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ADVANCED WELDING TECHNOLOGIES USED FOR ARCTIC METAL STRUCTURES

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Dr. (Tech.) Paul Kah

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ABSTRACT

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Rapid depletion of easy-to-access fossil fuel, predominantly, oil and gas resources has now necessitated increase in need to develop new oil and gas sources in ever more remote and hostile environments. This is necessary in order to explore more oil and gas resources to meet rapidly rising long-term energy demand in the world, both at present and in the nearest future. Arctic is one of these harsh environments, where enormous oil and gas resources are available, containing about 20% of the world total oil and gas, but the environmental conditions are very harsh and hostile.

However, virtually all the facilities required for the exploration and development of this new energy source are constructed with metals as

well as their alloys and are predominantly joined together by welding processes and technologies.

Meanwhile, due to entirely different environment from the usual moderate temperate region, conventional welding technologies, common metals and their alloys cannot be applied as this Arctic environment demand metals structures with very high toughness and strength properties under extremely low temperature. This is due to the fact that metals transit from ductility to brittleness as the temperature moves toward extreme negative values.

Hence, this research work investigates and presents the advanced welding technologies applicable to Arctic metal structures which can give satisfactory weldments under active Arctic service conditions.

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DEDICATION

This project work is dedicated to the glory of God Almighty who in His infinite mercy has preserved me up to this glorious moment and also to my lovely demised parents; Late Mr. And Mrs. Israel Aderinola for their ever-available support, may their soul rest in perfect peace.

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LIST OF SYMBOLS AND ABBREVIATIONS

^0C	Degree Celsius
AC	Alternating Current
AWS	American Welding Society
CO_2	Carbon dioxide
CTOD	Crack Tip Opening Displacement
CTWD	Contact Tip to Work Distance
DC-	Direct current straight polarity
DC+	Direct current reverse polarity
GMAW	Gas Metal Arc Welding
H_2S	Hydrogen Sulphide
HAZ	Heat Affected Zone
HPDL	High Power Diode Laser
HSS	High Strength Steel
KCV_{-40}	V-notch Charpy Impact test toughness value at -40 ^0C
kW	Kilowatt
LAHW	Laser-Arc Hybrid Welding
LBW	Laser Beam Welding
LNG	Liquified Natural Gas
LSAHW	Laser- Submerged Arc Hybrid Welding
MAG	Metal Active Gas

MIG	Metal Inert Gas
MIR	Submersible Vehicle
MPa	Mega-Pascal
Nd:YAG	Neodymium:Yttrium-Aluminum-Garnet
NDT	Non-Destructive Testing
NGW	Narrow Gap Welding
PAW	Plasma Arc Welding
PWI	Paton Welding Institute
SAW	Submerged Arc Welding
SAW-NG	Narrow-Gap Submerged Arc Welding
TMCP	Thermo Mechanical Control Process
UOE	U-shape O-shape (Method of Pipeline Production)
UV	Ultraviolet
YP	Yield Point
YS	Yield Strength

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1. INTRODUCTION

Alarming increase in demand for energy in world and decline of easy-to-access fossil fuel, predominantly, oil and gas resources have necessitated increase in need to explore and develop new oil and gas sources in ever more remote and hostile environments. This is to allow for exploration, development and production of more oil and gas resources in order to help meet the rapidly rising long-term energy demand in the world.

Arctic is one of these hostile environments, where enormous oil and gas resources are located but the environmental conditions are very harsh and hostile for easy exploration, development and production of its energy resources.

Likewise, Arctic is highly endowed with high and strong wind which has encouraged the use of its wind resource for power generation through installation of wind turbines and their auxiliary components in the Arctic environment. Meanwhile, experiences has shown that no matter how hostile these environmental conditions are, advanced technology is the key to meeting these Arctic challenges and make it possible to harness Arctic abundant energy resources [1, 2].

However, to operate successfully in Arctic region and to minimize risk to personnel, facilities, and the environment, Arctic environmental conditions, and their impact on materials, facilities, logistics, operations, and human factors must be taken into consideration. Hence, the Arctic rich energy resources should only be explored with application of modern and advanced technologies that help to reduce environmental and social impacts and consequently boost achieving high levels of safety [1, 2].

To harness these resources with high level of safety, some facilities are needed to be put in place, for example, offshore platform and its auxiliary facilities (ship barge, oil drilling rig, pipelines etc.), ships, transport system (which might include railway system in the future), ice breaker, wind turbines, structures etc. In the same vein, the exploration of the Arctic resources will require construction of structures, offshore platforms, wind turbines, ice breaker and many other facilities (including equipment and devices to be used on the platforms) capable of operating safely at temperature of -40^0 C and possibly lower down till -60 ^{0}C.

Moreover, most of these structures, platforms and facilities were used to be built with metals (mainly structural steels and HSS) and joined together by welding technologies. Though, new platforms and the facilities being built nowadays are more of welded HSS steels (amid many other metallic materials), because of steel's relatively low cost, ease of fabrication, high strength, and availability of grades that are highly fracture-resistant at low temperatures (high toughness property) [3] yet new development has shown that titanium (though thought to be expensive), can satisfy high toughness requirement at low temperature than steel. Likewise, research is on-going to apply some alloys of Aluminium for construction of Arctic structures.

As it has been implied earlier above, Arctic environment is potentially hazardous from a structural integrity standpoint because metals weldments have increased susceptibility to brittle fracture at low temperatures. This is because steel has transition temperature range from ductility to brittleness; figure 1.0 show this transition .Hence, high material toughness criteria are needed to ensure that metals with adequate fracture-resistance at low temperatures (high toughness property) are used to build these platforms and facilities [3].

Nevertheless, demands for properties of materials used for Arctic structures include the followings; strength, impact, toughness, fatigue property, corrosion resistance, transition temperature etc. The demand for these properties ranges from the best to highest level possible. Meanwhile, demand for welding technologies also becomes more stringent with these demands for material properties. The demanded properties of the welding technologies required include high efficiencies, high qualities, high productivity, high deposit rate, many functions, labour saving, low cost etc. [4].

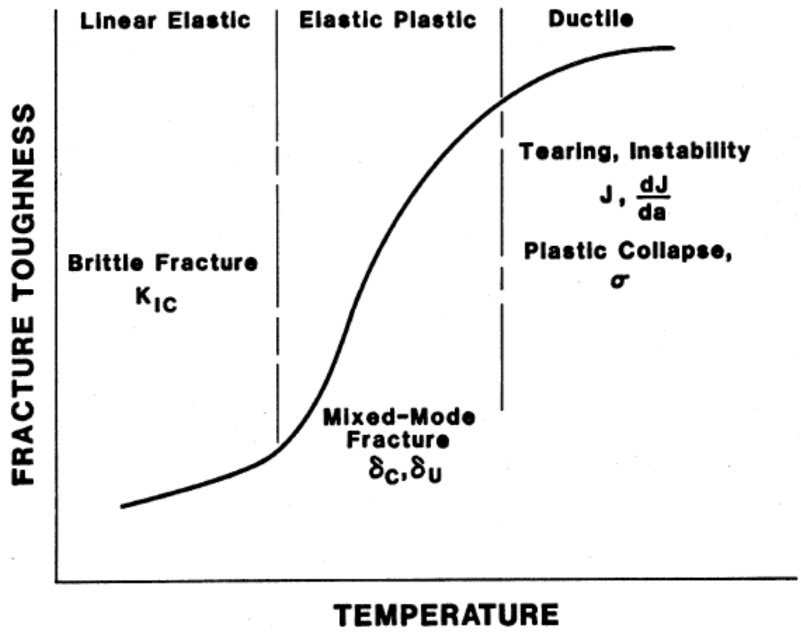


Figure 1.0: The ductile-brittle transition of steel showing brittle (linear elastic), elastic-plastic and ductile (fully plastic) regions [3]

Hence, as a result of these special Arctic environmental conditions, special and advanced welding technologies, and special and new grade of metallic materials (mostly steels) are inevitably needed to harness Arctic energy resources in order to ensure successful exploration. Consequently, this leads to reduction of failure of the platform, the facilities etc. and eventual protection of the personnel and the environment during operation.

Research has been carried out on various topics and in various ways and capacities on Arctic technology; however, research is still on-going in the following areas;

- Suitable advanced welding technologies required

- The grades of metallic materials that can fulfill these demanded service conditions.

Hence, this thesis investigates and presents various advanced welding technologies used in arctic environment and also, the arctic metal structures that can survive under these service conditions.

1.1. Concept of Welding Technology

The use of welding in modern day technology is very extensive; it had undergone a phenomenal development as far back as 1930, however, its growth has been faster than general industrial growth. Many common daily used items depend on welding for their economical construction; among such items are household appliances, machinery, ships, automobile cars, aircraft, electronic equipment etc. Hence, welding is considered as the most economical and efficient way of joining metals permanently [4, 5].

1.1.1. Operating conditions in Arctic regions

The operating conditions in arctic regions are extremely low temperature, ice gouging, wind disturbance, snow problem, among many others. Hence, the right welding technologies need to be chosen to be able to combat these harsh conditions.

1.1.2. Brief introduction to welding technology

According to American Welding Society (AWS), welding is a joining process that produces coalescence of materials by heating them to welding temperature with or without the application of pressure or by application of pressure alone and with or without the use of filler metal. Furthermore, Welding is a process whereby two materials (usually metals and their alloys) are permanently joined together through a localised coalescence originating from a suitable combination of temperature, pressure and metallurgical properties. The large bulk of materials that are welded are metals and their alloys, though the terminology also extends to joining of other materials such as thermoplastics and also to joining of two dissimilar materials such as plastic and metals. [4, 5, 6].

In welding metals and/or their alloys, the most essential requirement is heat which is supplied either through electrical process or by means of a gas torch. Pressure sometimes is needed but not really essential in many welding processes. Various sources of energy supplied are used in welding and these are usually in form of heat generated by a flame, an arc, resistance to an electric current, radiant energy or by mechanical means (friction, ultrasonic vibrations, explosion etc.). In some welding processes, pressure is used to force weld region to plastic condition while in fusion welding, the metal parts to be joined melt and fuse together in the weld region.

However, a wide range of welding processes has been developed as a result of different combination of temperature and pressure in a series of pattern which include a high temperature with no pressure; and a high pressure with low temperature. American Welding Society classified welding processes into various classes as shown in figure 1.1.1. Various welding processes differ in the manner in which temperature and pressure are combined and achieved.

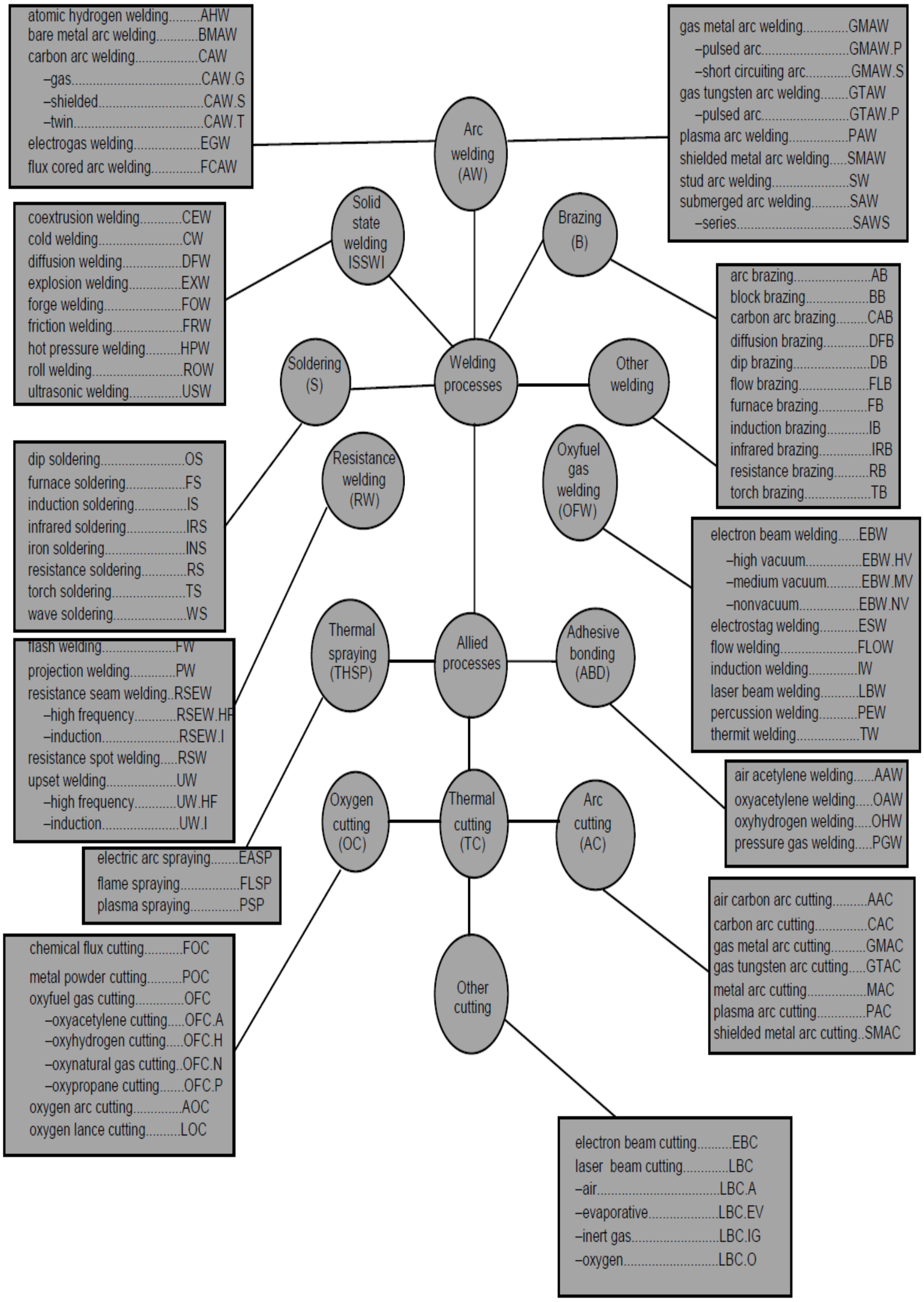


Figure 1.1.1: Master Chart of Welding and Allied Processes

Source: Welding Inspection Technology, American Welding Society (AWS) [5].

Though there are various welding technologies as shown in figure 1.1.1, this thesis dwell more on the advanced welding technologies applicable to welding of arctic metal structures. The advanced welding technologies considered were limited in this thesis to narrow gap welding (NGW), laser welding, laser-arc hybrid welding, tandem MIG/MAG welding and submerged Arc welding (SAW).

1.1.3. Importance of low temperature welding

As earlier stated, virtually 20% of the world oil and gas resources are found in Arctic region. However, the environmental operating conditions in Arctic are very harsh (extremely cold, among many other hostile conditions) and there is need to carry out welding operations under these conditions. Hence, there is need to study explicitly low temperature welding technologies in order to be able to operate safely under these conditions and also to ensure that Arctic structures are safe under the Arctic conditions.

1.1.4. Advanced welding technologies applicable to Arctic conditions

The advanced welding technologies applicable to Arctic conditions that were discussed in this thesis work are narrow gap welding (NGW), laser welding, laser-arc hybrid welding, tandem MIG/MAG welding and multi-wire submerged Arc welding (SAW). They are highlighted below.

1. Narrow gap welding (NGW)

2. Laser beam welding (LBW)

3. Laser-Arc hybrid welding

4. Tandem MIG/MAG welding

5. Multi-wire Submerged Arc welding (SAW)

1.2. Arctic Region: Geography and Climate.

Generally, whenever, the word Arctic is heard, it is believed to be one of the world continents just as its southern counterpart, Antarctic, being located at the southern-most part of the world global hemisphere. But, this is a very completely wrong opinion which must be corrected.

1.2.1. Brief introduction to Arctic

Arctic is an Earth geographical region located around North Pole, the Northern-most part of the Earth. Arctic is not part of the world continent division, unlike its southern counterpart, (Antarctica) which is located at the southern-most part of the world hemisphere. It is made up of territories and/or zones that fall within Arctic Circle (which is a parallel of latitude located at 66°32' or 66.5º north of Equator and it is also the approximate limit of midnight sun and polar night) [7, 8, 14]. It has a large, ice-covered ocean, surrounded by treeless permafrost. Two-fifths of Arctic is in a state of permafrost, a condition in which an area of ground remains permanently frozen. The remaining three-fifths melt during Arctic summer [13].

Politically, Arctic region includes northern territories of the eight Arctic states, although by natural science definition much of these territories are considered subarctic. The eight countries include Canada, Denmark (Greenland), Finland, Iceland, Norway, Sweden United States (Alaska) and Russia, which has the largest territory (see figure 1. 2.1).

Furthermore, Arctic is the geographical region within which there is one period of 24 hours in each year in which the sun does not rise and another similar period in which the sun does not set. In Arctic region, the average temperature for warmest month (July) is below 10 °C. Arctic climate is characterized by cold winter and cool summer; the region is customarily divided into two climate type, namely *ice caps* and *tundra*. The Ice caps climate type simply mean that mean monthly temperature never exceeds 0 ºC while tundra climate type mean that there is at least one month in which mean temperature is greater than 0 ºC, but there is no month in which the mean temperature is above 10 ºC. Average winter temperature can be as low as -40 °C and the coldest recorded temperature is approximately -68 °C. Based on study experience, temperatures of -70 ºC have been observed in Greenland. Coastal Arctic climates are influenced by presence of ocean, thereby resulting to warmer temperatures and heavier snowfalls than the colder and drier interior areas. Annual precipitation is low in this region, with most of the area receiving less than 50 centimetres and mostly come in form of snow, most time high winds stir up snow thereby creating illusion of continuous snowfall.

Arctic is endowed with a sizable number of natural resources which include oil, gas, minerals, fresh water, fish and forest (located within the subarctic region) and some of the countries within this region (especially Russia, Shtokman area) are considering these as a significant new opportunities to applied modern technology and obtain more economic advantage.

Moreover, Arctic region is a unique area among Earth's ecosystems. It is one of the last and most extensive continuous wilderness areas in the world, and it is very significant in preserving biodiversity and genotypes and now there is increasing presence of human activities in this vital habitat. Arctic is susceptible to wearing down of groundcover and also to disturbance of rare reproduction places of animals that are characteristic to the region. [8, 9, 10, 11, 12, 13, 14].

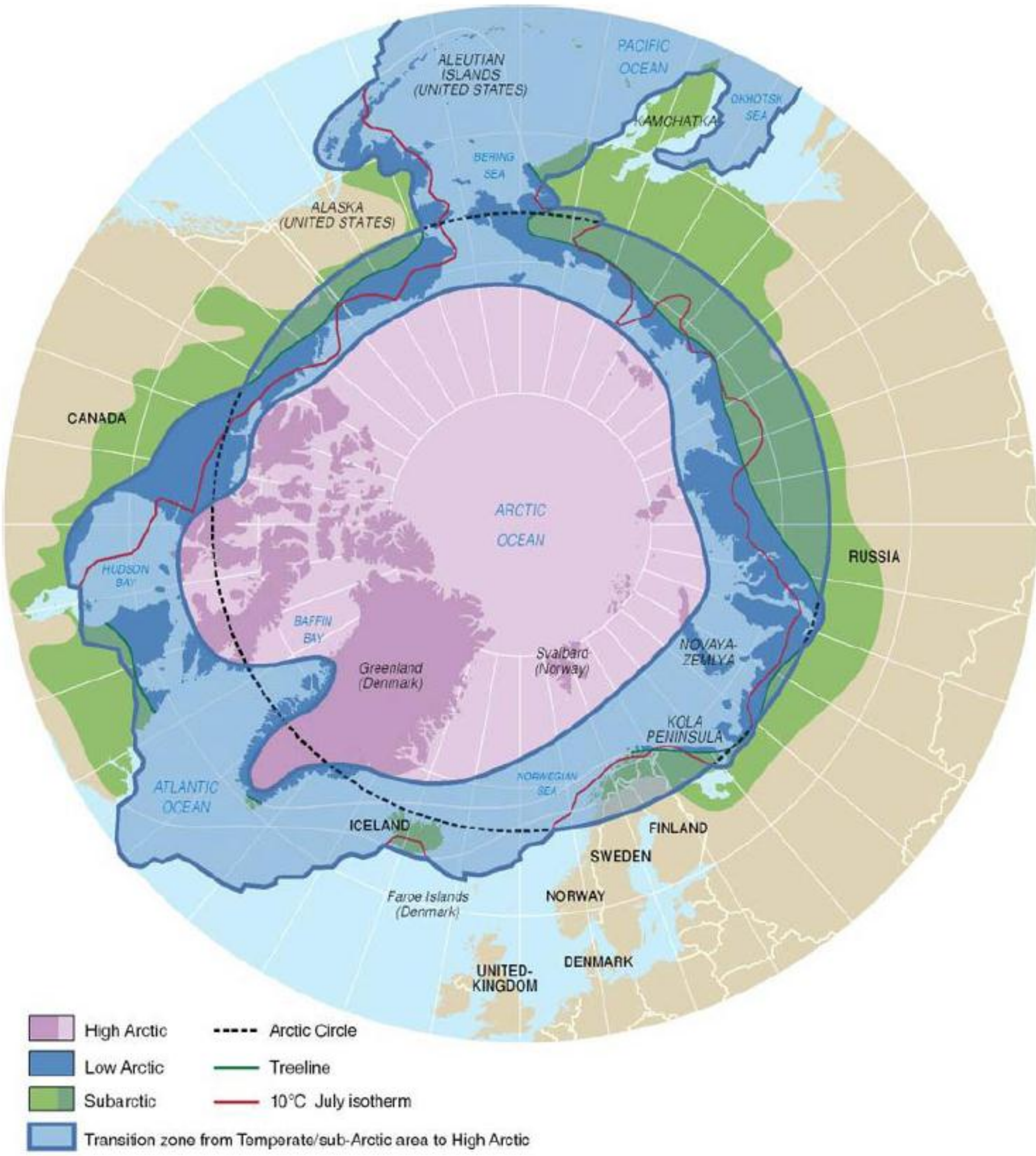


Figure 1.2.1: Earth Global structure showing arctic region, Arctic Circle and territorial countries.

Sources: CAFF, 2001, Arctic Flora and Fauna: Status and Conservation [15]

1.2.2. Special Arctic environmental conditions

Arctic possesses several physical challenges, among which are extremely low-temperature, remoteness, snow and ice etc. However, technology is the main key to meet these challenges and overcome them or at least bring them under control. The major physical challenges in Arctic region are highlighted below.

1. Extremely low temperature

Design temperature is one of the quality descriptions of any material. Generally speaking, metals (especially steels) are prone to brittle fracture at low temperatures. Steels have transition temperature at which their ductility property changes to brittleness. Hence, their design temperature normally lies 20°C below minimum expected service temperature and/or ambient temperature. In Arctic region, the minimum ambient temperature falls well below -40°C, consequently minimum design temperature down to -60°C must be accounted for. As a result, there is need for special grade metals (and/or higher grade steels) and other materials that can survive this extremely low temperature without failing under service conditions.

2. Snow and ice

Ice conditions in Arctic region vary considerably between territorial regions, within regions and depending on water depths and distance to shore. The ice also changes through the seasons, freezing up in autumn, getting thickest in winter, melting in spring and creating open water in summer. During the months when ice grows, wind and water currents cause it to move and form ice ridges that can be many times thicker than ice held fast to the land.

Ice problems, to large extent dictate criteria for Arctic design and operations. Sea ice presents the major challenges, being the single most important environmental factor affecting operations in the Arctic. Moreover, additional problems are created by other ice (such as ice islands, floebergs, and structural icing) to platforms, ships, and helicopters. The characteristics of sea ice, pressure ridges, and ice movement are the main concern in the design of Arctic structures. Some ice islands are very huge and as a result could create a major damage from a collision between them and an offshore structure. [1, 2, 8, 13].

3. Wind

Arctic is endowed with a very strong wind, which is due to large air pressure gradient. Although, this wind resource can be converted to energy source, it has great negative impact on oil and gas exploration facilities. The cyclic loading of the oil and gas facilities by the wind waves can easily leads to failure of the facilities.

4. Permafrost and seasonal frozen ground

Permafrost is permanently frozen bedrock. An area of ground (soil or earth) is said to be in a state of permafrost when it remained below freezing point for two or more years. It is an area of ground that has a temperature below 0°C which persists over at least two full winters and in-between summer. In a continuous permafrost zone, permafrost is found everywhere under the ground surface to a considerable depth, except for layers of ground below large water bodies, however, in a discontinuous permafrost zone, permafrost is not as thick as that of continuous permafrost zone but exists in combination with areas in which their materials are softened by thawing. Seasonally frozen ground, known as ***active layer***, is the top layer of ground in which the temperature fluctuates above and below 0°C during the year. The thickness of this layer is of order 1 m in Arctic southern reaches, decreasing by a factor of 7 in the far north [8, 13].

5. Remoteness

Arctic is spatially located far away, almost inaccessible and sparsely populated, if not populated at all. Icing and snow drifts make vehicle access difficult or impossible without snowmobiles or other over-snow transport. Access roads face seasonal restrictions because of ice, snow drifts, and even avalanches (skidding) during the winter and possibly swampy conditions or flooding during the spring and summer.

6. Long periods of darkness

Arctic is characterized by long periods of darkness and daylight due to its geographical position. At the North Pole, sun remains above the horizon for six months at a time and below the horizon for another six months, as a result of which, there exist six months of daylight, followed by six months of darkness in Arctic.

Other physical challenges include floating ice, seismicity, and fine and silty sediments. However, fine, silty sediments and sub-bottom permafrost are two geotechnical factors of concern in Arctic waters.

1.2.3. Common engineering challenges in Arctic region

Due to the hostile environmental conditions in the Arctic region, there are some common engineering challenges that come with these Arctic conditions. Some of the challenges are brittle failure of facilities made of metals, problem of corrosion, problem of large deformation of pipelines, power source for welding equipment, overloading of facilities due to ice gouging etc. Though, technology has been said to be the key to solving these challenges yet, research is on the way to reduce the extent of effect of these challenges [2, 3].

1.3. Materials Applicable in Arctic Structures and in Arctic Conditions

There is high demand for new grade of metallic materials structure for use in Arctic environment. Various metallic material producing companies are now involved in research to produce a higher grade of steel and other metallic alloys that can satisfy the service conditions in Arctic. Some of these newly used materials are steel grades of X70, X80, X100, X120, titanium alloys (Grade 5, Ti-6Al-4V (Ti64)), upgraded 9% Ni steels etc. Meanwhile, some Arctic structures and facilities have been built with the new materials and a lot are still underway. For instance, various part of MIR submersible (a deep submergence vehicle) was built mainly with combination of titanium and maraging steel [16] (see figure 1.3), new pipelines being laid now are made of new higher grades of steel and other alloys that have high toughness under very low temperature. Hence, material application in Arctic resources exploration and development cannot be overemphasised and the development within the field of Materials Technology is very vital to ensure success in reaching the aim of safe exploration, development and production of Arctic energy resources.

Figure 1.3: MIR submersible (deep-submergence vehicle)

Source: NOAA Ocean Explorer [16]

1.3.1. Material properties demand of Arctic structures

Arctic is such a hostile environment with temperature falling below -40^{0}C. Generally, metals (predominantly steels) are used for constructions of offshore platform and most facilities used in Arctic. However, metals are susceptible to brittle fracture at a very low temperature as in this case of Arctic conditions. Hence, there are specific properties that materials to be used under Arctic conditions must possess before they can be able to satisfy service conditions in this environment. One of the major properties is *high toughness at very low temperature*, others include transition temperature, mechanical properties such as impact, strength etc.

Base on the aforementioned material properties demand in Arctic service, the typical materials used are steels (most common) and titanium (often times). Examples of steel grades used are high strength structural steels: X70, X80, X100, X120 etc. Though, there is still on-going research to obtain more reliable materials that can provide better toughness properties [4, 17].

1.3.2. Arctic metal structures and metal properties

Technology development and advancement are making effort to ensure that Arctic region is more comfortable to explore the naturals resources there and also to make the region habitable to human and personnel. Due to earlier mentioned stringent Arctic physical challenges and conditions, common ordinary engineering materials especially metals used in temperate region cannot survive in this arctic region without short time failure. Hence, there is need to obtain new grades of metallic materials that can withstand the extremely low temperature and extra loading conditions of the Arctic region. Despite research is still on-going to obtain a better improved materials, some research have gotten some useful materials that can survive under this Arctic conditions, among which are titanium (though very expensive), steel grade X120 etc. The major properties of materials required are mechanical properties (which include strength, impact and toughness) and transition temperature.

1.3.3. Nanomaterial application in Arctic conditions: Metal protection

Nanomaterials are now applied in nano cladding of metal (mainly steels) structures to protect the metals against wear and corrosion that is inbound in Arctic region. Though a lot of protective mean of coating metal structures are available but the use of nano cladding seems to be gaining ground with respect to Arctic metal structures. The need to improve and protect Arctic metal structures is inevitable if failure due to corrosion is to be avoided. There are many method of protecting the surface of metals but the ones that have been applied to Arctic metals are cathodic bombardment protection, nano cladding etc.

1.4. Welding in Arctic Region

Welding in Arctic has become an essential part of developmental project to explore and develop Arctic abundant energy resources. Due to the challenges involved in welding metals in Arctic, advanced welding technologies must be applied to ensure a good weldment that can satisfy and survive Arctic service conditions. The advanced welding technologies presented in this thesis with respect to welding metals under Arctic conditions are Narrow gap welding (NGW, officially called narrow groove welding), laser welding, laser-arc hybrid welding, tandem metal inert gas/metal active gas (MIG/MAG) welding and multiwire submerged Arc welding (SAW).

1.4.1. Why welding in Arctic region is so important

Arctic is a new face of earth where the world is looking unto to satisfy the increasing demand for energy. Even, Arctic will be used more and more in the future than today. However, this environment needs to be developed and make conducive for exploration and production of its enormous energy resources. Safety during exploration of the energy resource and protection of the environment are very important in this area, hence, the only key to this development is technology.

Moreover, most of the facilities to be put in place for easy and safe exploration of these resources are made of metals and their alloys. However, welding is the most economical and efficient process for construction and joining of these metals and their alloys. For instance, offshore platforms, ships, wind plants, pipelines, railways, ice breakers, which are made of different steel grades, titanium, aluminium and other metal alloys structures will be needed in this harsh environment.

Hence, Arctic welding is the most essential process to ensure that these facilities and equipment are readily available and meet up with the service conditions in Arctic environment, in order to guarantee high level of success in exploration of these abundant resources.

Meanwhile, welding cannot go alone without inclusion of suitable materials to be used to construct these structures and facilities. Hence, special metallic materials and alloys together with advanced welding technologies are important to avoid failure of these facilities, structures and equipment while under active Arctic service.

1.4.2. Challenges associated with welding in Arctic region

The major challenges associated with welding in Arctic region are highlighted as follows [3, 4, 17]:

- Problem of residual stress
- Problem of failure and fracture of welded joints
- Brittle failure of facilities made of metals
- Problem of cold cracking
- Problem of heat affected zone (HAZ)
- Problem of corrosion
- Problem of large deformation of pipelines
- Problem of power source for welding equipment

- Problem of functionality of welding equipment
- Extra loading of facilities due to ice gouging

Hence, without mincing words, advanced technology is the main key to solving these challenges and research is really on the way to minimize the extent of effect of these problems.

1.4.3. The need for advanced welding technologies in Arctic

However, due to hostile environmental condition in Arctic and the above highlighted problems, conventional welding technologies cannot give satisfactory weldments that can survive the service conditions. This is because high heat input (controllable), special filler materials and power sources are needed. Also, the strength and toughness of the weld joints produced by these conventional methods do not meet the minimum safety requirement of the weld joints that can survive under active Arctic service conditions. Hence, there is need to apply advanced welding technologies that can give a higher percentage of assurance of reduction in failure of welded facilities and structures to be used under Arctic conditions.

1.4.4. Power source for welding equipment in Arctic

Power source for welding facilities is one of the critical issues to be considered while considering welding in Arctic conditions. Due to remoteness of Arctic, electricity power grid is not likely to be available in the location; hence there is also a need to research widely on power source for the welding equipment to be used on site. Some power sources have been proposed and some have been applied giving more chances for improvement. Among the suggested power sources that can be used are small wind charger, diesel engine, hybrid power system etc. A diesel engine can be combined with a battery bank to decrease engine run time and reduce the use of diesel fuel. However, the common source of energy on Arctic site nowadays is nuclear energy powered ship.

1.5. Motivation, Problem Statement and Justification of the Research

The motivation for this research work came from the circumstance of rapidly declination of easy-to-access fossil fuel, predominantly, oil and gas resources. This has now necessitated increase in need to develop new oil and gas sources in ever more remote and hostile environments in order to explore more oil and gas to meet rapidly rising long-term energy demand in the world both at present and in the nearest future.

Arctic is one of those environments, where enormous oil and gas resources are available but the environmental conditions are very harsh and hostile. However, virtually all the facilities required for this exploration and development of this new energy source are constructed by welding processes and technologies.

However, due to the entirely different environment from the usual moderate temperate region, conventional welding technologies and the common metals and their alloys cannot be applied as this arctic environment demand metals structures with very high toughness property under extremely low temperature. Hence, there is need to investigate the advanced welding technologies and the arctic metal structures that can give a satisfactory weldments under arctic service conditions.

1.6. Research Objective

The objective of this research work is to investigate and present advanced welding technologies and Arctic metal alloy structures that can be used for construction and maintenance of Arctic metal structures, equipment and facilities under active Arctic service conditions, without experiencing any failure. The essence of this is to know the suitable advanced welding technologies and the Arctic metal alloys needed for fabrication of Arctic metal structures and facilities used for exploration, development and production of abundant energy resources in Arctic.

2. WELDING METAL STRUCTURES IN ARCTIC CONDITIONS

Welding of metal structures is inevitable activities in fabrication of facilities used for exploration of Arctic energy resources. However, the issue of concern is selection of the most suitable advanced welding technologies that will guarantee high productivity, safety, and quality, among many other desired characteristics of weld joint.

2.1. Commonly Welded Structures in Arctic

Welding is the most economical and efficient method of joining metals and their alloys [5]. The commonly welded engineering structures in Arctic are pipelines, ship hulls, offshore barge/platform, ice breakers, drilling unit, ice ship etc. These are made up of different combination of metallic plates, bars, rod and column. Thick pipelines are produced mainly by UOE technique which involves bending and welding of plates, offshore support are made up of steel column welded at certain length, ship hulls are made from metallic plates welded together. Also, various components and gadgets on offshore ship barge are produced from this different combination of metallic plates, bars rod and column. However, there challenges that are involved in welding of these metallic plates, bars, rod and column. The challenges are emphasised below. However, a lot of high strength steels have been specifically developed to be used for Arctic construction in order to combat its inherent harsh environmental conditions. Among these steels grades are high strength structural steels:

X70($\frac{0.12\ C}{Nb\ V}$), X80($\frac{0.08\ C}{Nb\ Ti}$), X100($\frac{0.08C\ 0.2\ Mo}{Nb\ Ti}$) , X120 ($\frac{0.05\ C\ CuNiCrMo}{V\ Nb\ Ti\ B}$) etc. These steels have yield strengths ranging from 320-720 MPa and even above, which fall within the acceptable and required strength for Arctic materials.

Arctic metal structures are different from ‘normal’ metal structures in terms of their mechanical properties which are mainly impact toughness and strength values. The toughness of these metals is very high (as high as

150 J/cm^2 for KCV_{-40}) in comparison to the ‘normal’ metal structure toughness.

Also the strength of Arctic metal structures is very high, as high as 827 MPa (X120). This is because, Arctic is an extremely cold region, normal metals are very brittle at this temperature; hence, they cannot survive the active service life in Arctic region. As a result, there is need for Arctic metal structures of special attribute that can withstand this extremely cold temperature. Hence, special metals of high toughness value and high strength values are used as Arctic metals.

The metal alloys that have been used for construction of Arctic structures are structural steels mentioned above, 9% Ni steel plate, YS 500 N/mm^2 HSS, YP 355 MPa, YP 460 MPa, etc. Research into how to improve the properties of these materials and others are being conducted day by day by academic institutes, research institutes and various metallurgy companies. Thermo mechanical control process (TMCP), cladding etc. are part of the processes used to improve the properties of these materials. TMCP has been used to increase the strength and toughness, cladding has been used to increase corrosion and wear resistance.

Most Arctic structures are constructed with thick plates and the thicknesses of the plates are increasing in nowadays constructed structures, the thickness ranges from 30 mm to 100 mm and even more. However, as the thickness of the plates increases, the tendency for brittle failure increases, hence, there is need to use high toughness value plates for the Arctic structure construction. The toughness of the welded joints are measure using V-notch Charpy test and CTOD, there is a minimum toughness value required for metal alloys or their welded joint to be suitable for Arctic use.

Meanwhile, the high toughness and high strength value of Arctic metal structures have great influence on their weldability. The weldability has been greatly improved by the use of advanced welding technologies and method of increasing the metal alloys material strength and toughness (which is mainly by TMCP). The weld joints produced by these advanced welding technologies have very good well refined microstructures, high toughness value, high strength value, narrow HAZ, low distortion etc. The advanced welding processes have been shown to have high productivity, better economy, high safety and high weld quality.

Figure 2.1 shows the changes in strength and toughness required in the energy development field. The typical structures in Arctic are offshore platform, drilling units, ice breaker, ice ships etc. It can be seen from the figure that there are changes in the demand of steels to meet up the progressive requirement of various facilities. Hence, advanced welding technology is also in demand to be able to fabricate these facilities.

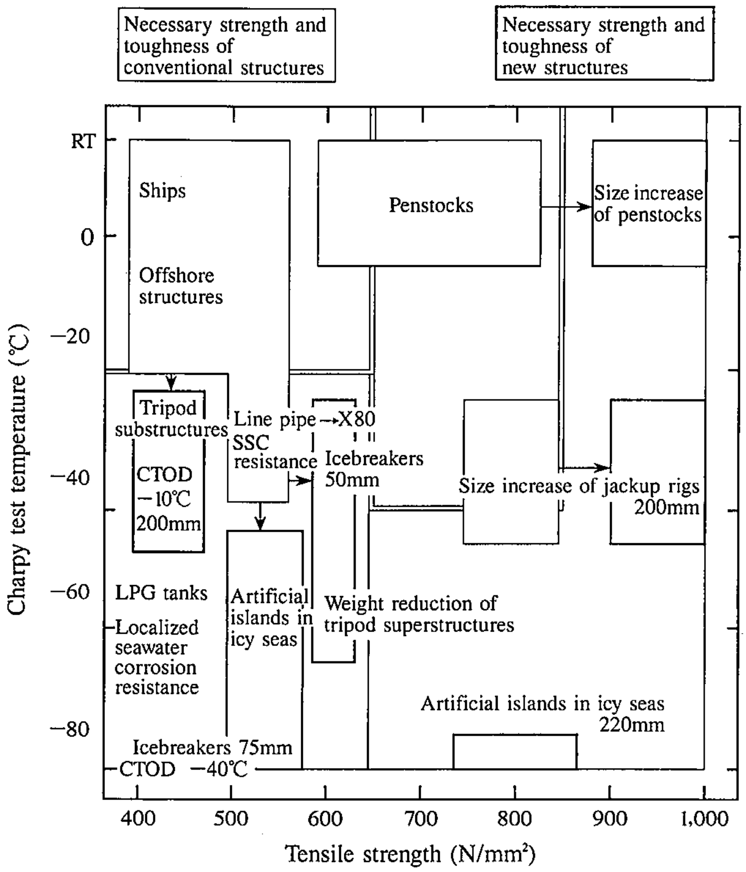


Figure 2.1: Changes in strength and toughness required in the energy development field [17]

2.2. Challenges in Welding Metal Structures in Arctic Conditions

The major challenges associated with welding of metal structures in Arctic region are problem of residual stress, problem of cold cracking, problem of failure and fracture of welded joints, brittle failure of facilities made of metals, problem of heat affected zone (HAZ), problem of corrosion, problem of large deformation of pipelines, problem of power source for welding equipment, problem of functionality of welding equipment, extra loading of facilities due to ice gouging, problem of high tendency of defect initiation during services etc. All these problems border mainly on toughness of the metal structure and the weld at the welded joint. Hence, without mincing words, advanced technology is the main key to solving these challenges and research is being carried out daily to minimize the extent of effect of these problems.

2.3. Advanced welding technologies used in Arctic Conditions

Due to the special demanded properties of metal by Arctic structures, there is need also for advanced welding technologies that can weld these metal structure successfully, producing a weld metal joint of high toughness and high strength. Generally, weld structures start to fail at the weld joint, meanwhile, most Arctic engineering structures are constructed by welding of metals plates and rods, hence, there is need for advanced welding technologies that can produce weld metal joint of high toughness and high strength values, which can survive the active service life in Arctic region.

The advanced welding technologies applicable to Arctic conditions that were discussed in this thesis work are narrow gap welding, laser welding, laser-arc hybrid welding, tandem MIG/MAG welding and multiwire submerged Arc welding. They are highlighted below.

1. Narrow gap welding (NGW)

2. Laser beam welding (LBW)

3. Laser-arc hybrid welding

i. Laser-MIG/MAG

ii. Laser-TIG

Iii.Laser-tandem MIG/MAG

iv. Laser-SAW

4. Tandem MIG/MAG welding

5. Multiwire Submerged Arc welding (SAW)

The above highlighted advanced welding technologies were examined in this thesis based on their productivity, quality, economy and safety. Productivity is defined on the basis of deposition rate, quality is defined on the basis of the nature of weld bead microstructure, economy is defined on the basis of cost of labour, time for weld groove preparation and post-welding activities, and safety is defined on the basis of weld-joint failure tendency.

The above mentioned welding technologies are considered to be very useful and suitable for Arctic applications in comparison to others base on their high productivity, production of well refined weld bead microstructures and save of cost etc. Some of them have been applied for Arctic structures and they have proved to be very efficient for this extreme cold condition.

2.3.1. *Narrow gap welding (NGW)*

This is one of the vital advanced welding technologies available in this modern day; it is actually not one of the classified welding processes as done by AWS but it is just a welding technique [5, 18, 19]. A lot of arguments have been made by different author concerning its definition. However, as at today, there is no universal agreement on the definition of this welding technique. This is because there are various authors perspectives about its definition, but the only common point of understanding is that, various views agree on the technique characteristics, its advantages and disadvantages [20, 21]. Hence, the commonly available definition is generally derived from the technique characteristics.

Meanwhile, an author named Malin [18, 19] was able to highlight the distinguished characteristics of NGW and was able to derive a definition from the characteristics. He defined NGW as ‘a property-oriented bead-deposition technique associated with an arc welding process characterized by a constant number of beads per layer that are deposited one on top of the other in a deep, narrow square groove’. Moreover, this same definition is in close resemblance with that given by Manzoli and Caccia [22].

Hence, in general, NGW can be defined as a welding technique used for welding metals and alloys to produce arc weld in thick metallic materials by using a square-groove or a V-groove weld joint with a root pass of 0.5 mm – 10 mm between different parts to be welded together [23]. In V-groove, the groove angle must not be more than 10^0. NGW can be further described as a group of welding processes developed from conventional welding processes (such as MIG/MAG, TIG etc.) and were specifically developed to reduce weld metal volume in butt welds [24]. For effectiveness of narrow gap welding, weld root design must employ the use a backing system or a U-groove design [5, 6], though there are other narrow-joint preparation design [25] as shown in figure 2.3.1.

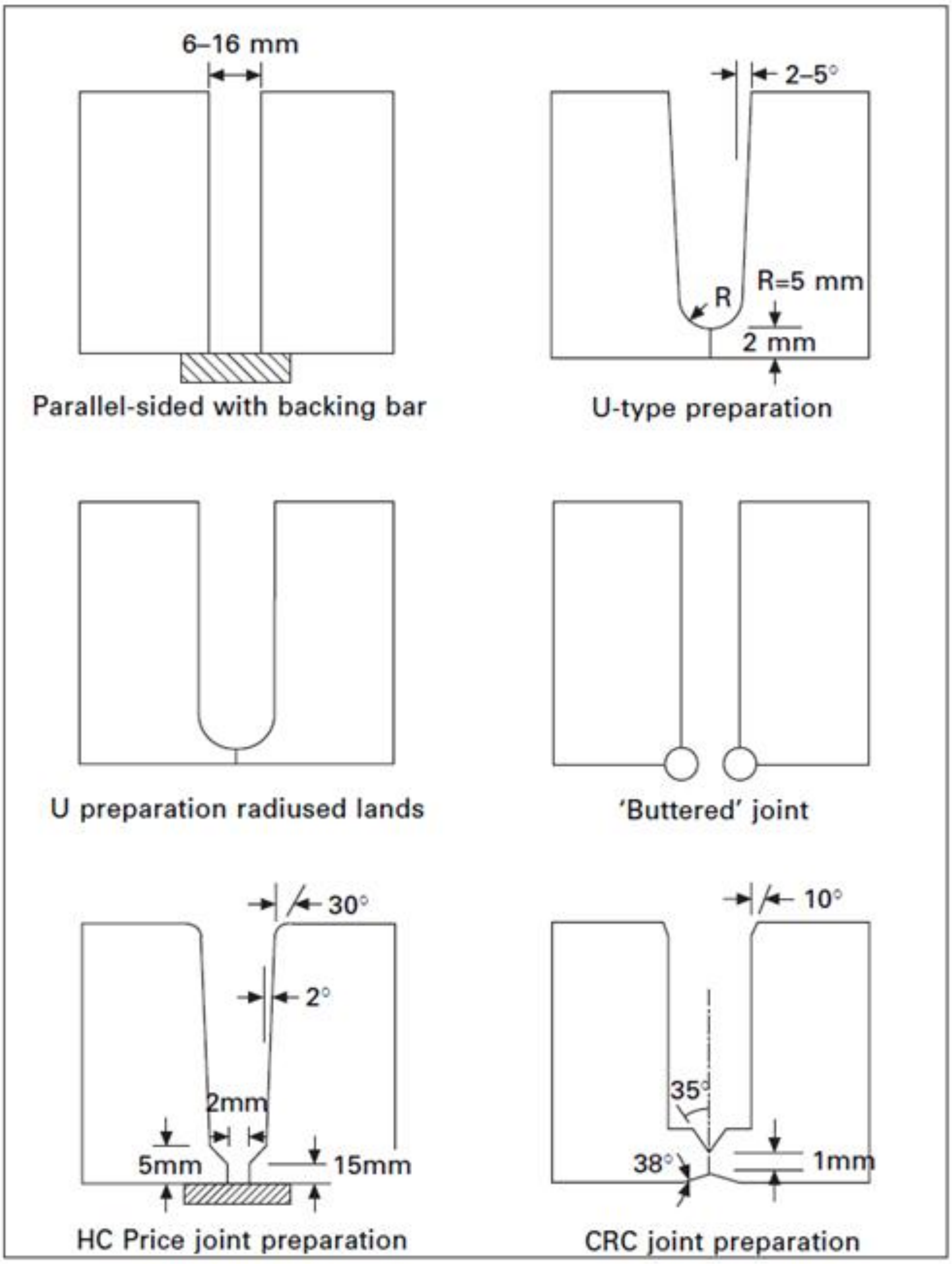


Figure 2.3.1: Typical narrow-joint Preparation. [25]

NGW came to lime light because of its high economic advantage with respect to welding of heavier and thicker metallic plates which are now being used for making ship hull, ship decking, pipelines, nuclear reactors, pressure vessels etc. [19, 24], its introduction has been very helpful in welding of thick plates . It has been established, as shown in figure 2.3.2, that when compare the conventional V-groove preparation with narrow gap groove preparation, the weld metal volume and the welding process completion time increases drastically in relative to square of metallic material thickness. However, as the V-angle of the groove reduces, the weld metal volume and welding completion rate decrease. It is very visible from figure 2.3.2 that when the thickness of the metal increases from 10 mm to 20 mm, the cross-sectional area of the weld pool increases. Also, as the 60 degree V-angle groove reduces to narrow parallel gap, the cross-sectional area of the weld pool decreases. Hence, if a narrow square gap is applied, the reduction in the weld metal volume and completion time become very significant especially with respect to welding of thicker sections [24].

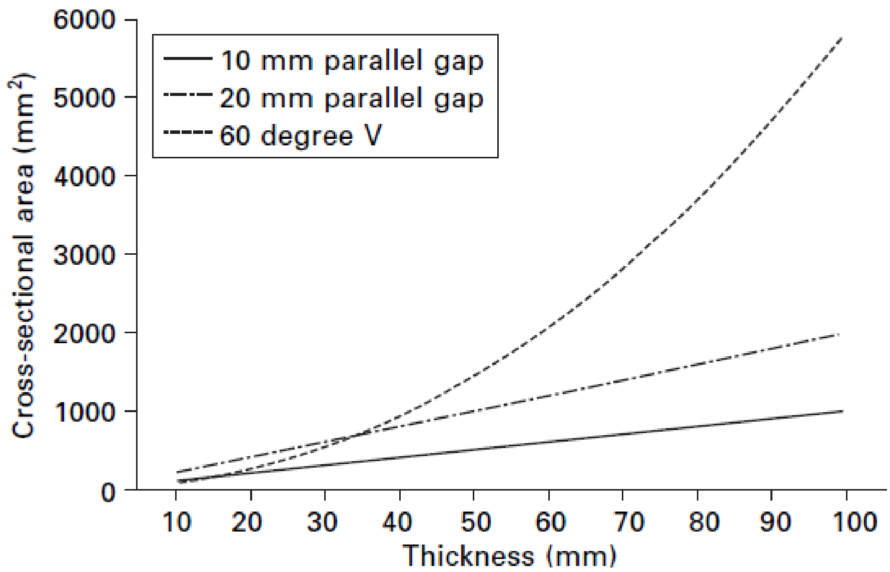


Figure 2.3.2: The principle of narrow-gap welding: The effects of joint preparation on weld cross-sectional area [24].

NGW has been used for welding of materials with thickness between 50 mm – 300 mm [5], however, better economic advantages is start to be obtained from welding of a plate thickness of 38 mm and above due to use of less metal weld volume and consequently saving of labour cost [5]. This is because lower weld volume is required to produce the weld joint in comparison to the known conventional method.

There are various variations of NGW with respect to arc welding processes and are mainly further developments of the conventional arc welding processes. It is applicable in various arc welding processes but some authors have included electro-gas, electro-slag and even electron beam welding and laser beam welding as narrow gap welding because of similarity in their principle of operation which is the use of square-groove weld, with small root opening (gap) on heavy metal plate materials [5, 21].

Moreover, in general, NGW has been mostly applied in MIG/MAG using spray transfer [5] but in Arctic offshore region, it is mostly applicable to TIG and SAW. Other variations where narrow gap welding is being applied are flux-cored arc welding (FCAW), submerged arc welding (SAW), tungsten inert arc welding (TIG) with the hot wire and cold wire [5, 21, 26]. Figure 2.3.3 shows a typical NGW welding head. Classification of various variation of NGW mostly used in Japan [27] is displayed in the flow diagram shown in figure 2.3.4. However, figure 2.3.5 shows a more recent and comprehensive classification done by Malin [19]. This classification is done based on the welding processes associated with NGW and the NGW techniques which entails electrode feeding techniques, bead deposition layout and the number of electrodes used per pass [21].

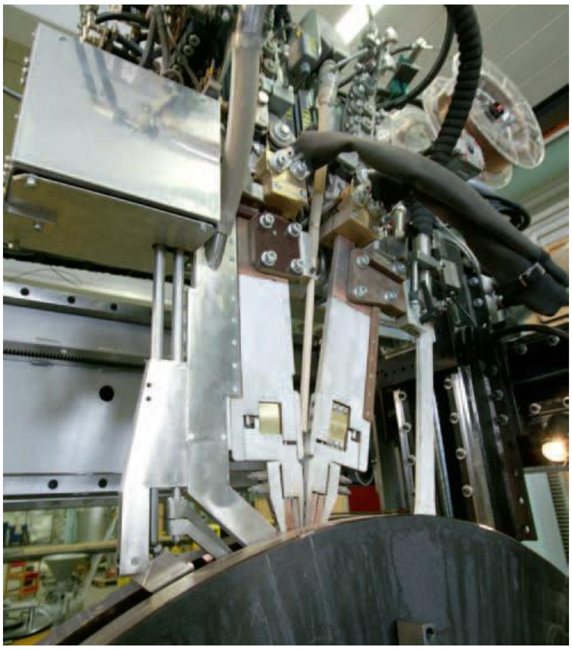


Figure 2.3.3: Narrow Gap Welding head [26]

The physical characteristics of NGW technique are highlighted as follows:

Physical characteristics of NGW technique [5, 18, 24]

1. The weld joint is narrow, parallel (for square groove weld joint) or has small preparation angle less than 10^0 (for V-groove weld joint).
2. The weld-build-up technique is multipass in nature and the weld bead is not more than two beads per pass. This help to give good mechanical properties due to continuous refinement of the weld bead by subsequent pass.
3. Due to its narrow weld joint, only small heat input is placed on the material, hence, it has very narrow heat affected zone (HAZ) and reduced distortion.
4. It makes use of special welding head and equipment.
5. It mostly requires arc length control or seam tracking to ensure sidewall weld fusion. Consumables modification might also be needed in some cases.

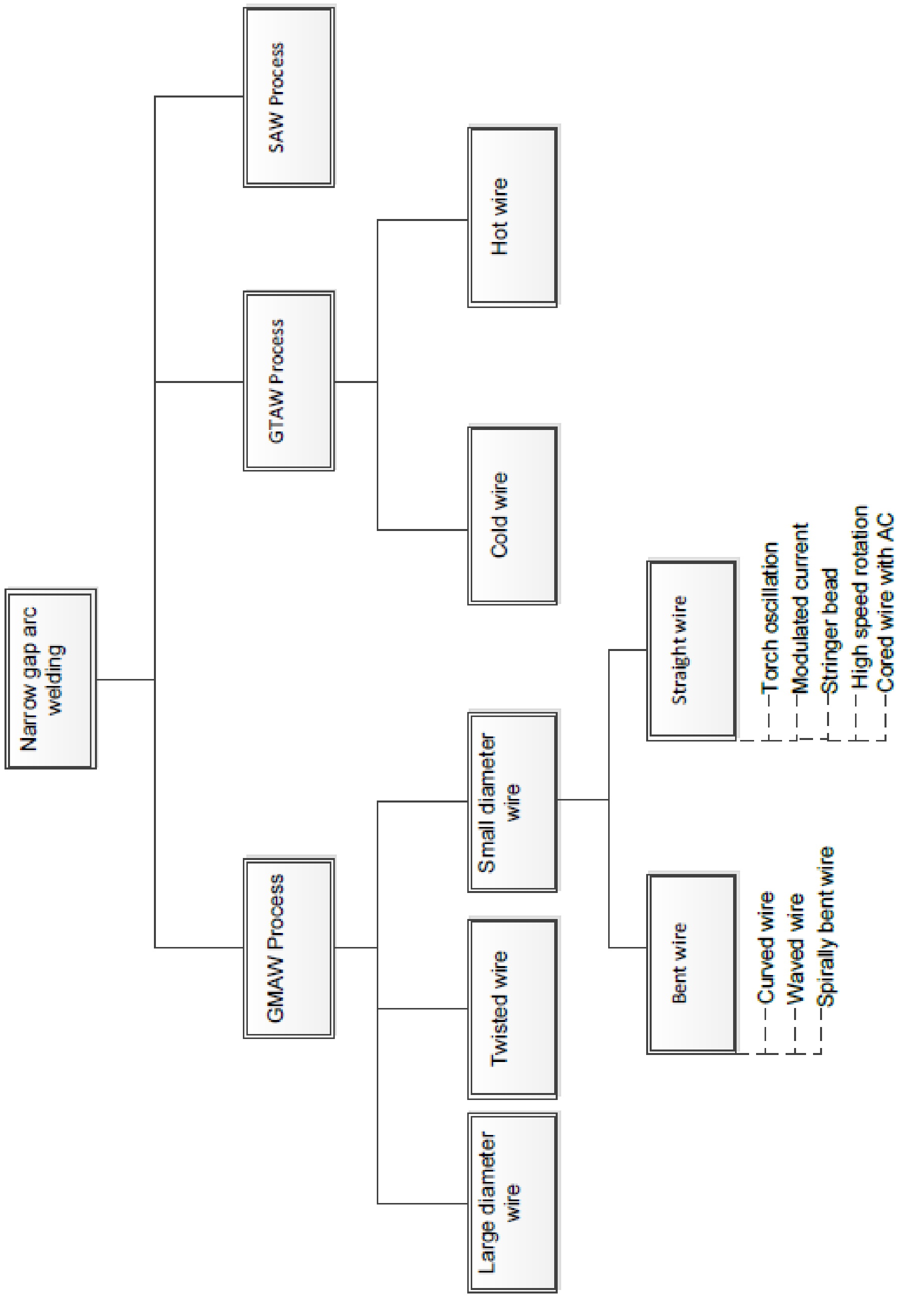


Figure 2.3.4: Classification of NGW processes in Japan [27]

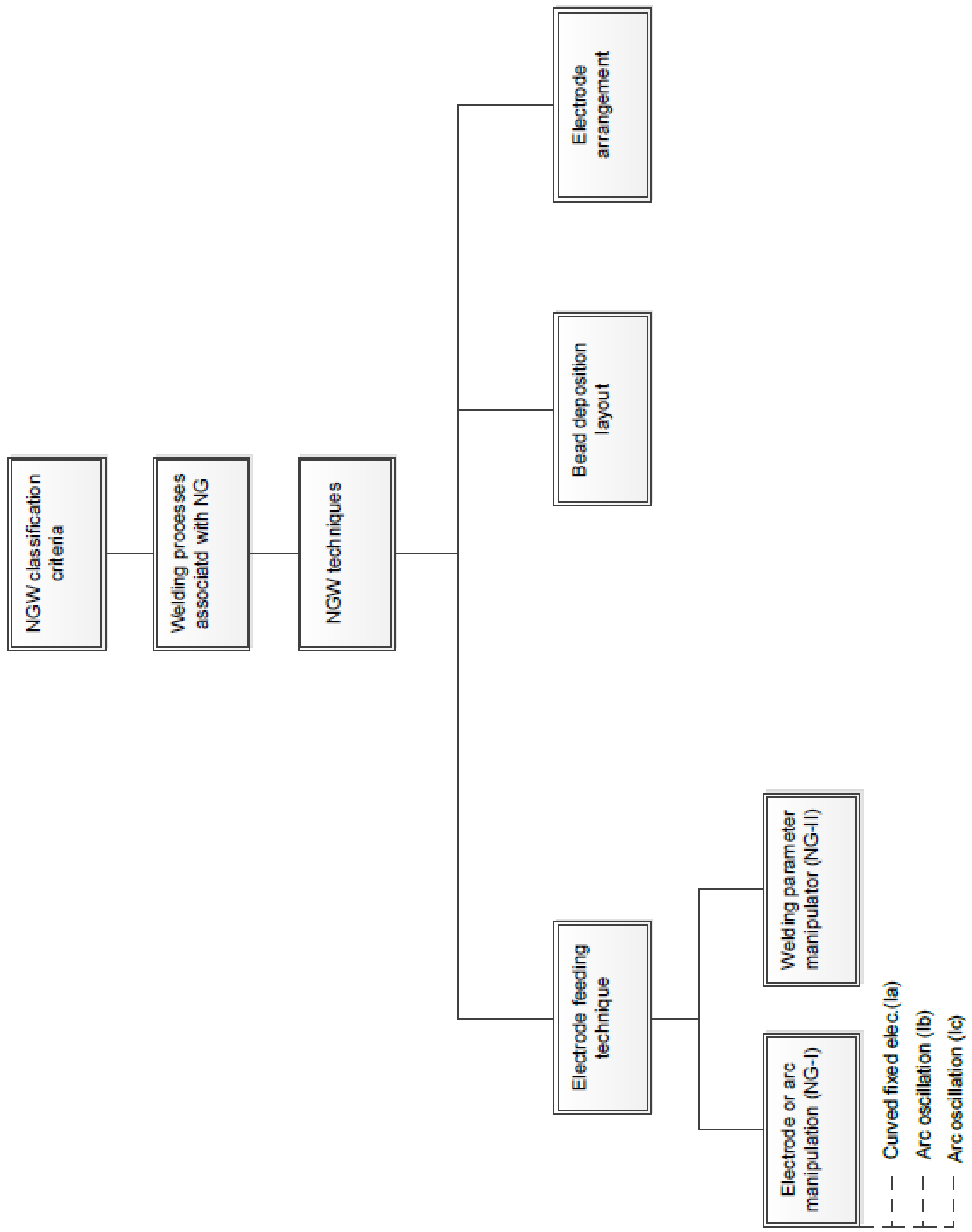


Figure 2.3.5: Classification of NGW processes according to Malin [19]

Advantages of NGW

The advantages of NGW are highlighted below [5,18,19,20,21,22,23,24]:

- Very high quality of weld metals in HAZ in comparison to conventional method due to low heat input.

- High productivity with respect to high deposition rate and faster welding speed.
- It can be used in all position.
- It produces less residual stress due to narrower heat affected zone
- It is economically profitable because of the narrow gap and small weld metal volume.
- Very low ability to shrink.
- Low distortion due to low heat input
- Uniform weld joint properties
- Good mechanical properties and well refined microstructure of the weld joint.

Disadvantages of NGW

The disadvantages of NGW are highlighted below [5,18,19,20,21,22,23]:

- The technology is complex and more demanding; hence it requires highly technical know-how welding operators.
- The welding head and control gadgets are expensive and may also be complex due to different function.
- Filler metals required are special and may be more expensive.
- Magnetic arc blow problem, which occur when applied with gas metal arc welding.
- It is very difficult to repair and carry out post-weld inspection on the welded joint produced by NGW and often, repair has to be done using conventional techniques.
- Joint fit up must be well prepared and must be very accurate to ensure consistent weld throughout the whole length of the joint.
- Risk of some errors when welding large thick walls due to difficult accessibility during process control.

Welding Arctic metal structures requires high toughness in the weld area and in heat affected zone. From the various advantageous points of NGW, it produces a fine microstructure bead weld and narrow heat affected zone which guarantee certain high level of toughness within the zone. Hence, narrow gap welding has been one of the welding techniques used for welding metals and their alloys in Arctic region. But the major issues with this are the demand for precision welding performance and adequate in-process control and monitoring [24]. The productivity of NGW, economic factor (when compare to the cost of the welding head) and quality of weld beads have been shown to be on the high side with respect to welding of thick metallic materials. NGW is a very effective, useful and better welding technique for welding materials under Arctic conditions.

2.3.2. Laser beam welding (LBW)

The application of laser to welding has been dated as far back as 20th century when it was noted that laser could heat, melt and vaporised metals. It was further reviewed that if laser output was properly controlled, the melting and solidification would results to welds between two metals pieces. Hence, the market was flooded with laser welding equipment by three different suppliers of laser equipment who were seeking to expand their markets [28, 29, 30].

Laser is an acronym for light amplification by stimulated emission of radiation. Laser is a high energy density radiation which can emit large amount of heat, hence, this advantage is explored in welding process called laser welding. There are different types of laser but those that are commonly used for welding purpose are CO_2 welding (the most common) and Nd:YAG solid state laser. However, recent development in laser has included the use of high-power diode lasers (HPDL) and fibre lasers.

Laser beam welding is a welding process which involves the use of high heat energy generated by a focused laser on striking a material for welding purpose with or without the use of shielding gas and without the application of pressure [5]. LBW is inherently a narrow gap welding and produces narrow small heat affected zone. Laser has been used to weld various metals and due to its advantage of producing low distortion narrow weld with small HAZ, it is very suitable for welding of arctic structures.

There are two different type of laser welding and these are highlighted below.

1. **Conduction limited (or melt-in) welding**: in this type of laser welding, the size of the weld pool is very small due to conduction away of heat produced by laser on the material. Hence, the material only melts at the surface and produces very low penetration. It is usual used for very thin material.

2. ***Keyhole welding***: this is the major welding process required for Arctic structures as it gives a deep penetration. It is produced by high intensity laser beam that causes a hole filled with metal vapour to occur in the material.

Conduction limited welding typically gives weld bead depth-to-width ratio of around unity but the keyhole welding can produce depth-to width ratio up to 10:1 [24, 31].

Application of laser welding to Arctic used structure is very important. Laser welding is one of the processes that inherently has the characteristic of narrow gap welding, as a result has some advantages in producing weld joint with excellent high toughness.

Advantages of LBW

The advantages of LBW are highlighted below [5, 24, 28, 31]:

1. It gives a deep weld penetration.

2. It produces a very narrow HAZ.

3. There is low distortion of the welded structures.

4. It produces a better improved toughness of the weld joint in comparison to conventional arc welding process.

5. It is very easy to automate.

6. It enables welding of thick materials at high speed in a single pass. It is very important to note that the speed of LBW has been adopted for welding pipeline on offshore pipe-laying platforms because of the speed of the process. This enables saving of lots of money as it is very expensive to operate this platform per day.

Disadvantages of LBW

The disadvantages of LBW are highlighted below [5, 24, 28, 31]:

1. It requires an excellent precision edge preparation, because the process will only allow a very small gap between the two parts to be welded. A maximum gap of 3% of material thickness is required when welding thick materials of thickness greater than 20 mm [32].

2. Laser welding equipment are more expensive than arc welding equipment

3. Laser welding is mostly done inside a safety enclosure due to safety of personnel; hence this mostly acts as impediment to loading and unloading weldments rapidly.

4. Rapid cooling rate can result in cracking problem.

Moreover, based on aforementioned characteristics of laser welding, it becomes very relevant to welding in Arctic, due to the fact that it can produce high toughness and high strength weld joint needed on Arctic metal structures, with a very high speed in relative to convectional arc welding process.

2.3.3. Laser-Arc hybrid welding (LAHW)

This welding process came to limelight when it was discovered that combining laser and conventional arc welding could produce a better weld result by combining the advantages offered by each of the welding processes. It was first done and developed by Steen and Eboo when they combined a 2-kW CO_2 laser and TIG. They observed, among many other observations that the laser stabilizes the arc and increase the depth-to-width ratio of the resulting weld [33].

Meanwhile, laser welding is initially acclaimed for deep penetration, high welding speed but poor root opening close fit-up, however, conventional arc welding is acclaimed for good root opening close fit-up. Hence, the hybrid combination of these welding processes produces better weld, where one welding process advantages compensate for the other welding process disadvantages.

Laser-Arc hybrid welding, as the name implied, is simply defined as a welding process in which laser welding and conventional arc welding are combined together at the same time during a welding operation [34-38]. In this type of welding, the arc controls the weld width and root opening bridging while the laser controls the penetration [39 - 42]. A typical process representation of laser-arc hybrid welding is shown in figure 2.3.6.

There are different combinations of laser-arc hybrid welding, but the major and common ones are Laser-MIG/MAG, Laser-tandem MIG/MAG, Laser-SAW and Laser-TIG. The different combinations are highlighted below. Generally, the advantages offered by the hybrid welding are higher welding speed, deeper penetration, better weld quality and better tolerance to joint fit-up. However, the following limitations are quite visible; it is capital intensive because the welding head is very expensive and complex; the need for automation and the need for laser beam and arc precision alignment.

However, the above mentioned advantages of LAHW makes its application in Arctic region very important, as more research are being tailored towards getting the best results out of various combination of laser and arc welding processes.

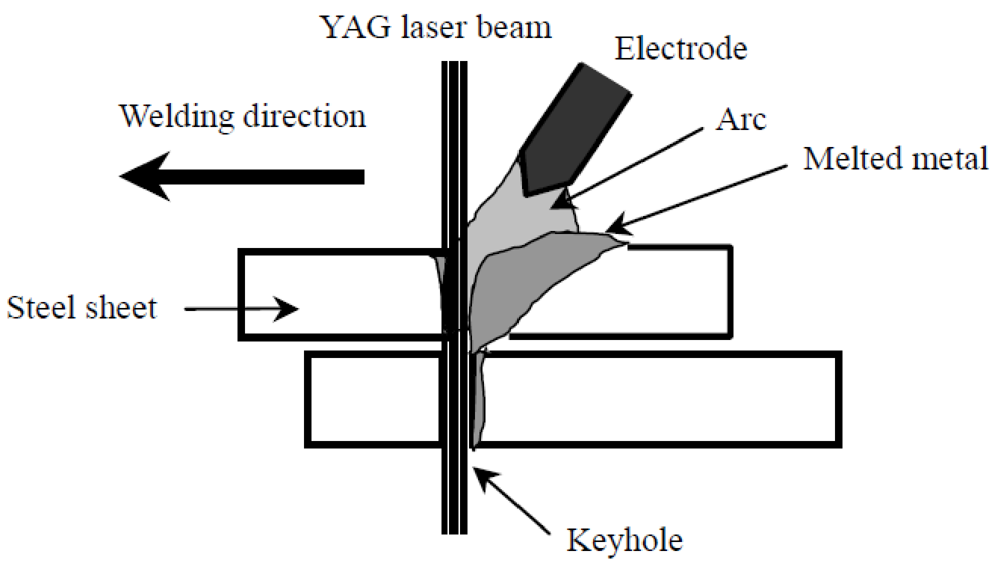


Figure 2.3.6: A typical hybrid laser-arc welding [43]

i. Laser-MIG/MAG

This is the combination of laser and MIG/MAG welding process. There have been different use of this welding process and it has provided a visible advantage over each of the individual welding process. A typical schematic representation of a laser- MIG/MAG hybrid welding head is shown in figure 2.3.7.

This hybrid welding has been applied in various applications including shipbuilding, automotive fabrication, pipelines etc but not to offshore structures [24, 44]. It has been shown that the process provides higher welding speed and increased penetration than MIG/MAG and also improved tolerance to fit-up more than laser welding. Inclusion of laser ensures arc root stability of the arc process and also reduces arc ignition problems [24].

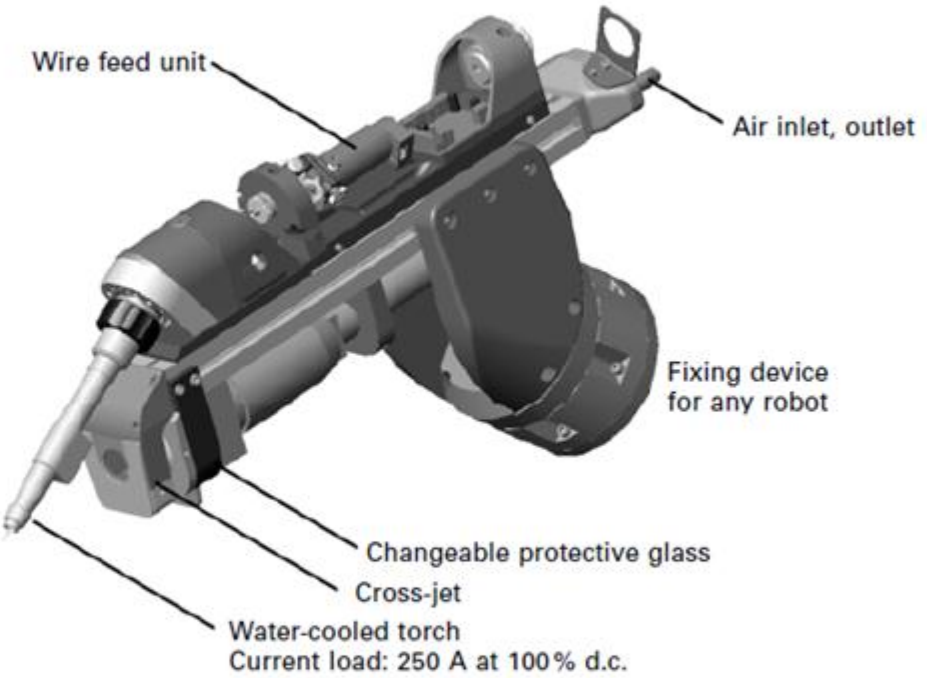


Figure 2.3.7: Schematic representation of a laser- MIG/MAG hybrid welding head [45].

ii. Laser-TIG

This entails hybrid combination of laser welding and TIG. This hybrid combination has been investigated by several workers and it has been shown that TIG arc provide the heat to pre-melt the material while laser ensures increased penetration and welding speed [33, 46]. It has been also been reported that combining a 300 A TIG arc with 1 kW laser produced equivalent welding performance to a 2 kW laser device [24].

iii. Laser- tandem MIG/MAG

This is the combination of laser welding and two MIG/MAG in a single weld pool. The laser ensures deeper penetration while the following two MIG/MAG arcs increase the bridgeability of the root gap and also increase the throat thickness due to the use of more filler materials. Various parameters can be adjusted to obtain some desired metallurgical properties [47]. Three different power output is used by the process, hence, this can be adjusted to obtain a better weld output and also a higher welding speed. It has been reported that two different filler metals of varying compositions can be used to obtain a desired metallurgical properties [47].

iv. Laser- SAW

This is another variation of laser-arc hybrid welding. It came into play when there was problem of pore formation at the root of the workpiece in the lower weld zone when using laser-MIG/MAG hybrid welding. This is due to insufficient degasification of deep penetrating laser welds [64], however, LSAHW provide solution to this problem by maintaining the weld pool for a long period. However, in using LSAHW, there is problem of flux dropping into the keyhole of the laser beam and part of the energy of the laser beam being absolved by the flux. However, this problem has been solved by the use of separating plate which separates the laser beam from the flux feeder. Better efficient is obtained with the use of solid-state laser which offer advantage of reducing the risk of plasma shielding [64].

Meanwhile, the combination of laser and SAW provides the opportunity to weld plates of higher thickness (more than 20 mm) in a single pass and also provides the opportunity for welding of thicker plates with the double sided single pass techniques [64].

2.3.4. Tandem MIG/MAG welding

MIG/MAG otherwise called gas metal arc welding (GMAW) was developed as far back as 1940 [5]. It is a welding process that burns arc between a continuous constantly fed filler metals and the weld pool, with application of externally supplied shielding gas and without application of pressure [5,6]. A typical process representation is shown in figure 2.3.8. In the same vein, figure 2.3.9 showed a schematic view of MIG/MAG welding system, displaying the main components.

There are various variations of this welding process with respect to number of wire electrodes, the type of arc, the type of shielding gas, the type of metal being welded, the type of metal transfer etc. This has enabled it to bear different names depending on the nature of use and application. However, this thesis dwell more on the variation type that encompasses multi-wire application, which is one of the major advancement in the development of conventional single wire MIG/MAG. The main variations in this regard with respect to the number of wire electrodes used are highlighted as follows [48];

1. ***Twin welding with one feeding unit***: Here, two wire electrodes are fed by only one feeding unit. The two feeding wires have exactly the same potential and are connected to the same power source.

2. ***Twin welding with two feeding units:*** Here, the two wire electrodes are fed separately by each of the feeding units. Also, the two wires have exactly the same potential and are connected to the same power source.

3. ***Tandem welding***: This entirely involves two wire electrodes feeding units and two power sources. The two wires which are electrically insulated from each other in welding gun are fed separately by each of the feeding unit and are separately connected to each power source. However, the two wires can be supplied with different potentials, and welding parameters can be set in a free manner for each of the wire.

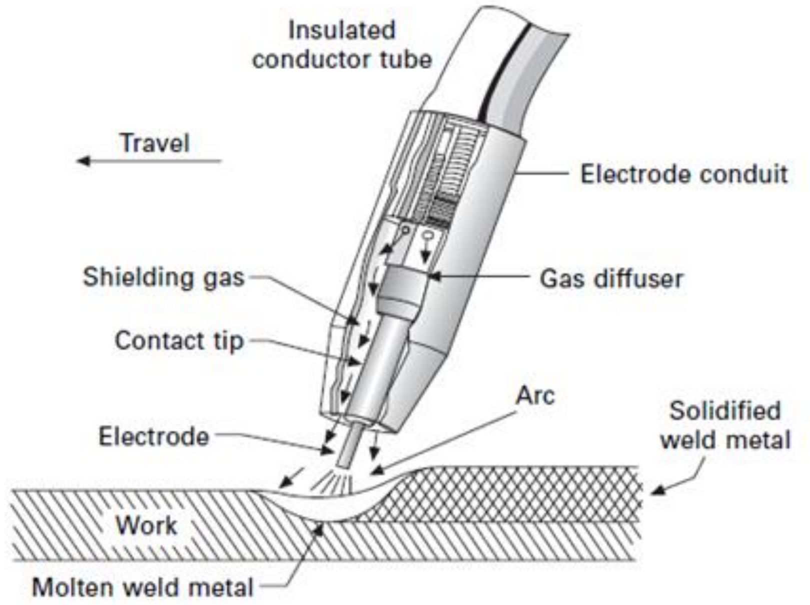


Figure 2.3.8: Schematic representation of MIG/MAG process (Longitudinal-Section View) [49]

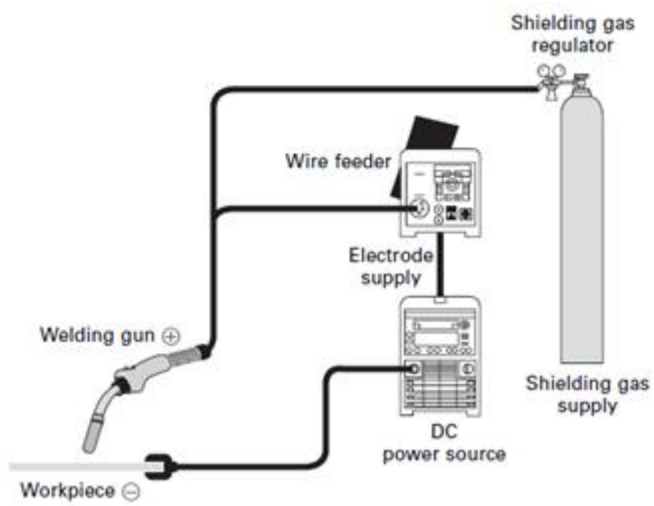


Figure 2.3.9: Schematic view of MIG/MAG welding system showing main components [45]

Moreover, this thesis concentrated more on the tandem variation which gives higher welding speed in relative to the other variations.

Tandem MIG/MAG welding, as rightly said above, simply means the use of two wire electrodes and two power sources the for welding process. The features of this welding process are highlighted below.

Physical features of Tandem MIG/MAG welding

1. Two wire electrodes and two feeding units are used. Usually, master (or lead) wire electrode operates in continuous arc while the slave (or trail) wire electrode operates in pulsed arc mode.

2. The electrodes are electrically insulated from each other, hence droplet wire transfer mode can be controlled independently as against that of twin-wire welding.

3. Two power sources, two wire drives and one control unit are used.

4. The two wire electrodes can be supplied with different potentials, and welding parameters can be set in a free manner for each of the wire electrodes.

The need for this variation of MIG/MAG came into limelight when there was high demand to increase welding speed drastically and consequently reduce the cost. Prevention of downtime is very important in any welding process because it determine to a large extent the economics of the process. This is due to the fact that downtime leads to high loss of efficiency and can be extremely expensive especially when considered with respect to mechanised and robotic applications.

In MIG/MAG, downtime usual result from the need to stop the welding process in order to exchange wire spools and also by irregularities in wire feeding which usually leads to unnecessary and unplanned maintenance. Hence, the need to use tandem variation of MIG/MAG which supplies high volume of wire electrodes to resolve this problem of downtime. This eventually leads to reduction in downtime, improvement in process stability, increase in output, increase in welding speed and quality of the weld. The use of tandem MIG/MAG requires the use of specially designed welding torch that can give the required weld quality. A typical welding torch used for this variation of MIG/MAG is shown in figure 2.3.10.

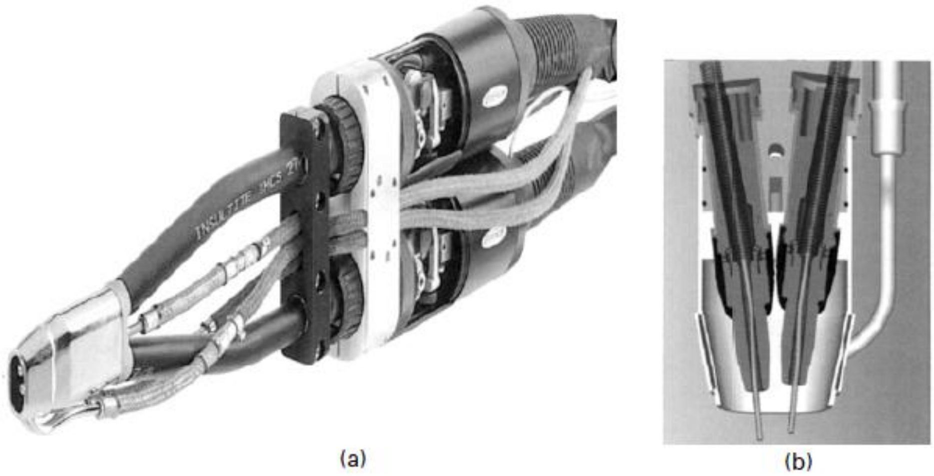


Figure 2.3.10: Tandem GMAW torch view (a) and cross-section (b) [31].

Meanwhile, the determinant of successful operation of tandem MIG/MAG is based on proper and full understanding of the set-up of the specially designed tandem MIG/MAG welding torch [49]. Usually, the central axis of the welding torch should be normal to the weld joint, the master (or the lead) arc has a built-in 6^0 lagging electrode angle and the slave (or the trail) arc has a built-in 6^0 leading electrode angle [48, 31].
It has been established that Tandem MIG/MAG has a higher welding speed which is about 1.5-2.0 times the speed of a single wire electrode. More so, welding speeds greater than 3.81 m/min and deposition rate of 19.1 kg/h can be obtained for welding of heavier plate [49].

Mode of metal transfer in MIG/MAG determines to a large extent its overall performance. It has a significant effect on weld quality, spatter generation, process stability and the positional capabilities of the process [50]. There are many modes of metal transfer used in MIG/MAG and these include: globular, short-circuiting, spray, pulsed-spray etc. A simplified classification is shown in figure 2.3.11. However, the mode of metal transfer used for the tandem MIG/MAG is axial spray metal transfer or pulsed spray metal transfer. The different combinations of this metal transfer that are commonly used are highlighted below:

1. Axial spray transfer on the master arc followed by pulsed spray transfer on the slave arc.
2. Pulsed spray transfer on both the master and the slave arc.
3. Axial spray transfer on both the master and the slave arc.

Moreover, in applications where special heavy and thicker plates need to be welded to obtain a deeper penetration, higher energy spray and spray configuration is used. Using two Pulse arc in master and slave arc gives heavy welding and high-speed sheet metal welding [31].

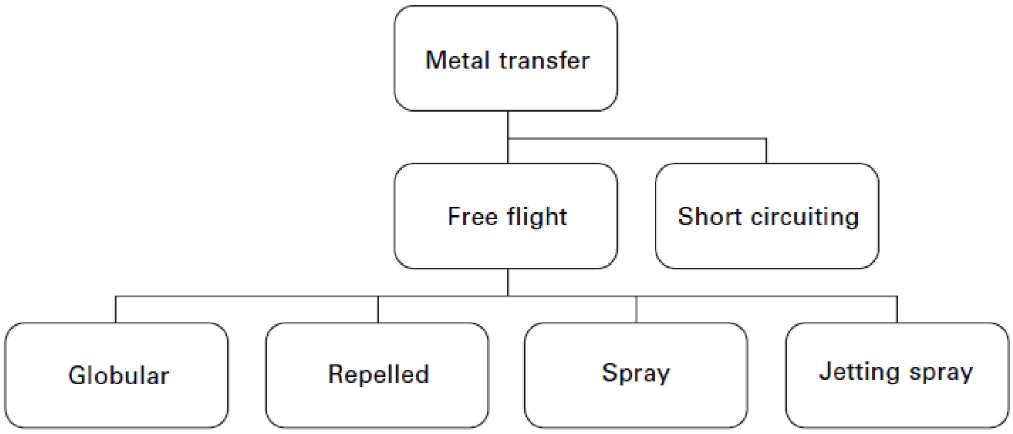


Figure 2.3.11: Classification of metal transfer in MIG/MAG [24]

Tandem MIG/MAG has been compared with various variations of MIG/MAG and also with conventional single wire MIG/MAG. Figure 2.3.12 showed the comparison from productivity perspective and figure 2.3.13 showed it from weld joint application perspective. It is visible from the figures that the productivity and the welding speed of tandem MIG/MAG is higher than the other variations, hence the welding cost will surely be lesser.

Moreover, contact tip to work distance (CTWD) is a major factor to be considered with respect to the quality of weld produced. A longer CTWD of about 25.4 mm is required if tandem MIG/MAG is to be used for welding of heavy and thick plates. The longer CTWD allows for correct spacing between the two arcs, and this enables the arcs to move very closely together. Also, when the arcs are placed at the longer CTWD they lend themselves for use with much higher wire feeding speeds [31].

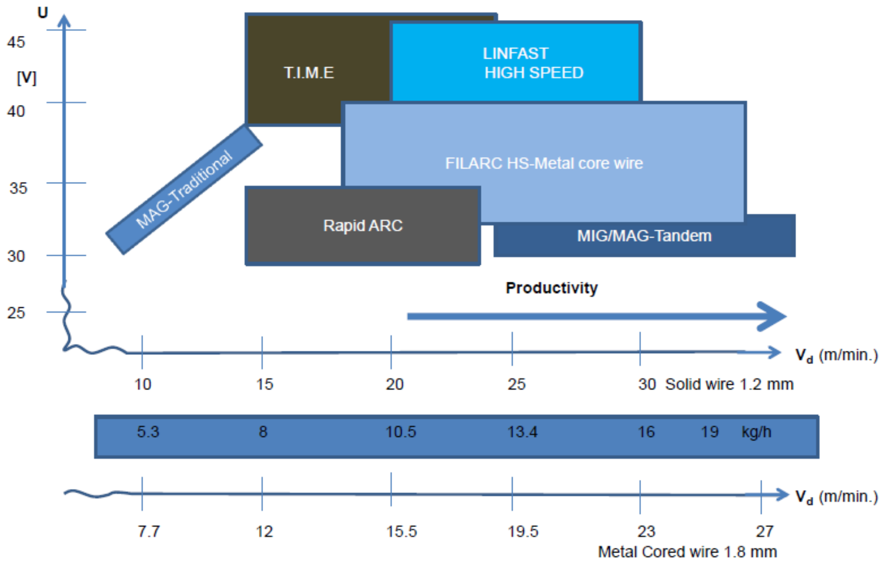


Figure 2.3.12: Comparison of different highly-productive MIG/MAG welding systems [48]

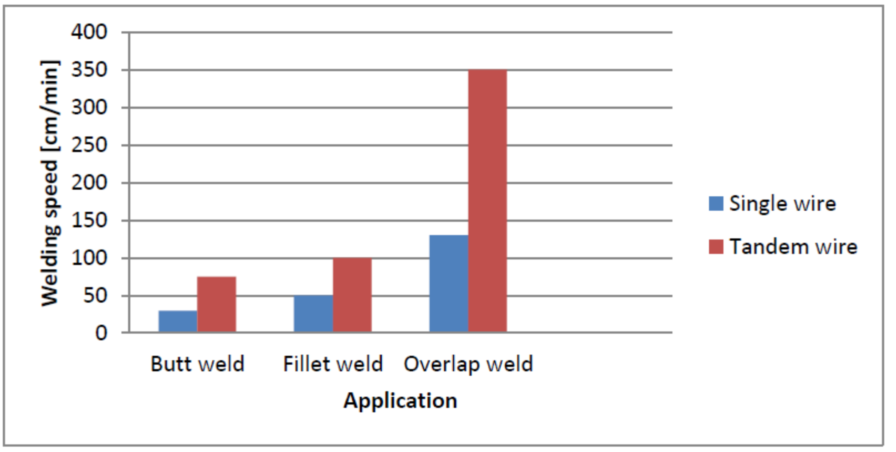


Figure 2.3.13: Comparison of welding speeds for the single wire and tandem wire applications [48]

Advantages of tandem M*IG/MAG welding*

The advantages of tandem MIG/MAG welding are highlighted below [5, 31, 48]:

1. High productivity: High deposition rate and High welding speed
2. High operating factor
3. Reduction in smokes and fumes
4. Ease of automation
5. High use of filler metal
6. It is very flexible
7. Lower spatter

Disadvantages of *tandem MIG/MAG welding*

The disadvantages of tandem MIG/MAG welding are highlighted below [5, 31, 48]:

1. Complexity of the equipment

2. The need for automation
3. Big and large welding torch
4. Excessive high heat input

2.3.5. *Multiwire Submerged Arc welding (SAW)*

SAW process was developed in the late 1920s and was introduced in the early 1930s. The welding process burns arc between a continuously fed bare/core wire or strip metal electrode and weld pool, with blanket of flux (initially placed on the workpiece) shielding the arc and the molten metal pool. It is done only with the application of electric current and without pressure but with the use of filler metals. There is no visible arc and no sparks, spatter or fume due to the use of blanket of flux. The electrode may be a solid/bare wire, cored wire or a strip (usually used for cladding purpose). It is a high heat input welding process, this is because heat loss is extremely low due to the fact that arc is completely covered by the blanket of flux [5, 51].

Multiwire SAW is a variation of SAW which makes use of multiple filler wires (up to 6 wires) in a single weld pool. The essence of this variation is to increase the deposition rate and welding speed. This variation makes SAW suitable for Arctic welding purpose in addition to the fact that SAW produce very high quality weld.

SAW is easily automated; the most common methods of operation are mechanized and automatic methods. Semiautomatic method which uses hand-held flux hopper or pneumatic system (forced air) to convey the flux to the workpiece can also be used but it is less efficient in comparison to the mechanised and automatic methods. A typical process representation of SAW is given in figure 2.3.14 while figure 2.3.15 shows the welding machine carriage and the welding head.

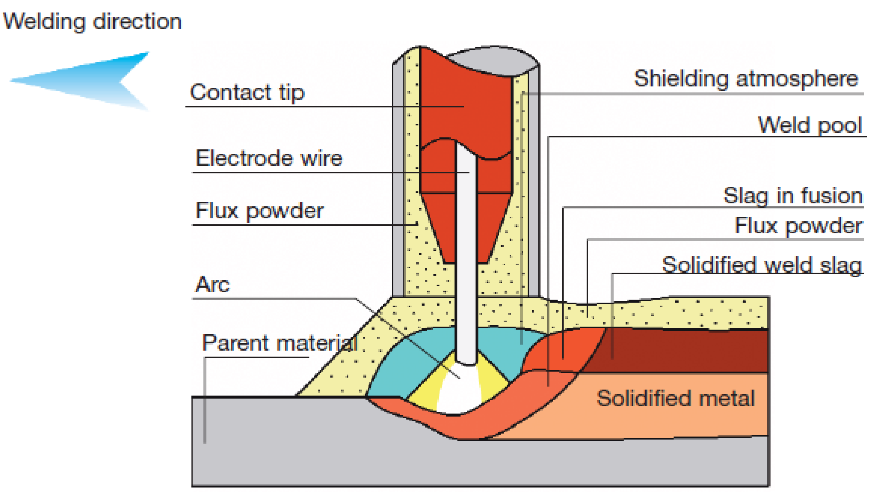


Figure 2.3.14: Schematic representation of SAW process [51]

Figure 2.3.15: SAW travel carriage and head [52]

SAW has limited welding position where it can be applied. Mostly, welding is very comfortable in flat position and in horizontal fillet position. However, it is not used in vertical or overhead position due to the fact that the process produces large pool of molten metal and slag (which is also very fluidic) and these tend to run out of the joint [5, 53]. As a result, SAW is very ideal for circumferential and longitudinal butt and fillet welds.

SAW can be used both in the factory and on the site. Welding current used for SAW ranges from 300-2000 A, DC+, DC- and AC power source are commonly used but DC- gives a higher deposition rate than the rest and deposition rate for AC lies between DC+ and DC- [5,53]. It can use between 1-6 filler wires in a single molten weld pool, the welding speed ranges from 30-350 cm/min and the deposition rate ranges between 2-100 kg/h [53]. The high welding speed and high deposition rate which are peculiar characteristic of submerged arc welding makes it suitable for Arctic welding. SAW is peculiarly important to Arctic welding because it has very good tendency to produce weld joints that can meet up requirement of service under Arctic conditions.

SAW is mostly being used for welding structural steels and stainless steels. It has a very good weldability with steels, even with the HSS Arctic metal structures such as X80, X100, X120 etc. [5, 54]. This is due to the fact that it requires a lower preheat temperature and has a very higher welding efficiency. For application of SAW in Arctic welding, core wire must be used as the welding filler wire in order to achieve excellent toughness through the addition of some weld-joint and HAZ toughness-improving powder elements inside the core of the wire. The use of core wire also increases deposition rate.

SAW is used in Arctic welding because it produces weld joint of very high quality, it has high deposition rate (productivity) and high welding speed due to its high heat input. Hence, it produces required strength and toughness for Arctic structures. It has been used to weld pipes, offshore structures and platforms. Using core multiwire and narrow gap techniques increases the deposition rate, welding speed and hence the productivity. The toughness and strength are increased by microalloying with toughness-improving elements such as titanium that can be added in form of powder through the core wires.

For SAW to be fit for Arctic welding, the following minimal modifications must be met [5, 53]:

- There should be use of backing.
- DC- produces higher deposition rate than DC+ and AC. Hence filler wire should be connected to negative pole. The reason is that the filler wire is preheated.
- There should be use of long distance tip, 50-150 mm, this increases the voltage and consequently the deposition rate.
- Addition of Iron powder which produces 20-60 % increase in deposition rate.
- The use of twin increase the deposition rate by 65%, the use of tandem increase the deposition rate by 90%, the use of multiwire (e.g. 6 wires) increase the deposition rate by 260%. Hence, multiwire must be used.
- Due to higher thickness of Arctic metal alloys, multipass weld procedure is usually used.

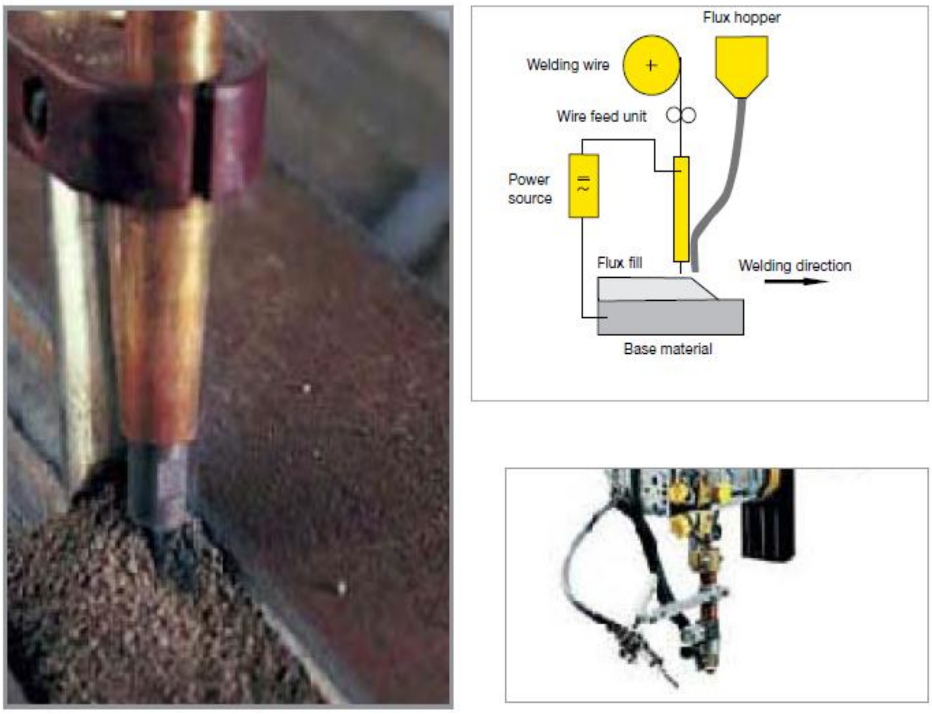
Variations of SAW

There are variations of SAW, these are highlighted below:

- Core wire
- Single wire
- Twin wires
- Tandem wires
- Tandem twin wires
- Multi wires

Another special variation/technique is called narrow-gap submerged arc welding process (SAW-NG). This is a variation of tandem method. The advantage of this is that, it reduced welding time, reduces potential for defects and improves 'as welded' properties. SAW-NG is capable of producing high-quality joints in thick sections in the flat position with considerable improvements in running costs. Conventional SAW equipment may be used for relatively thick material (e.g. 70 mm) but special-purpose equipment is available for welding thicknesses up to 600 mm [24].

Typical process representations of these variations are shown in figure 2.3.16-2.3.18, while figure 2.3.19 shows the comparison of their deposition rates. Also, table 2.3.1 and table 2.3.2 shows the characteristic parameters of each variation.

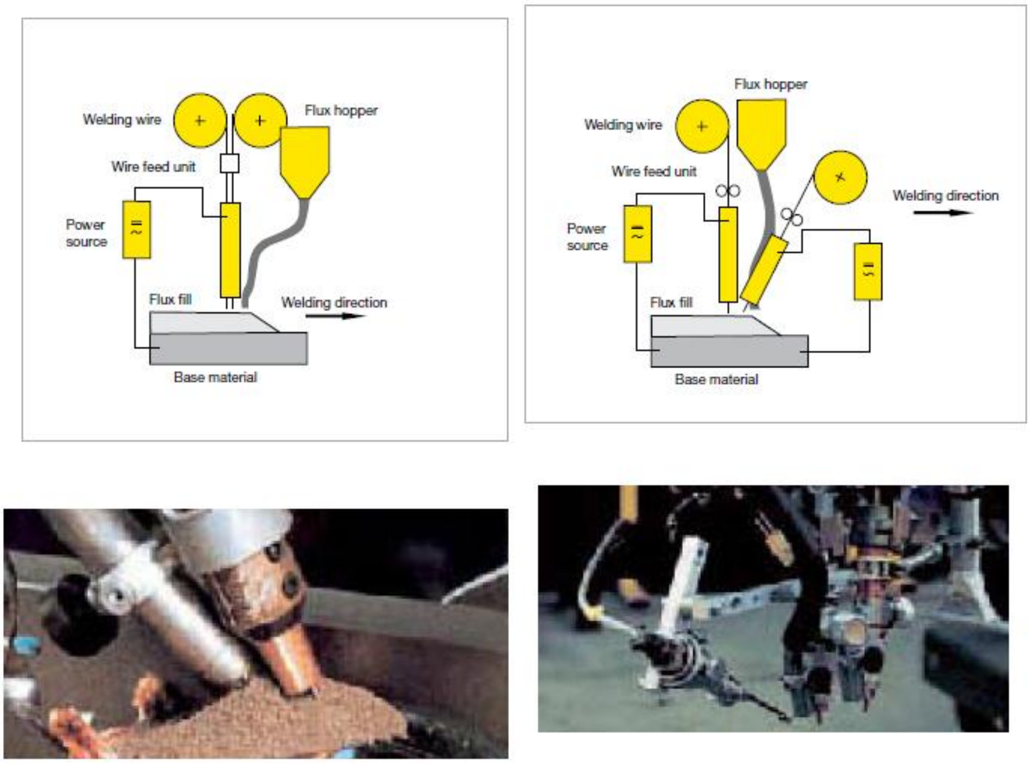


(a) (b)

Figure 2.3.16: Core wire variation (a) and Single wire variation (b) [53]

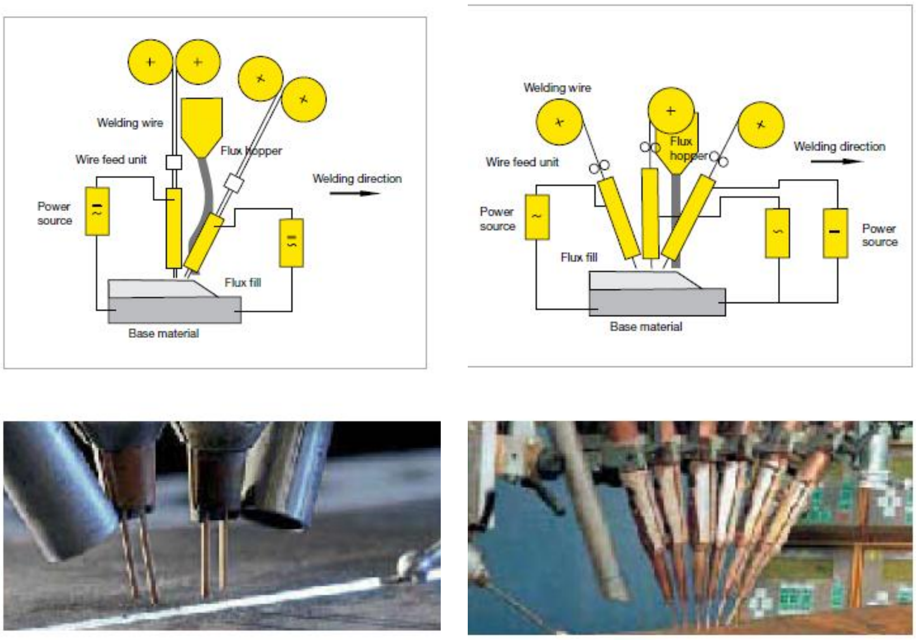
Table 2.3.1: Core wire and single wire variation parameters [53]

Number of Wires	1	2
Number of Power Sources	1	1
Wire Diameter Range (mm)	1.6-5.0	1.2-3.0
Current Range (A) total	200-1000	400-1200
Current Type	DC+	DC+
Voltage (V) per wire	25-38	26-38
Max. Total deposition rate solid wire (Kg/h)	Up to 12	Up to 15



(a) (b)

Figure 2.3.17: Twin wire variation (a) and Tandem wire variation (b) [53]



(a) (b)

Figure 2.3.18: Twin Tandem wire variation (a) and Multiwire variation (b) [53]

Table 2.3.2: Twin, Twin Tandem, and Multiwire variations parameters [53]

Number of Wires	2	4	3-6
Number of Power Sources	1	2	3-6
Wire Diameter Range (mm)	3-5.0	2.5-3.0	3.0-5.0
Current Range (A) total	1500-2400	1500-2200	2000-5500
Current Type	DC+, AC	DC+, AC	DC+, DC-, AC…
Voltage (V) per wire	28-38	26-38	30-42
Max. Total deposition rate solid wire (Kg/h)	Up to 25	Up to 38	Up to 90

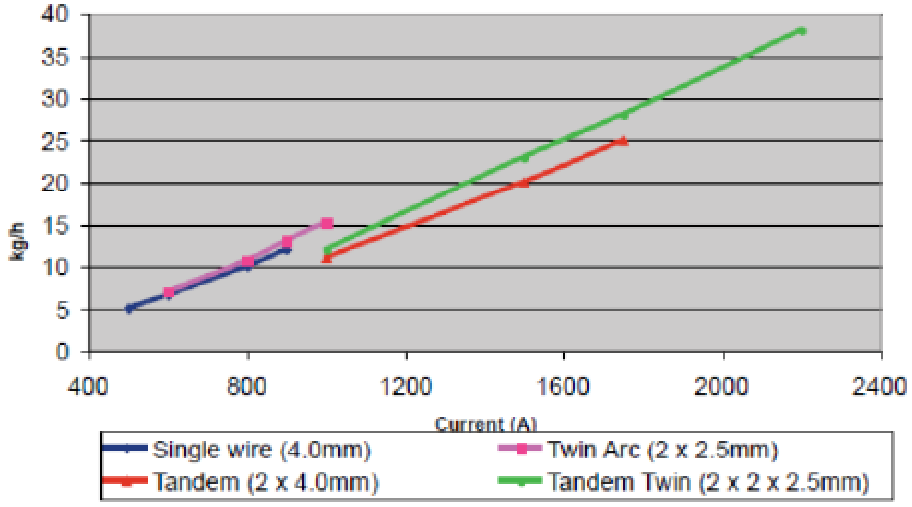


Figure 2.3.19: SAW process variations and their deposition rates [53]

Advantages of SAW [5, 53]

1. It offers reduction in exposure to UV radiation; there is no visible light due to the use of flux which blankets the arc.
2. It prevents hot materials from splattering and splashing back because of its submerged nature.
3. There is no need of fume extraction.
4. There is no need of pressure to create the weld since the electric current does the work.
5. Ease of automation
6. There is no spatter as the arc is completely covered
7. High weld metal quality
8. High productivity: High deposition rate and speed than any other arc welding process, deposition rate of 100 kg/h is possible
9. It only requires low operator skill
10. It has high thermal efficiency
11. It has very little risk of lack of fusion due to deep and safe penetration
12. It has very little risk of undercut and porosity

Disadvantages of SAW [5, 53]

1. There is limitation to the positioning during welding process.
2. High heat input and slow cooling cycle affects greatly microstructure and metallurgical properties of the material, especially the toughness properties.
3. It requires precise joint preparation.
4. There is no possibility to observe arc and the process during welding.

3. FUTURE TRENDS IN WELDING IN ARCTIC CONDITIONS

It is very clear now that welding in Arctic is very important nowadays and in the future. There are various current research on the best welding process and technique applicable that will guarantee high productivity and safety [55]. There are trends that are foreseen in welding in Arctic conditions, various modifications are being done day by day to the conventional and even to presently available advanced welding technologies. For instance, laser-hybrid welding has been applied to aerospace, automobile etc. but is yet to be applied to Arctic offshore platform, though it has been applied to pipeline welding [44]. Likewise, there are development and improvement on metallic alloys to make them suitable for Arctic applications.

There are two major requirement needed for development and improvement in respect to welding in Arctic region, namely:

- Metallic alloys with very high toughness and strength, of good weldability with the currently available advanced welding technologies (with little or no modifications).
- Advanced welding processes and techniques that will produce high toughness and high strength weld in conjunction with high productivity, economic and safety.

Hence, all major research with respect to welding in Arctic is being tailored towards these directions. The future trends of welding in Arctic can be divided into two categories, namely; material trend and welding technologies trend (which include both the welding processes and welding consumables trends). More high strength and high toughness metallic alloy materials are being developed from time to time. Likewise, modifications to available welding processes are being done to ensure weldability of these new materials.

3.1. Material Trend

The future development of Arctic metals is directed towards having metal alloys with both high strength (more than 800 MPa) and high toughness (more than 150 J/cm^2 for KCV_{-40}). Research is being directed towards reducing non-metallic content of presently available Arctic metals alloys. This will help to increase strength and also toughness. For instance, it has been reported that small percentage reduction in silicon, phosphorus and small percentage addition of titanium and boron can modify the strength and toughness values in such a way that both values will have a reasonable net increase [56, 57]. However, there are challenges associated with doing this and there are also consequential challenges with the new materials produced. Some of these challenges are highlighted as follows:

1. The need to know the percentage of reduction to ensure that, increase in strength does not lead to significant decrease in toughness and vice versa.

2. The need to increase the weldability of the new Arctic metal alloys. It has mainly been done by using TMCP and also by adjusting the percentage of the alloying components.

3. The need to ensure that the developed materials will be very good high cold-resistant materials in such a way that all efforts will not be in vain.

Hence, research is tailored in this direction to solve those above mentioned challenges.

Likewise, research is being tailored towards introducing the use of high strength aluminium for weight reduction and also nanomaterials for wear and corrosion reduction.

3.2. Welding Technologies Trend: Processes and Consumables

The present challenges of welding technologies in Arctic and the future trend of development and improvements are highlighted as follows:

1. The need to modify available welding technologies in a way such that they can produce a very good weld joint. The weld joint strength and toughness need to be increased.

2. The need to modify the parameter of the available welding technologies to be able to weld efficiently, the new Arctic metallic alloys.

3. The need to update methods of determining weld joint quality. More research is needed on application of NDT method to observe the weld quality of the new class of metallic alloys. Also, the critical need to improve method of evaluation of crack resistance of welded joint to brittle fracture, though, V-notch Charpy test and CTOD test are in existence.

4. The need to develop methods of predicting the strength of welded joint with respect to brittle fractures. This is needed to ensure that the welded joint will be able to survive under Arctic active service. Likewise, it will help to establish applicability of materials and welding technological processes.

5. The need to increase welded joint strength and toughness. It has been observed that addition of some powder element to weld pool during welding can help to increase the toughness and the strength of the weld joint. Some of these elements are titanium, boron, vanadium etc. Hence, there is need to concentrate more in this direction. The elements can be added through electrode coatings or flux-cored wires.

6. Continuous development of cold-resistant steels, welding consumables and technological processes which produce high metal resistance to brittle fracture.

7. Implementation of the use of laser-arc hybrid welding for construction of Arctic offshore structures. This has been noted to be more productive than the multipass MIG/MAG and other convectional arc welding processes.

8. Welding to withstand strain due to ice gouging and thaw settlement.

9. Weld cooling temperature control. Rock-wool blanket has been used but there is need for improvement.

10. The need for more research on welding ***consumables*** that can satisfy Arctic marine pipeline toughness requirement based on CTOD fracture toughness measurement. This trend goes to development of electrodes, wires and fluxes that can produce satisfactory weld joint. The consumables must have similar properties to the base metal alloys. This should be centered on application of modifiers in form of nanoparticles, added to the composition of fluxes and electrode coatings. There will be increase in pipe and column thickness being welded, hence, welding consumables and high welding speed techniques will be needed. Corrosion resistant consumables are highly needed because of presence of hydrogen sulphide (H_2S) and carbon dioxide (CO_2) alongside with crude oil.

Nevertheless, Arctic welding requires electrodes of high technological characteristics and quality [56]. There is need for improvement of welding technological properties of the electrodes and consequently, the mechanical indices of the weld metal joint. This should lead to production of low-hydrogen electrodes with more modifications on the electrodes coating. Also, there is need for more modifications on the electrodes coatings in order to improve stability of welding arc burning, reduce spattering of molten weld, improve weld formation and easy slag detachment.

However, some modifications have been made by PWI that leads to production of low-hydrogen electrodes but there is room for more improvement. It has been stated clearly that reduction in non-metallic components of weld metal and addition of some metallic elements such as titanium to the weld pool improves and increase the weld metal joint toughness and strength. Figure 3.2.1 and Figure 3.2.2 shows the influence of manganese content and titanium content on impact toughness of weld metal at different temperatures.

From Figure 3.2.1, it is very clear that the optimum manganese content that gives the highest values of weld metal impact toughness at Arctic temperature range for general-purpose low-hydrogen electrodes is 1.4-1.5% [56, 58].

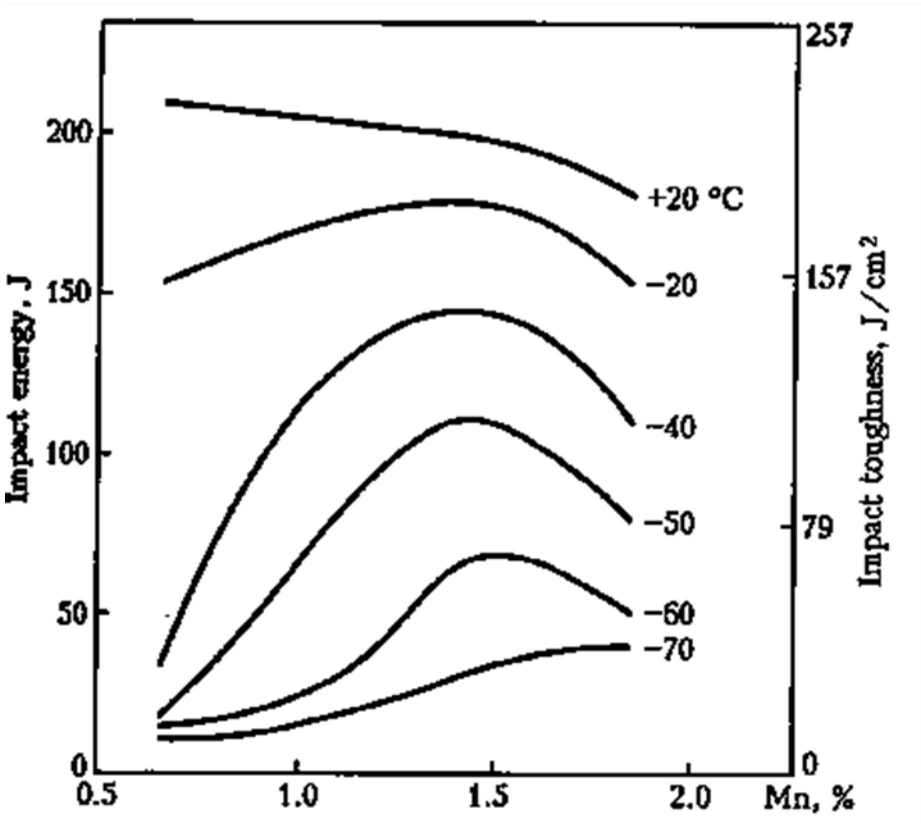


Figure 3.2.1: Influence of manganese content on impact energy and impact toughness of weld metal at different temperature [58]

Likewise, it has been reported that the optimization of titanium content in weld metal also influences its impact toughness values [56]. However, optimization of titanium content is influenced by the basicity of the flux or slag-forming base of the electrode coating, welding process and the alloying system [59]. Meanwhile, the optimum titanium content in the weld metal when welding with carbonate-fluorite coated electrodes was stated to be 0.1% [60] while it was stated to be 0.2% [61] according to the Figure 3. 2.2.

However, loss of balance in the deoxidation system in some electrodes grades with basic coating can leads to a reduction in toughness value of weld metal joints [56]. Hence, more extensive research is being done to produce electrodes that will give higher corrosion resistance and higher toughness value weld metal joints.

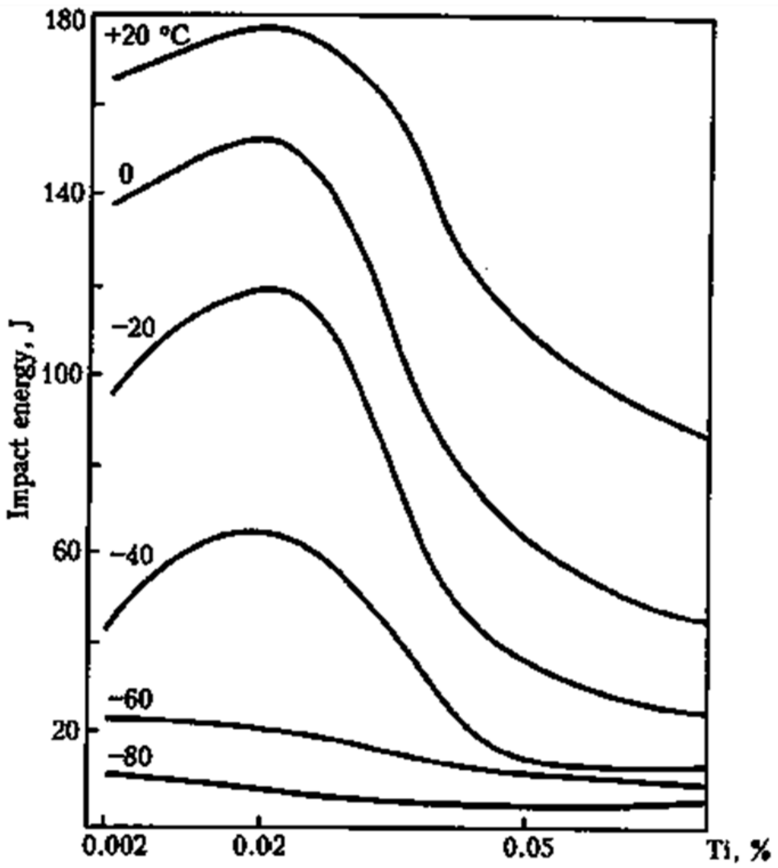


Figure 3.2.2: Influence of titanium content in weld metal on impact energy at different temperature [61]

However, the trend and the future of Arctic welding processes lie in the following highlighted processes:

1. Narrow Gap welding
2. Laser-Arc hybrid welding: Laser-MIG, Laser-TIG and Laser-SAW
3. SAW with multiple wire feeding
4. Tandem MIG/MAG

These welding processes are specifically selected due to the fact that they have potentials to give the minimum and even better toughness value required for weld joint in Arctic region. Some of them have been applied and the weld joint were tested using V-notch Charpy toughness test and CTOD. Moreover, Laser-MIG/MAG has been numerically simulated in comparison to the common multipass MIG/MAG and the result shown that laser- MIG/MAG give a better future for Arctic welding than the old conventional process of MIG/MAG even if multipass techniques is applied [44].

4. CURRENT PROJECTS IN ARCTIC WELDING

There are projects that are being currently carried out in and for the Arctic region. The basis of the projects is on environmental and safety exploration of Arctic energy resources. The project ranges from wind turbine installation to huge marine structures such as offshore platform, drilling rig, pipeline laying across the continent, among many others.

In the past, Trans-Alaska pipe laying project was done in Canada [62], the project is currently being maintained as there about 100000 weld joints along the 3500 km long pipeline. Recently, Russian is into the construction of offshore platform, ice breaker and drilling rig for oil exploration, as Russian is now very ready to explore the economic advantage of her Arctic region [63]. Some of the project that has been done and still being currently being done and improve on by Russia are Construction of offshore sleet-proof platform (OSPP); Construction of floating drilling units (FDU); Construction of ice breaker and ice ships; Development of materials for the construction of Arctic facilities.

Construction of ice breaker: There is everyday development and advances in shipbuilding technology to build powerful ice breaker. The ice breaker is a vessel strong enough to withstand the crushing power of the ice and to break through it. Nuclear powered ice breaker has being built before and more are now being built now. Icebreakers were the platform for opening up Arctic, especially for Russia. Figure 4.1 and 4.2 showed ice breakers in action. The ice breaker served as a symbol of Soviet technological power for many decades. Today, this fleet is used to aid ship navigation in the seas north of Siberia and for elite tourism [65].

Figure 4.1: The nuclear-powered icebreaker 'Vaigach' towing an oil rig [65]

Figure 4.2: The nuclear-powered icebreakers; 'Taimyr' and 'Vaigach' in convoy [65]

Meanwhile, the major current project starting in the Arctic region is called ***Shtokman project.*** This project is being carried out by Russia to explore the natural gas deposit in Arctic region within Russian domain of the region. The project involve the following:

- Construction of offshore sleet-proof platform (OSPP)
- Construction of floating drilling units (FDU)
- Construction of ice breaker and ice ships
- Development of materials for the construction of Arctic facilities
- Construction of flowlines, linepipes and riser made of pipes
- Construction of LNG tank with 9% Ni thick steel plate

PROMETEY Central Research Institute of Structural Materials (FSUE) is the body in charge of the Shtokman project. The project is all about integrated development of Shtokman gas condensate field in Barents Sea and this is basically a Russian project with international investment and expertise. The production site is located far beyond the Arctic Circle in severe climate conditions (see figure 4.3) and the main target in this project is efficient development of mineral resources of the Russian continental shelf. It has been noted that the development of the Shtokman gas and condensate field will create a basis for further harnessing the Arctic's offshore hydrocarbon potential in Russian region. This is because it has been noted that the development of oil and gas fields on the Arctic shelf of the Barents Sea will boost the economy of the northwestern region of Russia, mainly Murmansk and Archangel oblasts.

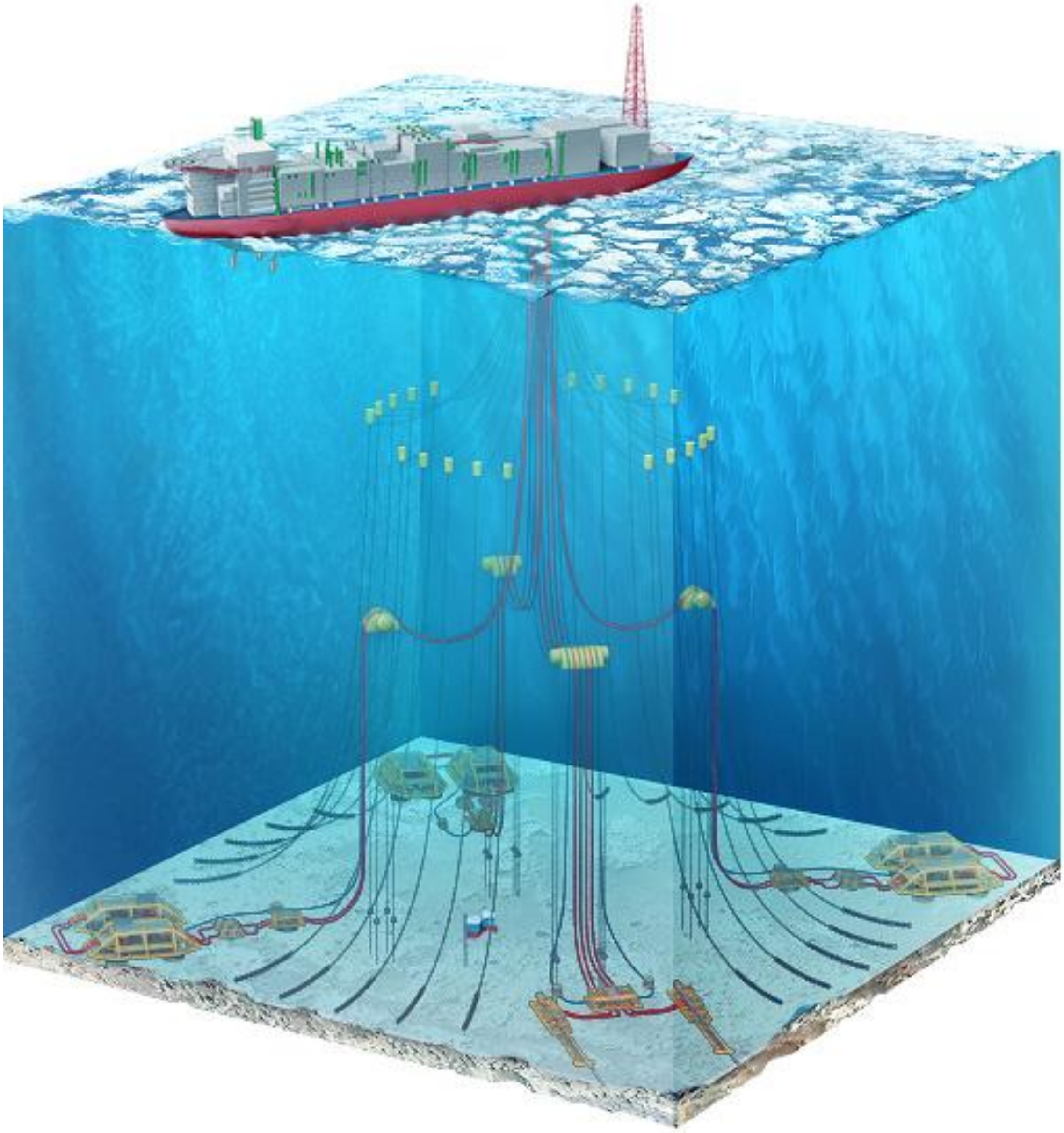


Figure 4.3: The offshore facilites for Shtokman project [63]

5. DISCUSSIONS AND CONCLUSIONS

5.1. Discussion

After carefully reviewing relevant literatures, some statements of facts can be deduced about the application of advanced welding technologies to Arctic metal alloys structures, used for construction of Arctic offshore metal structures, operating under active Arctic service conditions. Similarly, some factual deduction can be made about the Arctic metal structures themselves.

Higher strength and higher low-temperature toughness are being demanded for weld joints in new steel structures constructed and fabricated for use in the Arctic energy exploration fields. In addition welding efficiency calls for higher heat input, lower preheat temperature, and higher speed.

It is a known fact that the integrity of welded joints determine to greater extent, the integrity of the whole welded structures. As a result of this, failure of welded joint implies failure of the welded structures. Development of Arctic energy resources will sure make use of engineering structures such as drilling rig, ice ships, ice breaker, offshore jacket platform, ship barge, LNG tanks, linepipes etc.

Meanwhile, these different structures are being made of different Arctic metal alloys which are mostly HSS (for weight reduction), with X70 being majorly used now for linepipes, 9% Ni steel plates for LNG tanks, YS 420 for steel structures networks, X100 for ship hull etc. There have been also applications of X100, X120 HSS in one way or the other. All these metals are welded together in order to form the Arctic offshore structures.

However, some conventional welding methods including MIG, MMA etc. have been applied for welding of these metal alloys but the productivity, quality (in terms of weld joint toughness, strength and bead microstructures) and safety of the welded structures are very low. These give great concern due to huge loss that could be incurred in case of any failure of any of these welded structures. Hence, application of advanced welding technologies is inevitable in construction and maintenance of Arctic structures using Arctic metal structures. This is because applications of advanced welding technologies give a very good promising future and tends to reduce drastically the defect created by the use of the conventional welding methods.

Actually, some of the conventional processes are modified to give these new advanced welding technologies applicable now. For instance, MIG/MAG is upgraded to use multiwire to increase productivity; the filler wires are core wire with inclusion of powder form of titanium, boron, vanadium etc. This helps to add these elements to the weld pool and therefore increase the toughness and strength of the welded joints. Likewise, SAW was upgraded to use multiwire feeding system. The advanced welding technologies (NGW, multiwire MIG/MAG, LAHW, and multiwire SAW-NG) are the future of Arctic welding. These welding technologies meet the demanded toughness and strength requirement of Arctic weld joint with increased productivity, quality and safety of the welded structures. Further modification and improvement procedures are also been carried out on daily research activities in order to give an improved welded joint characteristics.

Meanwhile, considerable research effort has been made to improve process performance and control strategies for the various advanced welding processes used for Arctic metal structures. However, there are still some problems to overcome. The major efforts on research and development should be focused on the following topics:

- Automation of the welding process and inspection of the welded joints and structures. Although, automated MAG is a tried and tested process. Hence future developments will tend to be concentrated in more of computer control and subsequent progression from automated to robotic automation and also to adaptive welding.

- Mechanized welding to accommodate usage of very large floating structures.
- Investigation of the tendency of using a robot manipulator for ultrasonic testing of weld joints in complex geometry.
- Understanding the characteristics behaviour of materials after the welding and process optimization.
- Generation of research data book on weldability of materials during welding process.

5.2. Conclusion

Advanced welding technologies give a promising future for Arctic welding. The above discussed welding technologies are envisaged to take the turn of event in welding in the nearest future. It can be concluded that the productivity, safety and quality of the weld produced by these advanced welding technologies give the best shot of the moment and will also do for the future. Though the initial set up cost might be a bit above the conventional processes due to the special welding head, however, the overall benefit of the welding process in terms of net cost, productivity and safety of the welded structures give optimum desired interest.

6. SUMMARY

The objectives of this research work was to investigate and present advanced welding technologies and Arctic metal alloy structures that can be used for construction and maintenance of Arctic metal structures, equipment and facilities under active Arctic service conditions without experiencing any failure. Furthermore, the essence of the research work is to know the suitable advanced welding technologies and the Arctic metal alloys needed for fabrication of Arctic metal structures and facilities used for exploration, development and production of abundant energy resources in Arctic.

Firstly, the reasons for looking towards Arctic region for energy production were examined, then the Arctic geographical features were analysed, including the energy resources found in the region and the environmental challenges associated with Arctic region. The harsh environmental conditions of Arctic and the potential of exploring its huge energy resources reserve were also examined and analysed.

Afterwards, the importance of low temperature welding; challenges associated with welding in Arctic region; the need for high toughness and high strength materials; and advanced welding technologies in the region were presented. The available metal alloys materials used for Arctic offshore facilities construction were studied with the relevant available advanced welding technologies used for joining them.

It was observed that in developing Arctic energy resources, both advanced metallic materials development and advanced welding technologies development must go in hand to hand to bring about the desired weld joint properties. It was also noted that high toughness and high strength metallic materials and weld joints are needed for construction of facilities in order to ensure their productivity and safety when operating under active Arctic service conditions. This is due to the fact that failure of welded joints implies failure of the whole metal structures.

Various developmental trends with respect to Arctic welding were also analysed, especially in relation to materials trend, welding trend and welding consumables trend. Some old and current Arctic projects that have been done and that are being planned to be carried out were also examined and presented.

Finally, it was concluded that, only advanced welding technologies give a promising future for Arctic welding. It was concluded that the productivity, safety and quality of the weld joints produced by the examined advanced welding technologies give the best shot of the moment and will also do for the future, fulfilling the desired weld joints properties needed in Arctic conditions.

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