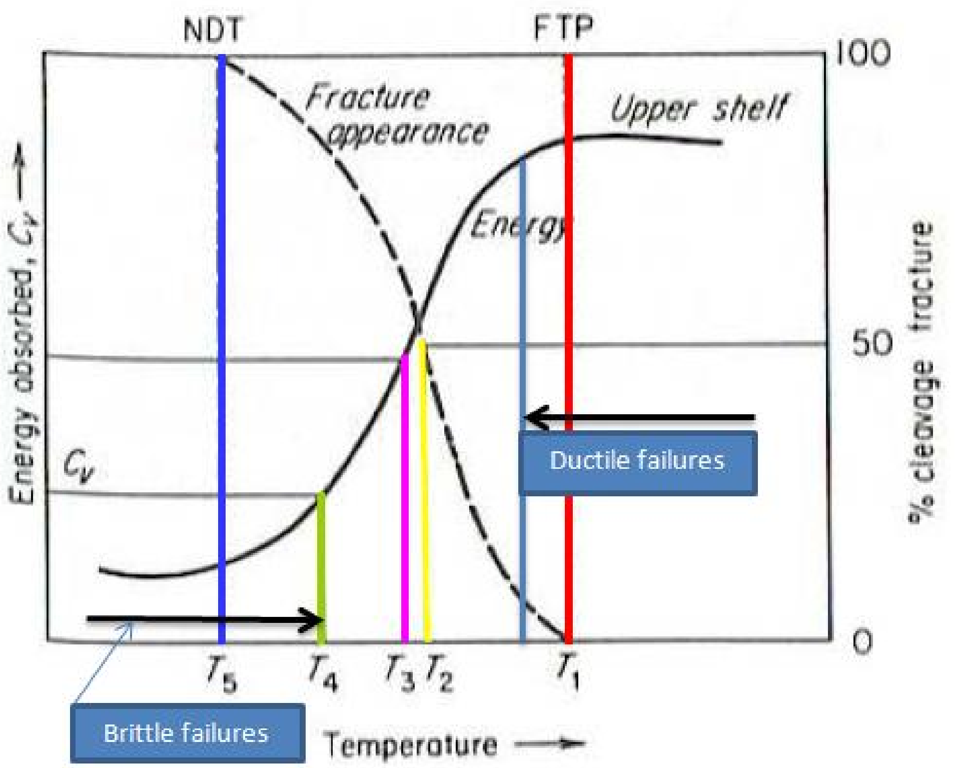


Fig. 29 Transition temperature, redrawn from [38].

Where

T1 transition temperature is the temperature at which fracture is 100% ductile.

T2 transition temperature is the temperature at which fracture is 50% brittle and 50% ductile.

T3 transition temperature is the average energy absorption of upper and lower shelves.

T4 transition temperature is the temperature defined at Cv = 20J.

T5 transition temperature is the temperature at which fracture is 100% brittle.

NDT is Nil Ductility Temperature.

FTP is Fracture Transition Plastic which is the lowest temperature at which the specimen exhibits 100% shear fracture.

A reduction in grain size helps to lower the transition temperature as shown in Fig. 30 below. Reducing the grain size shifts the ductile-brittle transition temperature to the left which has a wider service life. Heat treatments such as air cooling, recrystallization provide grain refinement and lower the transition temperature.

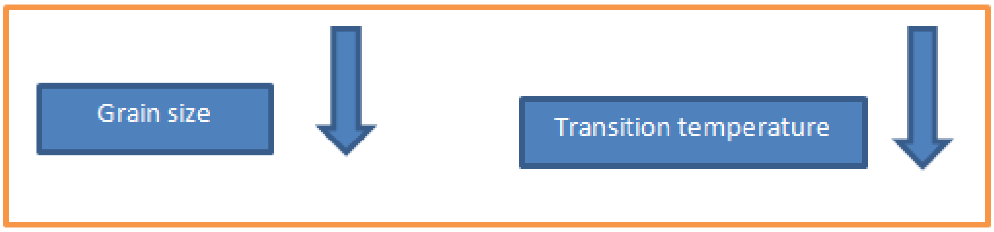


Fig. 30 Effect of grain size on transition temperature.

Depending on the fracture toughness of the steel, the level of stress and the minimum service temperature during the service life Tables 34, 35, and 36 gives the maximum thickness value of the parent material depending on the steel grade and type, the reference stress level and the reference temperature. The Tables 34, 35, and 36 are applicable for members that are subjected to tension and bending fatigue. It applies to members that are welded and non-welded. The reference stress is a standardized value in percentage (75%, 50% or 25%) of the nominal yield strength of the steel of a certain thickness.

Table 34 Maximum thickness (mm) of parent material σref= 0.75 fy(t).

				Reference temperature Tref (^{0}C)						
Steel type	Grade	Resilience T(^{0}C)	Resilience Jmin	10	0	-10	-20	-30	-40	-50
				σref= 0.75 fy(t)						
S355	JR	20	27	40	35	25	20	15	15	10
	J0	0	27	60	50	40	35	25	20	15
	J2	-20	27	90	75	60	50	40	35	25
	K2, M, N	-20	40	110	90	75	60	50	40	35
	ML,NL	-50	27	155	130	110	90	75	60	50
S420	M,N	-20	40	95	80	65	55	45	35	30
	ML,NL	-50	27	135	115	95	80	65	55	45
S460	Q	-20	30	70	60	50	40	30	25	20
	M,N	-20	40	90	70	60	50	40	30	25
	QL	-40	30	105	90	70	60	50	40	30
	ML,NL	-50	27	125	105	90	70	60	50	40
	QL1	-60	30	150	125	105	90	70	60	50

Table 35 Maximum thickness of parent material for σref= 0.50 fy(t).

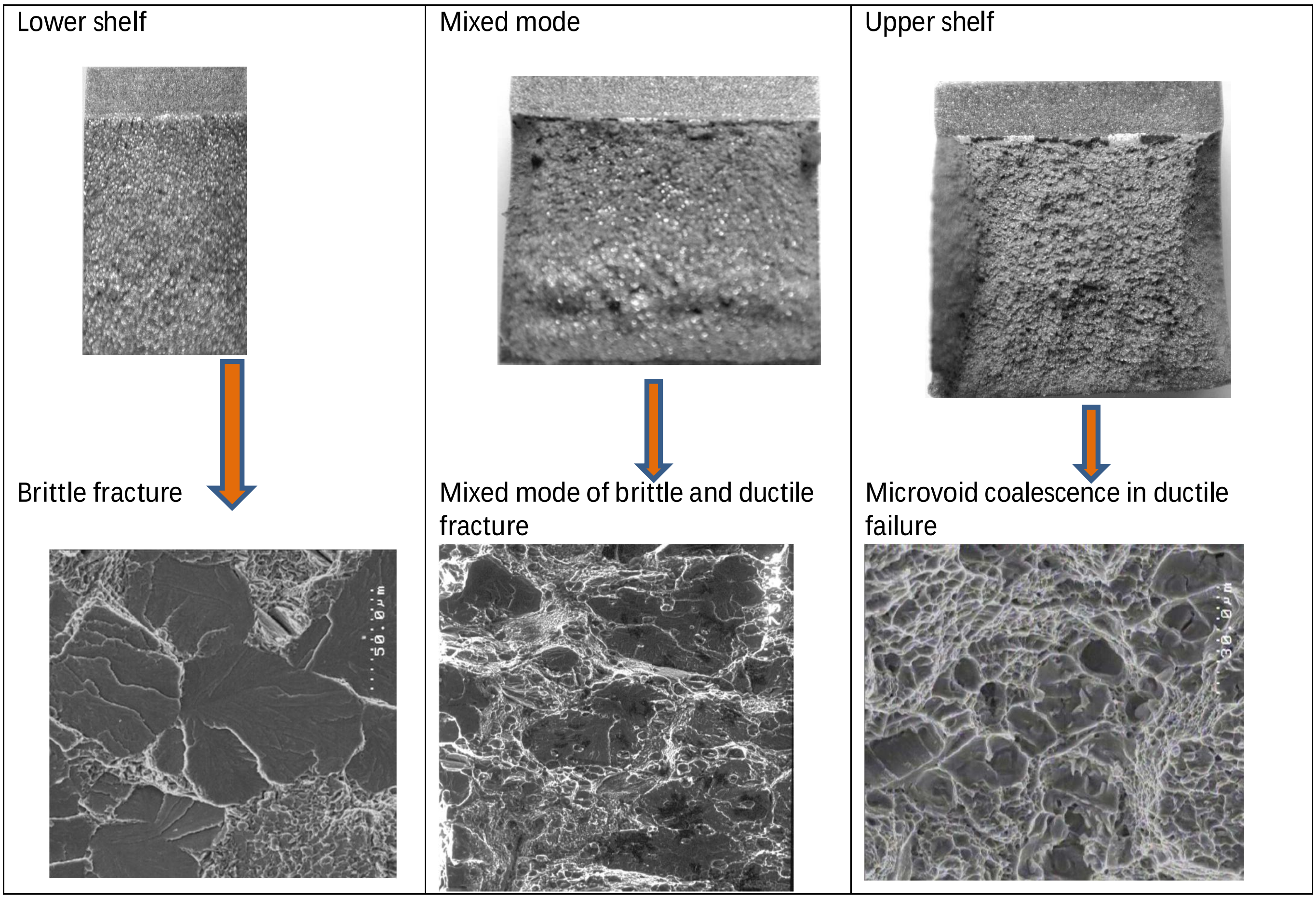
				Reference temperature Tref (^{0}C)						
Steel type	Grade	Resilience T(^{0}C)	Resilience Jmin	10	0	-10	-20	-30	-40	-50
				σref= 0.50 fy(t)						
S355	JR	20	27	65	55	45	40	30	25	25
	J0	0	27	95	80	65	55	45	40	30
	J2	-20	27	135	110	95	80	65	55	45
	K2，M, N	-20	40	155	135	110	95	80	65	55
	ML,NL	-50	27	200	180	155	135	110	95	80
S420	M,N	-20	40	140	120	100	85	70	60	50
	ML,NL	-50	27	190	165	140	120	100	85	70
S460	Q	-20	30	110	95	75	65	55	45	35
	M,N	-20	40	130	110	95	75	65	55	45
	QL	-40	30	155	130	110	95	75	65	55
	ML,NL	-50	27	180	155	130	110	95	75	65
	QL1	-60	30	200	180	155	130	110	95	75

Table 36 Maximum thickness of parent material for σref= 0.25 fy(t).

Steel type	Grade	Resilience $T(^0C)$	Resilience Jmin	Reference temperature Tref (^0C)						
				10	0	-10	-20	-30	-40	-50
				σref= 0.25 fy(t)						
S355	JR	20	27	110	95	80	70	60	55	45
	J0	0	27	150	130	110	95	80	70	60
	J2	-20	27	200	175	150	130	110	95	80
	K2，M, N	-20	40	200	200	175	150	130	110	95
	ML,NL	-50	27	210	200	200	200	175	150	130
S420	M,N	-20	40	200	185	160	140	120	100	85
	ML,NL	-50	27	200	200	200	185	160	140	120
S460	Q	-20	30	175	155	130	115	95	80	70
	M,N	-20	40	200	175	155	130	115	95	80
	QL	-40	30	200	200	175	115	130	115	95
	ML,NL	-50	27	200	200	200	175	155	130	115
	QL1	-60	30	215	200	200	200	175	155	130

The Fig. 31 below show the surface of fractured specimen for different zones such as lower shelf, mixed mode, and upper shelf.

Fig. 31 Fracture surface of tested specimens [36].



7 Underwater welding

The first underwater welding was used to seal a leaking ship rivets by British Admiralty-Dockyard in the early 1900s [39]. Failure of offshore structures requires repair welding which are done underwater. Underwater welding is classified into wet and dry underwater welding. Wet welding is done directly in the exposed environment of the water. While dry welding is carried out in a dry chamber near the area to be welded.

Underwater welding is carried out with SMAW and FCAW. The water environment causes fast quenching and this forms hardened HAZ and making it susceptible to hydrogen cracking. This makes it difficult to weld steels with high carbon content. Steels with carbon content less than 0.4 % are weldable with wet underwater technique. [40] At greater water depth, higher strength steels with over 350 MPa are used and this makes it more difficult to weld because of the high carbon content they contain. In underwater welding, the applied stress can be reduced by improving the fit up of the weld joint , the repair of platforms, scalloped sleeves are frequently fillet welded over the damaged region. Residual stresses are difficult to address because of the difficulty for post weld heat treatment. Some of the welding practices used to reduce residual stresses are

- The use of small weld deposits
- Using consumables that have compatibility of thermal expansion with the base material
- The use of edge preparation to reduce the total weld deposit. This is because the cross sectional area of the total welds bead deposit is a direct relationship of shrinkage formation.

The applications of underwater welding are as follows [41]**.**

- Repair work of damaged offshore structure caused by ship collision
- Rescue sinking vessels in the sea
- Repair and maintenance of ship
- Construction of huge ship beyond the capacity of the docks available

Characteristics of a good underwater welding [41]**.**

- Good visibility
- High quality and reliable welds
- Minimum electrical hazards
- Ease of operator to support himself
- Flexibility of welding in all positions

Despite the difficulty to reduce the residual stress and hydrogen cracking in wet underwater welding, there is an investigated approach known as temper bead practice which reduces the tendency of cracking of the near fusion line. The temper bead practice is the deposition of weld on a previous weld deposit that has a lower tendency to crack than the base metal. The second deposition is carefully placed to the previous bead fusion line in a way that the thermal energy tempers the near fusion line HAZ of a cracking susceptible base metal. The temper bead approach is an optimum practice for wet weld of steels with higher carbon equivalent. A base metal free from weld metal hydrogen and thus cold cracking is a successful management of the mechanical integrity of underwater wet welding [40].

The Fig. 32 below explains the temper bead practice. For a single run, the parent material directly below the weld will be highly coarsed which is the region shown as red in the Fig. 32a below. The parent material below the coarsed region will have a refined grain shown as blue in the Fig. 32a below.

In other to improve the HAZ toughness, the temper bead technique will either reduce or eliminate the coarsed region from parent material. In the Fig. 32b below, the first layer of weld constant of small beads which are deposited using low heat input which ensures minimum penetration. The 50/50 bead overlap will reduce the coarse grained area [42].

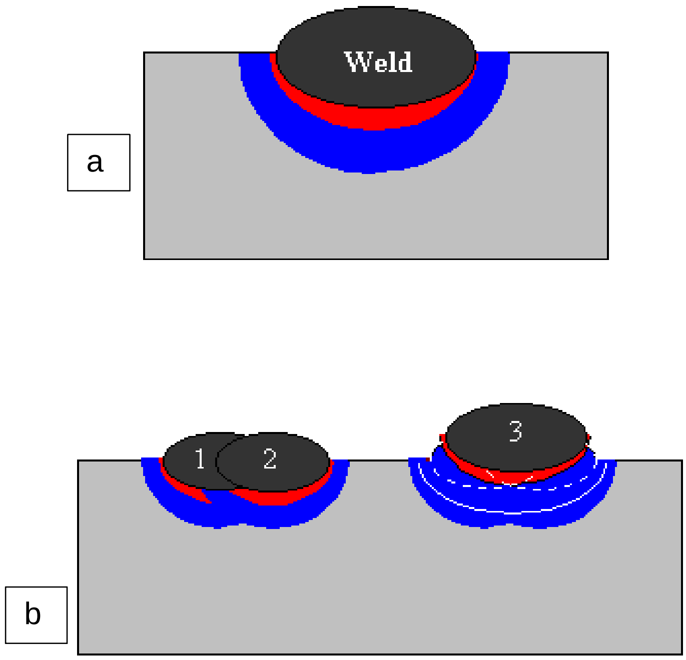


Fig. 32: Temper bead welding technique [42].

Advantages of wet underwater welding

It allows easy access to restricted areas which cannot be accessed by dry underwater welding

Welding support equipment can be easily mobilized to site

Repair operations are easily planned and carried out due to welder accessibility [43].

Disadvantages of wet underwater welding

The surrounding water causes rapid quenching of the weld metal and this causes reduction in ductility, impact strength and increase in porosity and hardness.

Poor visibility and the welder cannot weld properly.

Presence of large amount of hydrogen and causes embrittlement [44].

The Petrobras underwater activity in Brazil

In Brazil, the oil reserve in the offshore located at depth between 400 to 1000 m (deep water) and beyond 1000 m (ultra-deep water) accounts for fifty percent of the total oil and gas in Brazil. About sixty 66% potential oil discoveries are in the deep and ultra-deep water. This has led to the application of underwater welding at Petrobras. The use of underwater wet welding for structural requirement is limited to the installation of braces to give support to production risers by welding the base plate of the brace to the waiting plate of the shoulder of a concrete platform. Most of the wet welding takes place in shallow water. Petrobras is carrying out a research on SMAW with the aim of qualifying wet welding procedures in line with the ANSI/AWS D3.6 class B [40].

Underwater laser welding

Other advanced underwater techniques are friction welding and laser welding. An advanced welding technique for underwater welding is application of laser welding process. Westinghouse is using this technology for underwater repair in the nuclear power industry. Underwater laser welding has several advantages compared to the traditional welding processes. This technique is suitable for cladding or stress corrosion cracking reduction and welding of component with high irradiance. This welding technique is automated and it has several advantages as listed below [45].

The weld head can fit to various geometry and it is compact.

Low heat input to the base metal

The high ability of sealing can be used to eliminate small cracks

The laser unit can be located far from the work are

The Fig. 33 below is the welding machine use for underwater laser welding.

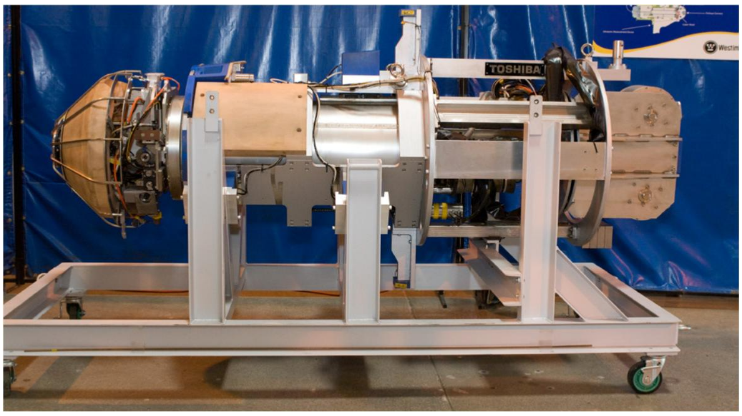


Fig. 33 Underwater laser welding machine used by Westinghouse [45].

7.1 Corrosion in the offshore environment

The offshore environment is very corrosive and there is the need for corrosion protection of offshore structures to improve the fatigue life of the structure and this should be considered during the design and maintenance phase. The corrosion rate for different levels of the offshore differs. The levels which are the immersion zone, atmospheric zone, and splash zone, see Fig. 34 below. The critical corrosion zone is the splash zone which is twice the rate of corrosion in the immersion zone [46, 47]. Corrosion in the marine environment is hazardous especially in the splash zone and topside. However this has not led to any major failure in the North Sea up to this day but it causes aging of structural installation [48].

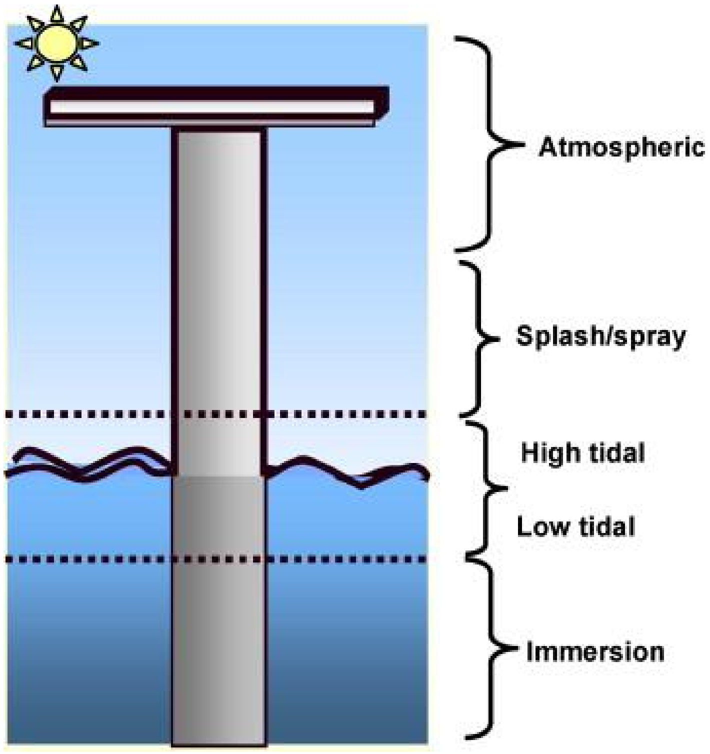


Fig. 34 Corrosion zone in the marine environment [49].

The most common corrosion protection method used for offshore structures are

- Protective coating
- Cathodic protection of coated steels
- Corrosion resistant metallic or plastic
- Cathodic protection of bare steels [47].

Requirements for coating system are:

- Can be applied above water
- Tolerant to surface
- Can displace water from the metal substrate
- Fit pit and surface irregularities

- Can withstand microbial action
- It is resistant to weather
- Can prevent or reduce corrosion [47].
- The corrosion rate at different area of the marine environment is shown in the Table 37 below. The causes of the corrosion and also the suitable protection method against the corrosion are suggested in this table.

Table 37 Offshore corrosion rate of steel as steel thickness loss per year [50].

Area	Corrosion rate	Suitable coating protection method	Causes
Atmospheric zone	80- 200 µm	Zinc-rich primer, Epoxies and UV durable topcoat	Extended period of wetness. High concentration of chlorides. UV light from sun
Immersion zone	200- 500 µm	Epoxy	Fouling.
Splash zone	100- 200 µm	Epoxy or polyester	UV light from sun. Erosion from water debris and ice.
Tidal zones	100- 200 µm	Epoxy	Seawater

7.2 Ongoing offshore projects

The offshore industry is experiencing a huge investment and production in different part of the world. Some of the factors which necessitate the oil and gas industries in investing in offshore projects are location of production site, field economics and political stability or regulatory environment. Africa and America are experiencing greater investments in offshore projects. It is expected that by 2015, Africa, Asia-Pacific, North Sea and South America will be experiencing greater investment expenditure in offshore projects at all depth of water [51].

Fig. 35 Deepwater drilling rig movements and associated displaced investment (ṡ Billions) [51].

Ofon field, oil and gas field- Nigeria (Africa)

Ofon field is located at about 65 km offshore in the south-eastern coast of Nigeria. The contractors for this project are HHI and Technip. HHI is responsible for the construction of the offshore fixed platform and the contract was awarded in 2007. The phase two of the contract was lunched by total in 2012 and awarded to Technip which is responsible for the loading, transport and installation of the topside for the fixed platform which is scheduled to be completed in 2014 [52].

Table 38 Ofon field platform specification [52].

Parameter of the platform	value
Weight	13,000 tons
Height	30 m
Width	47 m
Length	54 m
Production capacity	105,000 barrels of crude petroleum and 3 million m^3 of natural gas

Fig. 36 Ofon field project- Nigeria [53].

North Rankin redevelopment project, Indian Ocean, Australia

The North Rankin redevelopment project is presently the largest in Australia. It is aimed at increasing the service life of the North Rankin and Perseus field till 2040. North Rankin and Perseus gas and condensate fields are located approximately 137 km off the North-West coast of Western Australia. These facilities will increase the compression to pull out low pressure reserves from the two fields. The project is to construct and install and additional gas processing platform. This new platform will be connected to the old platform by a bridge 100 m long. The project includes the commissioning of new production facilities. The renovation of North Rankin A and completion of necessary tie-ins which will provide living quarters and helicopter deck. The North Rankin B topside which is manufactured in South Korea by HHI. The North Rankin B substructures which is manufactured in Indonesia. The North Rankin B platform is the largest platform in the world [54]. The table 39 which show the parameters of the platform and Fig. 37 show the platform are shown below.

Table 39 North Rankin platform specification [54].

Parameter of the platform	value
Weight	58,000 tons
Height	80 m
Width	50 m
Length	100 m
Service life	25 years

Fig. 37 North Rankin platform [54].

Seven-Borealis Clov crane vessel- Angola

The operator of the vessel is Total E&P and the contractor of the project is Subsea 7. This contract was awarded in 2010 at a sum of 1.3 billion dollars and the expected completion date is 2012. The vessel is located in the deep water. The vessel is located in the northern part of Angola Block 17, approximately 40 km North-North-west of the Girasol Development [55, 56]. The Table 40 below show the parameters of the crane vessel specification.

The J-lay installation system is developed for the installation of pipeline in very deepwater. This system is also suitable for deepwater and ultra-deepwater application. The J-lay systems are designed as modular systems which can be installed or removed easily without costly modification to the derrick barge. The J-lay system is mostly used for the fabrication of girth welds for thick wall pipelines of X65 steel grade or similar grades. The J-lay installation is used for offshore welding of onshore prefabricated lengths and where the pipeline is immersed vertically so that the pipeline takes J shape from the installation vessel to the seabed. The prefabricated length is placed in a tower and circumferential vertical welding is done at a single welding station before lowering the pipe. The Fig. 38 below shows the J-lay system [57].

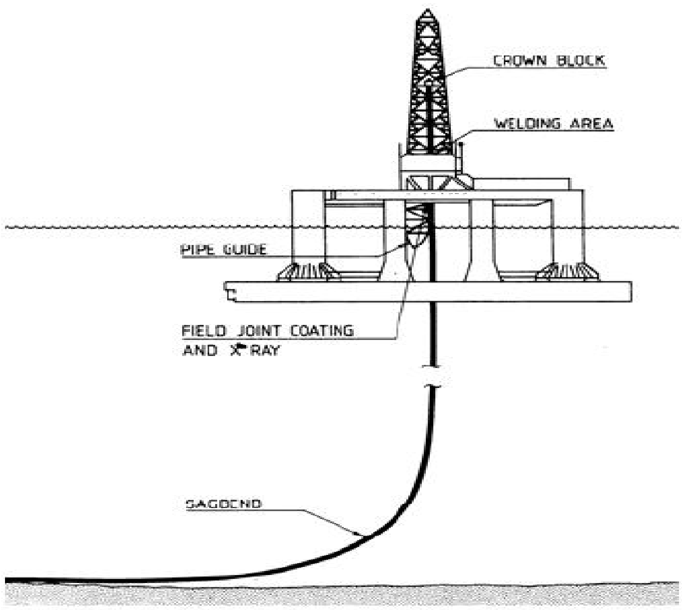


Fig. 38 Principle sketch of J-lay vessel [57].

The S-lay is used for the installation of linepipe in the horizontal position, immersing the pipeline into the sea at a certain angle across a stinger. This process gives the pipeline an S shape from the installation vessel to the seabed. The lay-rate for this type of installation process is about 4 km/day. However, the lay-rate depends on the vessel and pipe size [57]. The figure 39 below show the S-lay system.

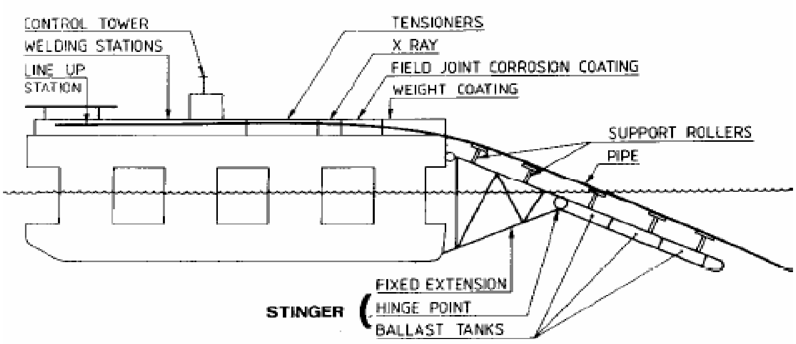


Fig. 39 Principle sketch of the S-lay systems [57].

Table 40 Seven-Borealis Clov crane vessel specification [66, 67, 68].

Parameter of the Vessel	value
Weight	58,000 tons
Depth of main deck	16.2 m
Operating draft	8.5 m to 11.35 m
Length	182.2 m
Breadth	46.2 m
Endurance	45 days in transit with 220 persons 45 days on DP with 399 persons
No of welding stations (J-LAY)	Pipelines welded (S-LAY)
1429 welds 324 mm (22.2 mm, X65)- 34.3 km **982 welds 324 mm (18.3 mm, X65)- 23.7 km** **1051 welds 324 mm (15.9 mm, X65)-36.1 km** **1481 welds 324 mm (14.3 mm, X65)- 36.1 km**	1270 welds 324mm (15.9 mm, X65)- 31 Km 7 welds 324 mm (22.2 mm, X65)- 0.17km

Fig. 40 Seven-Borealis crane vessel [56].

Hebron fixed platform project-Newfoundland (Canada)

Hebron oilfield is located 350 km south-east coast of the Newfoundland in Canada and it is located 92 m deep in the water. The Hebron project partners are Exxonmobil with 36% interest, Chevron with 26.7%, Petro-Canada with 22.7%, and Statoil with 9.7%. The project was signed in 2008 and it is expected to be functional before the end of 2017. The Hebron facility is designed to handle a production rate of about 150,000 barrels per day and it is expected to increase to 180,000 barrels per day. The project life is estimated to be 30 years from the development phase to the abandonment phase [58]. The Fig. 41 below shows the hebron fixed platform.

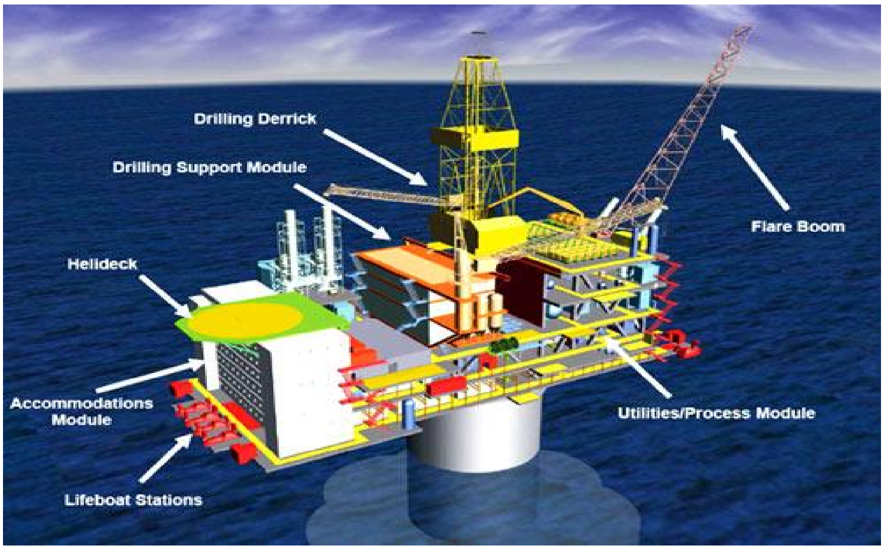


Fig. 41 Hebron oil project concepts [58].

7.3 Future trends

In the future, more research will be underway as to developing more suitable structural materials for offshore application with higher strength, good weldability and corrosion resistant materials.

The increasing challenge faced with underwater welding will be in the forefront of the offshore industries research and development project.

However, the offshore industries are able to withstand the present challenges with the available technology on ground. But more environmental friendly and construction made easy technology will be focused on.

8 Conclusions and summary

The main goal of the research work is to review the weldability of structural steels used in the warm offshore environment. In the view of getting a deeper understanding of the conditions which affect offshore structures as it relates to their weldablity in achieving a sound weld which gives the whole structure a high integrity, different offshore steels where analyzed. This paper describes different offshore structures and their applications and conditions for operation.

The importance of offshore exploration is of immense importance to the economy of many nations in the world today as it is also of great importance for natural resources which are useful in many applications. The unavoidable application of oil and gas as a means of energy has made many offshore industries to go into deeper waters and even ultra-deep waters. This makes it important for various research work to be carried out as to finding suitable materials which can fulfill the desired offshore requirement and are easily weldable and sound quality is achieved and it is economical to the offshore industries.

This research paper illustrates the various offshore conditions and their effect to the offshore structures and the considerations of these environmental conditions in the design phase of offshore structures. The marine environment makes it difficult to achieve quality welds and these factors are factored in the design so as select suitable materials with desired mechanical and chemical properties which will have the necessary impact toughness that is a major requirement to consider in offshore structural design, fabrication and welding phase. The steelmaker have been of immense importance in achieving new methods of manufacturing steel grades with low carbon content, high strength and improved weldability.

This Master's thesis considers offshore structural steel with improved weldability such as S355, S420, and S460 delivered in the normalized and thermo-mechanically rolled conditions. These offshore structures have a wider range of heat input and the thermo-mechanically rolled offshore steels require preheating to remove moistures. These steels have a carbon content of about 0.08% and this makes it possible to achieve quality welds and improved ductility and toughness.

Heat input: The welding heat input is a very important factor as it affects the cooling rate and the microstructure of the welded joint. It is important that a microstructure that has desired ductility and necessary toughness is the focus in welding offshore structures. However, this research work has been able to identify offshore structural steels with a wider working range and application of minimum and maximum heat input.

Phase transformation: The phase transformation of the HAZ of a welded joint determines the mechanical properties of the joint. A welded joint with fine grain size and sufficient ductility in the HAZ is important for offshore structures because the HAZ is the site that is prone to weld defects.

Weld defects: Welding defects are signs of bad quality weld. Defects such as hydrogen induced cracking, lamellar tearing and solidification cracking should be avoided in welding offshore structures because these structures are applied in critical conditions and the risk of any structural failure due to weld defect cannot be accepted. In welding offshore structures, low hydrogen welding processes are used and importantly the thermo-mechanically rolled steels used for offshore structures are suitable to be welded without weld defect because of the reduced carbon content.

Weldability: This research work has been able to identify weldable offshore structures with improved weldability properties. Structural steels such as S355M, S420M, and S460M are weldable offshore steels.

Underwater welding: Underwater welding is an area which needs more research because we cannot overemphasize the importance of repair work in the offshore industries. The difficulties associated with underwater welding are a great challenge that makes impossible to have quality welds underwater because of the very high cooling rate. However some companies such as Petrobras have been able to overcome this using the SMAW processes. Investigations have shown that using the temper bead technique, the difficulty associated with residual stress and hydrogen cracking can be reduced.

Corrosion: The marine environment is corrosive to offshore structures and this reduces the structural integrity of the structures and needs to be controlled. The effective corrosion methods used for offshore industries are cathodic protection and coating method.

Finally this research work has made an important finding that the ability of improving structural steels during the manufacturing phase by the steelmaker is an important process of increasing the weldability. It is important to note that some of the defects which are caused as a result of the material itself from the steel making process are sometimes unavoidable. Thanks to improved thermo-mechanically rolled steels with reduced carbon content, high strength and toughness for offshore structure.

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