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Advanced Orbital Pipe Welding

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ABSTRACT

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Since the introduction of automatic orbital welding in pipeline application in 1961, significant improvements have been obtained in orbital pipe welding systems. Requirement of more productive welding systems for pipeline application forces manufacturers to innovate new advanced systems and welding processes for orbital welding method.

Various methods have been used to make welding process adaptive, such as visual sensing, passive visual sensing, real-time intelligent control, scan welding technique, multi laser vision sensor, thermal scanning, adaptive image processing, neural network model, machine vision, and optical sensing. Numerous studies are reviewed and discussed in this Master's thesis and based on a wide range of experiments which already have been accomplished by different researches the vision sensor are reported to be the best choice for adaptive orbital pipe welding system.

Also, in this study the most welding processes as well as the most pipe variations welded by orbital welding systems mainly for oil and gas pipeline applications are explained. The welding results show that Gas Metal Arc Welding (GMAW) and its variants like Surface Tension Transfer (STT) and modified short circuit are the most preferred processes in the welding of root pass and can be replaced to the Gas Tungsten Arc Welding (GTAW) in many applications. Furthermore, dual-tandem gas metal arc welding technique is currently considered the most efficient method in the welding of fill pass.

Orbital GTAW process mostly is applied for applications ranging from single run welding of thin walled stainless tubes to multi run welding of thick walled pipes. Flux cored arc welding process is faster process with higher deposition rate and recently this process is getting more popular in pipe welding applications. Also, combination of gas metal arc welding and Nd:YAG laser has shown acceptable results in girth welding of land pipelines for oil and gas industry.

This Master’s thesis can be implemented as a guideline in welding of pipes and tubes to achieve higher quality and efficiency. Also, this research can be used as a base material for future investigations to supplement present finding.

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First, I would like to thank God for giving me the strength, courage, and health to do this project work. The author wishes to express sincere appreciation to the laboratory and welding department, where this project work was done for their guidance and financial support.

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Background

Orbital welding was developed at the beginning of the 1960s by the aerospace and nuclear power industries to provide the basic conditions to manufacture highly reliable components [1, 2, 3, 4, 5]. The first orbital welding system was a mechanism of rotating tungsten electrode that produced welding arc around a tube weld joint. The system was supported by a controlling system for entire process by which obtained result was more precise and reliable than manual welding [3]. The first use of mechanized orbital welding of cross-country pipelines with carbon dioxide process was laid in the US in 1961 and at the same time five different orbital Gas Metal Arc Welding (GMAW) processes were under research and development [6, 7].

By the early 1980s, Orbital welding became practical for many industries thanks to the development of portable combination power supply/control systems by reducing the size of equipment. The portability of equipment made multiple in-place welds possible around construction sites [3, 4]. In the late 1990s, improvement of microprocessor technology leads orbital welding to the position of a cost effective and preferred method of making connections provides more welding options for welders of different skill levels [5].

Nowadays, orbital pipe welding is one of the key methods applied in almost every industry, such as food, dairy, beverage, power, chemical, oil and gas, pulp and paper, etc. [1, 8]. However, in some developing countries, this method of welding is still quite new and has not been in use so often.

Contents

List of Symbols and Abbreviations

A	Ampere
AC	Alternating Current
ACC	Accelerated Cooling
API	American Petroleum Institute
Ar	Argon
ASME	American Society of Mechanical Engineers
BPE	BioProcessing Equipment
CC	Constant Current
CCD	Charge Coupled Device
CCW	Counterclockwise
cm	Centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
CPT	Critical Pitting Temperature
Cr	Chromium
CTOD	Crack Tip Opening Displacement
CV	Constant Voltage
CVN	Charpy V-Notch
CW	Clockwise
DC	Direct Current
DE-GMAW	Double Electrode Gas Metal Arc Welding
DT-GMAW	Dual Tandem Gas Metal Arc Welding
El	Elongation
EWI	Edison Welding Institute
FCAW	Flux Cored Arc Welding
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
He	Helium

HLAW	Hybrid Laser Arc Welding
ID	Inside
J	Joule
kg/hr	Kilogram per hour
kHz	Kilohertz
kJ/mm	Kilojoule per millimeter
kW	Kilowatt
LNG	Liquid Natural Gas
m	Meter
m/min	Meter per minute
MAG	Metal Active Gas
MIG	Metal Inert Gas
MJ-6	Material Joining-Weld Acceptance Criteria
mm	Millimeter
mm/s	Millimeter per second
Mn	Manganese
Mo	Molybdenum
MPa	Megapascal
µm	Micrometer
Nd:YAG	Neodymium-doped: Yttrium Aluminum Garnet
NG-TGMAW	Narrow-Groove Tandem Gas Metal Arc Welding
Ni	Nickel
OD	Outside
P	Phosphorus
PAW	Plasma Arc Welding
P-GMAW	Pulsed Gas Metal Arc Welding
PQR	Procedure Qualification Record
PS	Pressure Strength
Rm	Tensile strength
Rp0.2	Yield point 0.2 %
S	Sulfur

SAW	Submerged Arc Welding
SMAW	Shielded Metal Arc Welding
STT	Surface Tension Transfer
T-GMAW	Tandem Gas Metal Arc Welding
TIG	Tungsten Inert Gas
T.I.M.E	Transferred Ionized Molten Energy
TM	Thermo-Mechanical
T-SAW	Tandem Submerged Arc Welding
TS	Tensile Strength
TW-GMAW	Twin Wire Gas Metal Arc Welding
TWI	The Welding Institute
UK	United Kingdom
US$	United States Dollar
USA	United States of America
USSR	Union of Soviet Socialist Republics
V	Voltage
WOPQ	Welding Operator Performance Qualifications
WPS	Welding Procedure Specification
Yb	Ytterbium
5G	Horizontal fixed Groove
℃	Degree Celsius

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1. Introduction

Pipes and tubes welding are widely used in almost every engineering application, such as nuclear and thermal power plants, semiconductor fabrications, oil and gas industries, and petrochemical plants. Therefore, the welding quality of pipelines has a direct effect on the public safety and quality of the products [9, 10]. Oil and gas industry will be one of the key industries demanding extensive pipe welding due to the prediction of a doubling of natural gas consumption over the next 20 years [11, 12]. This increscent in requirements of pipe welding will require major investment in gas transmission pipelines. Trend of using gas transmission with higher operating pressure and higher strength steels increased demand of higher weld metals toughness and quality. On the other hand, the cost of pipelines constructed should be considered to be as low as possible.

Various automatic welding processes have been developed in pipe welding industries to speed up welding process, producing better weld quality, and reducing welding cost [12]. Also, development in orbital pipe welding technology helps to maximize the productivity of available welders and make welding process easier by employing a variety of automated features, such as data collection, programming, and live weld progress [11, 13]. Different factors, such as gravity, arc force, surface tension, heat accumulation, joint preparation, and fit up precision effect welding pool during automatic orbital pipe welding. Therefore, need of feedback and controlling system is a vital part of orbital pipe system to ensure high welding quality [9].

Orbital welding is finding increasing value because it can present a cleaner, virtually crevice surface and deliver highly repeatable and consistent quality welds. Consequently, today, orbital welding has become a practical tool for many plant and industrial operations due to the advanced technology [5]. These industries can be named as, boiler tube, food, dairy and beverage industries, nuclear piping, offshore, tube/pipe fitting, valve, regulators, power, chemical, oil and gas, aerospace, biopharmaceutical, medical, semiconductor, and pulp and paper industries, and for use in construction, plant maintenance, distillation and refining operations [1, 3, 4, 14, 15].

By 2003 in all around the world, almost 20,000 km of pipelines were completed at total cost of US$15 billion. 60 % of this number belongs to the natural gas pipelines [16]. Recently, significant improvements have been obtained in adaptive orbital pipe welding system. Various studies have been done in weld pool geometry sensing, modeling and intelligent control of the weld quality, and process monitoring. In this research work, the most typical welding processes used in orbital pipe welding as well as adaptive controlling system of orbital pipe welding are explained.

1.1. The Objective of the Work

Due to the fact that standards are getting more stringent in pipelines welding, all joints are required to be uniform and it is difficult for the welder to comply with these requirements [17]. Also, by growth of pipe welding applications, the need of orbital pipe welding process with higher productivity, greater weld quality, lower cost, and accuracy in manufacturing is sensed more than before. In this case, an adaptive orbital pipe welding system provides dramatic improvements over existing methods [18, 19, 20]. The main objectives of this thesis work are to:

- Introduce mechanized pipe welding and its variation
- Explain orbital pipe welding and its variation
- Explain applications of orbital pipe welding
- List advantages/disadvantages of orbital pipe welding
- Explain properties of possible pipe's materials for orbital welding applications
- List the most used pipes in orbital welding especially for oil and gas pipelines
- Explain the most used welding processes for orbital pipe welding
- Explain adaptive orbital pipe welding
- Explain seam tracking in orbital pipe welding
- Investigate the economical aspect of using orbital pipe welding

2. Pipe Welding

Welding which is used in pipelines, typically is divided into mainline welding, tie-in welding, and repair welding. Speed in mainline welding is critical factor and there is access for backing system, but in Tie-in and repair welding there is no access to the inside of pipe and speed is less important [21]. In this study, adaptive orbital pipe welding of mainline will be explained with different processes.

2.1. Variation of Mechanized Pipe Welding

Mainly, mechanized pipe welding is divided into stationary and orbital pipe welding which are explained below [22].

2.1.1. Stationary Pipe Welding

In the stationary pipe welding systems, welding head has a fixed position while the pipe rotates [22]. This system is one of the most used processes in the oil and gas pipeline industry. Figure 1 depicts an example of rotational mechanism which is called “roller bed” [23]. As can be observed from the figure, pipe is positioned in rotational mechanism and motors have the duty of pipe rotation.

Different processes, such as Plasma Arc Welding (PAW), GMAW, and Gas Tungsten Arc Welding (GTAW) can be used in stationary pipe welding system. Submerged arc welding (SAW) is popularly employed as one of the major fabrication processes in pipe manufacturing industries. Possibility of using SAW as an orbital process is low due to the flux powder which is used in this process. Because of wide applications of SAW process, in next sections this process will be explained by more details.

Figure 1 Rotational mechanism for stationary pipe welding [23]

2.1.2. Circular Pipe Welding (Orbital)

In this pipe welding method, the welding head rotates around a fixed vertical or horizontal pipe [22]. Moving of electrode circumferentially around the pipe has more advantages compared to the stationary pipe welding [24]. This type of pipe welding which is main part of this study will be explained by detail.

Pipe Fixing Mechanism in Orbital Welding

Fixing of pipe in orbital pipe welding system is an important factor due to the sensitiveness of precision in this system. Small positioning error may lead to incomplete or misaligned weld and growth of welding cost by re-welded or cut out of the weld [14].

2.2. Submerged Arc Welding (SAW)

SAW is an arc welding process that established arc between a consumable electrode and the weld pool heats workpiece to join them. In this process fluxed powder used to cover and shield both, the arc and molten weld [25].

There are several advantages involved with SAW process, such as deep penetration, relatively free of the intense radiation of heat and light, free of spatter, welding of very thick sections at low velocities, high efficiency, a smooth bead, availability in automatic or semi-automatic mode, and good reliability [26, 27, 28]. On the other hand, there are few limitations of using SAW process. SAW is limited to flat and horizontal positions welding due to the effect of gravity [26]. A full time operator is needed in welding of pipe, pressure vessel, and ship structure by SAW, although this process is typically a mechanized process [29, 30]. In pipe welding applications by SAW, finding suitable values for the process parameters to obtain a desired quality and bead geometry is not easy work [31, 32]. This welding process requires work pieces to be rotated under a fixed torch. Also, this method requires considerable capital expenditures for turning rolls and positioners, especially if the pipe work consists of larger-diameter pipe, long lengths and heavy assemblies [33].

The benefits of SAW process make this process robust in the fabrication of pressure vessels, marine vessels, pipelines and offshore structures [28]. Improving the deposition rate of SAW process has been always the main issue and lots of effort has been done to achieve this purpose. Higher deposition rate can be obtained by increasing heat input. One way is using Tandem Submerged Arc Welding (T-SAW) [34] by twin arc mode [35, 36] or multi wires (four-wire) which is becoming more popular in longitudinal seam pipe production and leads to higher proficiency [37], and another way is adding metal powders [38, 39].

Beside productivity, bead geometry such as adequate penetration is an important factor in welding process [40]. Possibility of obtaining poor bead geometry is always high due to the demand of deeper penetration. Therefore, having knowledge of changing a particular parameter on the bead geometry is an important issue and many efforts have been made to correlate the bead geometry with the welding parameters [41, 42, 43].

In the study [40], the author used software developed at Carlton University [44] to predict the weld bead geometry for SAW process. The following conclusion can be listed from the study:

- Four methods can be used to increase melting rate of SAW process which are; higher current, straight polarity, smaller diameter of electrode, and longer electrode extension.
- Current level and polarity influence the percentage difference in melting rate, bead width, bead height, and bead penetration.
- The reduction in electrode diameter increases the melting rate, bead height, and penetration.
- There is a linear relation between electrode extension and current. Bigger electrode extension at low current raises bead height and penetration.

One of the stationary pipe welding mechanisms used mostly for large diameter pipes is column and boom manipulator. This mechanism is mainly adapted with SAW process and one of which was visited by author in Iranian marine industry which works also in oil and gas development. Figure 2 shows the column and boom mechanism in the mentioned industry used in welding of carbon steel pipe [23].

Figure 2 Column and boom manipulator use with SAW process [23]

Figure 3 (a) shows the root pass welding result of Chinese's carbon steel pipe with size of $1524 \times 4450 \times 12000$ millimeter (mm). Mr. Ahoochehr, Construction Manager of Iranian marine industry (SADRA) explains, "The root pass and hot pass welding are done with four welders by Shielded Metal Arc Welding (SMAW) process. The most typical electrodes used in root and hot pass welding are 718/1-HF made by French company "SAF". Pipe thicknesses are varies from 45, 63, 76.6, 88.9, 117, 123, and 137 mm depending on the applications." Figure 3 (b) shows the final weld bead result of multipass welding done by column and boom manipulator SAW process (Figure 2). Mr. Ahoochehr says, "with this system a full multipass welding of one pipe takes almost 24 hours while with SMAW process by using four skilled welders it takes almost four days.”

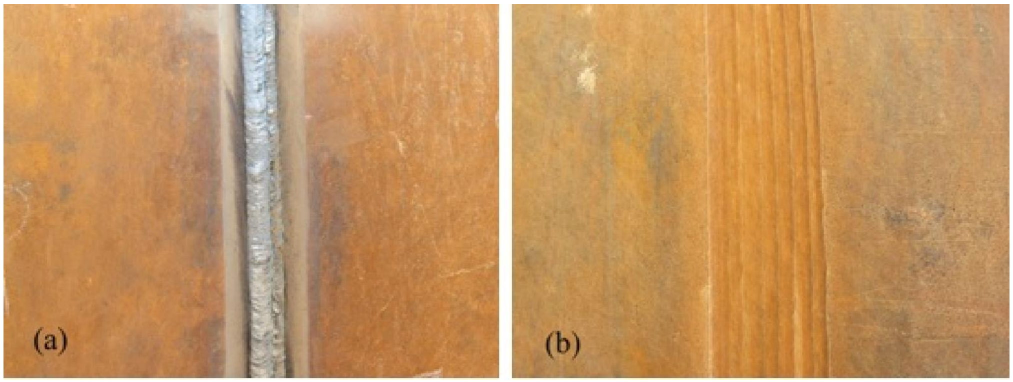


Figure 3 (a) Root pass welding of carbon steel pipe with SMAW process (b) the final weld bead with several passes done by column and boom manipulator SAW process [23]

3. Orbital Pipe Welding

The term orbital pipe welding is an automated process performed on tubing and pipe in a fixed position where a weld head is track mounted for all position welding. Weld head of orbital welding systems rotates an electrode and electric arc around the weld joint to make the weld (Figure 4) [45, 46, 47]. In applications, such as pipeline welding, welding nuclear spent fuel canisters and so on, that high quality welds, reliable and high productivity are required, orbital pipe welding is one solution and manufacturers are constantly innovating to produce next generation systems of it [8].

Figure 4 Standard enclosed orbital weld heads can be used to weld tube size from 1.6 mm up to 152.4 mm and wall thicknesses up to 4 mm [4]

Orbital pipe welding technique could yield in significant reductions in the processing time, skilled welder, and welding costs but improvements in the joint quality [17]. In this section, relevant features of orbital pipe welding will be explained in details.

3.1. Advantages of Orbital Pipe Welding

The first and foremost advantage of orbital pipe welding over manual welding mentioned in various studies is the present shortage of skilled welders. In orbital welding one operator can control several machines and whole procedure. Orbital welding systems perform a set of operations in a controlled manner where variables are controlled to ensure a greater degree of accuracy but the operator still continues to play an important role [5, 29, 48, 49]. Orbital welding systems are portable, accessible, fast, precise, and cost effective which make them a more practical for a range of applications [5, 50].

The automated orbital welding process for pipelines aids to provide for more uniform, high-quality, consistent and repeatable results since the systems make the welding decisions, such as travel speed, arc gap, current control, and etc. [5, 29, 48, 49, 50]. Also, higher productivity, higher welding speed, lower distortion, well-documented, controlled and limited heat input which lead to lower Heat Affected Zone (HAZ) are further advantages of orbital pipe welding [11, 12, 48, 50]. The number of defects minimized and program can be repeated several times without mistakes [11].

Manual welding is slower and subject to human error with inconsistent results, although the welder may be highly skilled and experienced [5, 50]. Manual welding needs more space around the pipe to provide welders enough clearance for full body access to the weld location with switch position and repeatedly starting and stopping [5, 11]. Another disadvantage of manual welding is documentation, which may not be carried out regularly from operator to operator [48]. Figure 5 (a) illustrates the manual GTAW welding and (b) orbital GTAW of stainless steel tubes to see the advantage of using orbital welding in quality. It easily can be observed that the welding done manually is significantly more oxidized and less consistent than the automatic weld [51].

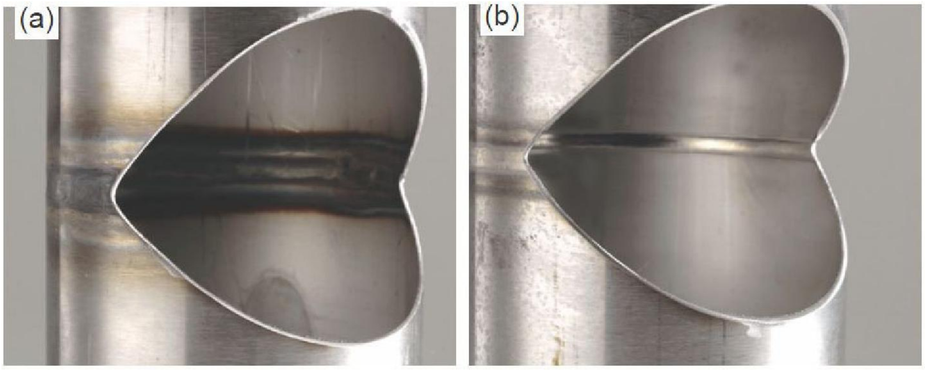


Figure 5 (a) Manual welded process tube (b) Orbital welded process tube [51]

3.2. Fundamental of Orbital Pipe Welding

Typically, orbital pipe welding machines are divided by closed head (full function in place) and open head (full function orbital) [45]. For welding of tubes, mostly closed head machines are used and for welding of pipes with large diameters open head machines are used. Both types of these machines are shown in Figure 4 and Figure 6.

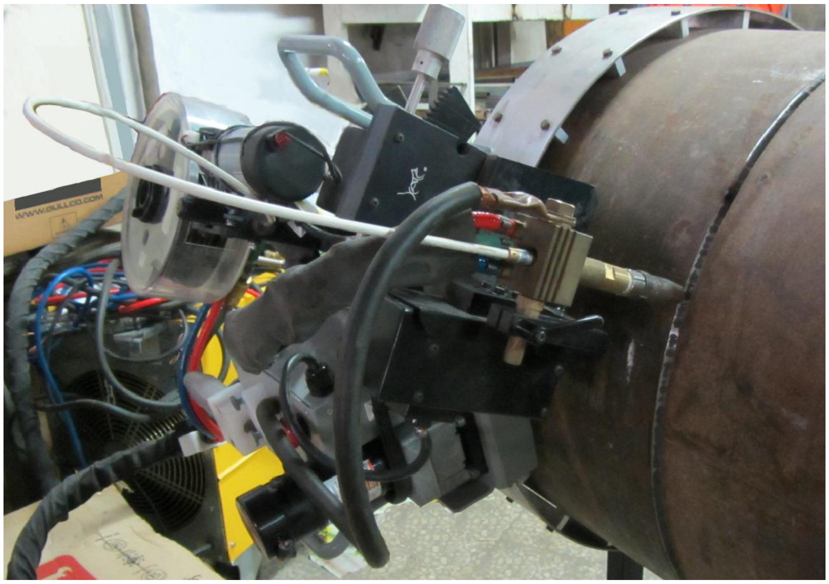


Figure 6 Open head welding machine for welding of pipes with large diameter [52]

3.2.1. Closed Head Mechanism (Full Function in Place)

For welds critical thin-wall tubing and pipes with small and medium-sized, fabricators select a closed head device [22, 46]. Standard closed orbital weld heads can be used for tube sizes from 1.6 to 162 mm (this number can be varies e.g. up to 200 mm [22] or 6.3 to 203 mm [46]) with wall thicknesses of up to 3.9 mm (0.4 to 12.7 mm [46]) [4]. The head housing in close head systems can be fixed or adapter types with limited range of accommodation [46]. Generally, during designing of welding heads, pipe standards and limitations are taken into account by manufacturers, in order to make the range of a single welding tool proportionately broad [22]. For welding of particular applications requiring extreme purity, thin-walled aluminum tube, small diameter tubes, titanium and stainless steels pipes, and so on, closed head welding system can be used [2, 22, 45].

This system performs autogenous welding and the tubes are maintained in a fixed position. The head cover the entire weld area while the tungsten electrode holder moves along the joint driven by a small dc gear motor inside of head. The enclosed chamber filled with inert gas (usually argon) which is responsible for shielding the end part of the electrode and the fusion zone and the heated regions of the component to prevent the hot weld zone from oxidation [2, 22, 46, 51]. Arc length in this system remains fixed [46] and wire feed is and arc voltage control is not needed [45]. Figure 7 shows the principle of orbital GTAW closed head process explained [2].

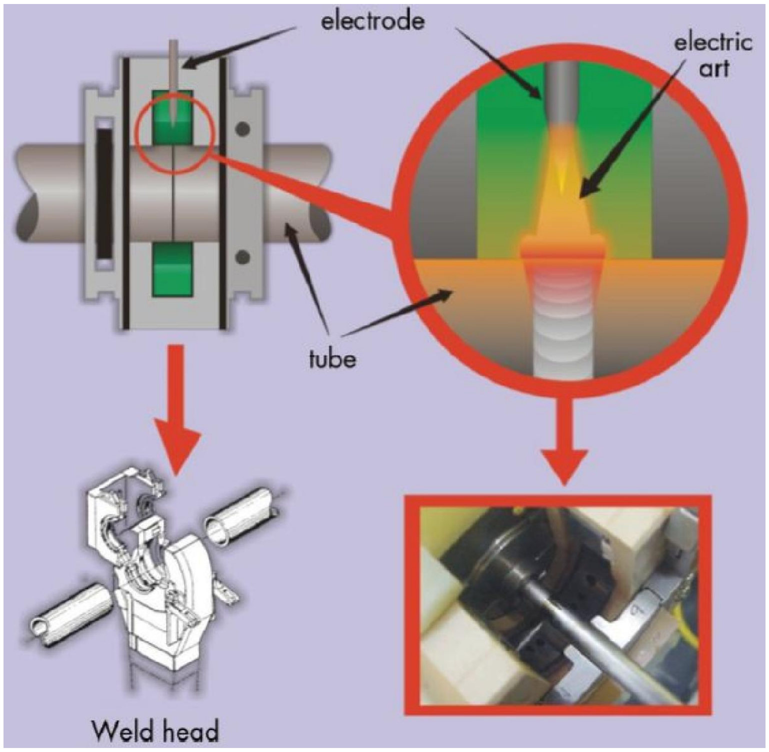


Figure 7 Principle of orbital GTAW process [2]

In welding of stainless steels with this mechanism, it should be considered that inside surface of the pipe as well as outside should be protected from oxygen during whole process. The reason is that stainless steel pipes content chromium and carbon and during welding without proper protection will react with the oxygen to form chromium carbides, commonly known as coking. To solve this problem internal bore of the tube should be filled by an inert gas. This method is well known by back purging [51].

3.2.2. Open Head Mechanism (Full Function Orbital)

Generally, open head systems are used for pipe welding with large diameters and wall thicknesses (above 170 mm [22]) and are considered full function heads [4, 22, 45].

There are two approaches for designing of this welding system. In the first one, within of an external frame the welding heads mounted, introduced since 1960s, and its main application is on lay barges, planned for the wide, open space of the USA and USSR. In the second approach, welding system consists of welding head or "bugs", bands or chains, power supply, wire feeder, a programmable controller, shielding gas, and coolant. Bands or chains are a device attached to the pipe or tube to move the head around the joint. The controller may be mixed into the power supply and cable for delivery of power. The welding heads mounted on bands or chains and travels the circumference of the pipe along a track. In welding of thin wall tube, welding head mostly consists of water cooling system to reduce heat input. The main application of this welding system is onshore pipelines [7, 22, 46].

By starting welding procedure by operator, the weld head and its inside electrode house rotates in a precise orbit around the joint. The process is highly controlled, and there are at least four servo controlled axes (travel, wire, arc voltage control, and center steering) to ensure high quality welds that can be produced on a consistent and repeatable basis. Precise controlling of all parameters in welding head requires a state-of-the-art computer due to the complexity of this welding process [45, 46, 48]. It takes slightly more time to install these systems than to install an in-place head. This type also may require a longer straight length of pipe for mounting. In orbital multipass pipe welding, welding heads typically feature [1]:

1. Torch rotation
2. Filler wire feed capability
3. Electronic control of arc length (arc voltage control)
4. Torch oscillation (weave) capability with programmable width, speed, and independent end point (sidewall) dwell times.

The direction of welding head will change by changing of applications. If the position of pipe weld is horizontal (5G) both, a double up and double down technique (6 to 12 O'clock CW, followed by 6 to 12 O'clock CCW) can be used [47]. Also, weave technique is usually used in the 5G position welding. To ensure complete sidewall fusion, most of available systems are possible to be programmed dwell or delay period at either end of the oscillation stroke. Orbital pipe welding with oscillation motion is a useful feature in pipe welding industries [53].

One way to improve productivity in open head mechanism is to mount two welding torches on one head. The improvement continues by reducing the distance between two wires and using shared gas and weld pool. In a further development, it has been proposed to replace the two torches of a system with tandem torches, creating the so-called “Dual-Tandem” process [54].

3.3 Properties of Pipe

Welding of thick wall pipes has become a key process in several important industrial areas, including offshore and onshore pipelines, vessel fabrication, and nuclear industry [29]. The majority of welded steel pipe is produced from coil or plate [55]. Choosing proper pipe for special purposes is a factor that influences the whole job by minimizing the possible generation of any defects. The first and foremost step is selecting material of pipe. Factors in choosing ideal pipe for special application are, pipe wall thickness, outside diameter, and cleanliness. Storage and handle of pipe in welding industry are important as well and pipes should be stored in a proper weather condition. Also, dust, moisture, and dirt inside of tube or pipe, makes welding difficult and costly [14].

The result of experimental test done by UNAMON in 1996s [24] showed orbital welding are more efficient for the small diameters and thicknesses. Measuring proper thickness in pipe welding is essential to prevent hardening of the structure in the HAZ and cold cracking. The greater thickness of the pipeline causes higher cooling rates [56].

3.3.1. Possible Pipe Materials in Orbital welding

Controlling of certain elements, such as sulfur in the composition of material is very important in welding procedure [14]. Generally, weldability of 300-series stainless steels with orbital system which used prevalently are good with the exception of the types 303 which contain high sulfur and 303SE which contain selenium for ease machining. Weldability of 400-series stainless steels is good, however possibility of requiring post-weld heat treatment is also high [3]. Recently, usage of high strength low alloy (HSLA) steels, greatly increased in welding of pressure vessels, tube and pipes with orbital systems [57].

Titanium and its alloys pipe are using in applications that corrosion resistant and particular strength are required and can be welded by orbital pipe welding systems [58, 59]. In Gulfstream pipeline project [60], grades were used for the majority of the offshore pipeline was APL 5L Grade X70. American Petroleum Institute (API) 5L X60 pipe with diameter of 406.4 mm was successfully laid recently in the UK sector of the North Sea [61].

High strength X80 pipe were used for the first time in Europe by 1980s in Germany using SMAW welding and at almost the same time, Nova Company in Canada used mechanized pipe welding for X80 pipe [21]. Common X80 steels used in industries has properties of: 615 Megapascal (MPa) of yield strength, 680 MPa of tensile strength, 21 % of elongation, 226 HV10 of hardness, and 330 J of Charpy impact energy at 20 ℃ [37]. Other high strength steels, such as X90, X100, and X120 are also possible to be welded by orbital pipe welding system.

3.3.2. Materials Weldability for Oil and Gas Applications

There is a strong demand for gas and oil in the world especially in the fast growing economies like China and India, which implies continued growth of oil and gas pipeline installation [62, 63, 64]. Worldwide gas consumption is predicted to be almost double over 25 years, from almost 2540 trillion liters in 2000 to 4980 trillion liters in 2025 [16]. The main problem of using gas is that many of gas resources situated in remote locations and transportation of gas from those resources needs long distance pipelines transmission [62, 63].

Crude oil is a heterogeneous mixture of hydrocarbons with non-hydrocarbon components which includes alcohols, phenols, sediments, water, salts, sulfur compounds, acid gases (such as Hydrogen Sulfide H_2S), carbon monoxide (CO), etc. [65, 66]. There is always high level of corrosion possibility in inner surface of pipe by oil during its movement due to the corroding agents (water and oxygen). Settled water which contains dissolved salts and acids, in bottom of pipe has corrosion effects on those parts in the pipeline [66]. Therefore, high level of safety and trust direct to reduction of cost, highest efficiency, and lowest defects, required in oil and gas pipeline distribution. So, special attention required in material selection of pipe and recent research focuses on the fracture toughness property which is a main factor in the design of oil and gas pipelines [67, 68, 69, 70, 71].

Demand of liquefied gases worldwide, such as Liquid Natural Gas (LNG) which may be obtained by cooling down methane gas to temperature below -163 ℃ has increased [72]. Higher pressures and flow levels towards using line pipe of larger diameter and/or higher operation pressure. To improve operational efficiencies, avoid large wall thickness of pipe, and cost saving, development of higher strength steel grades with relatively thinner wall pipe started more than 30 years age [16, 37, 47, 62, 73, 74].

Thermo-mechanical rolling (TM treatment) method which provides possibility of producing material from steels up to X70 was invented in the early seventies to replace with hot rolling and normalizing method. X70 is micro-alloyed consists of niobium and vanadium with lower amount of carbon. Figure 8 depicts the historical development of the pipe steels [73]. X70 steel showed great welding result in China's East-to-West gas transmission project [37]. As can be seen from the figure, X80 steel were invented by combining TM rolling and subsequent accelerated cooling (Acc

Cooling) which lead to higher strength, lower carbon content and as a result better field weldability rather X70 steel [73].

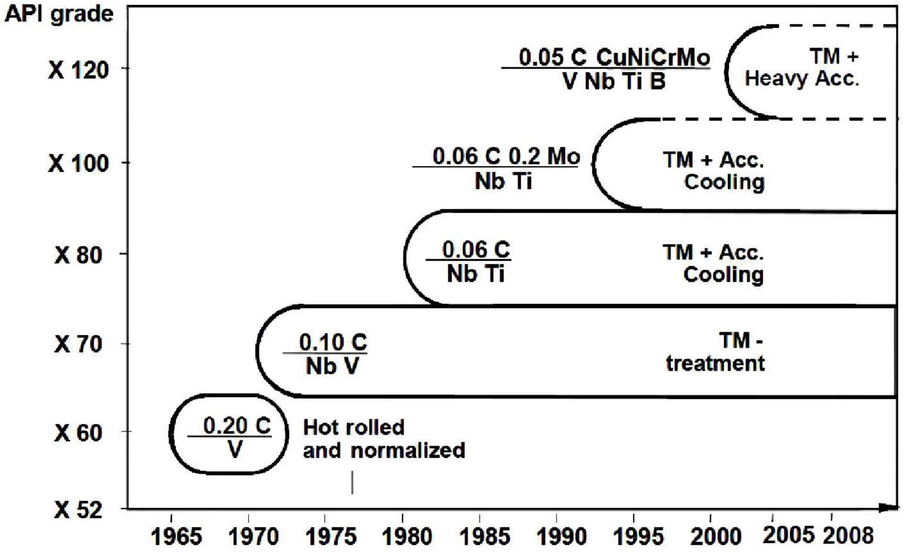


Figure 8 Development of pipeline steels [73]

X80 steel is purer and consists of lower sulfur compared with X70 steel and can be adapted to different welding heat input [37]. In the study [37] welding of X80 with submerged arc welding shows the suitability of this steel for welding at large heat input even for four wires SAW method. X100 steel produced by adding molybdenum, copper, and nickel and is processed to plate by combining TM rolling and modified accelerated cooling [73]. The first X100 steel section installed by TransCanada in September 2002 [16, 55] and X100 steels can tolerate pressure from 7 to 20 MPa [75]. Figure 9 compares microstructures of three typical X70, X80, and X100 pipeline steels. As shown in the figure, X70 steel has uniform grains and has within ferrite grains. X80 is obtained by changing the microstructure of the steel matrix from ferrite-Pearlite to ferrite-bainite. In X80 and X100, with accelerated cooling that follows TM rolling, more uniform and extremely fine microstructure is obtained [73].

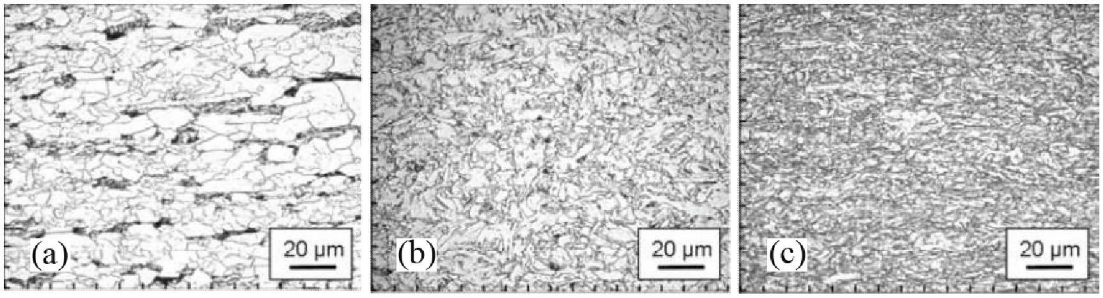


Figure 9 Microstructure of high strength pipeline steels: (a) X70, (b) X80, (c) X100 [73]

The X120 steel, with yield strength of 827.4 MPa, is 50 % stronger than standard gas transmission pipe. It means more and higher gas pressure can be transferred but requiring special welding procedure is its problem. Successful use of X120 in the project of transferring natural gas from northwestern Canada to markets all over North America, by TransCanada Pipelines Ltd shows bright future for this type of steel [76]. Also, high strength low micro-alloyed steel has been using in high pressure operation of oil and gas transportation for a while [34]. In designing of oil and gas pipelines, fracture toughness property should be considered as a major factor [68].

3.4. Various Welding Phase Types in Orbital Pipe Welding

Typically, welding of pipe with wall thickness up to nearly 3 mm can be done in a single pass while for thicker pipe wall a multipass welding is required [1]. Generally, the multipass process is divided into a series of phases; root pass (open root), fill pass, and cap (final) pass [29], however in the study [30] the numbers of phases is mentioned four and hot pass is count as a separated phase. First phase results in a fine back inside the pipe and then other phases are done to fill the groove. Figure 10 shows different welding phases in a U and V groove sample [30].

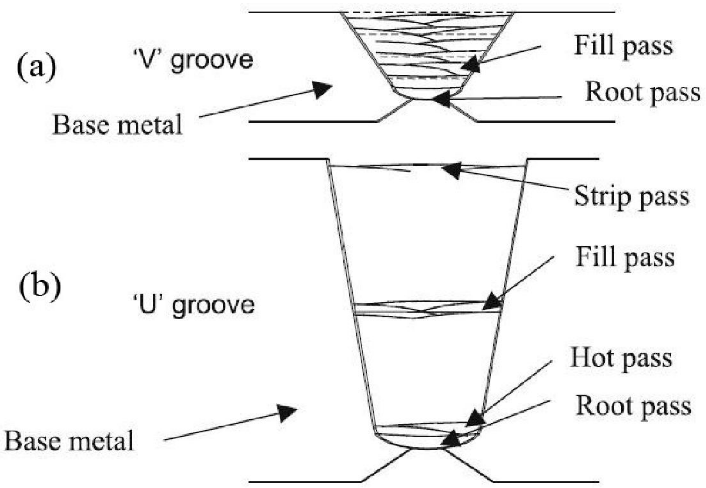


Figure 10 Type definition of weld groove, (a) V-groove (b) U-groove [30]

One of the most critical pipe welds especially critical in ensuring a defect free weld is root pass. Pipe welding codes, require high-quality and fully penetrated with good contour root pass welding [18, 19, 29, 77, 78]. Root pass welding can be affected by welding parameters, joint geometry, welding positions, gravity, arc force, and surface tension of weld pools [9].

GTAW, SMAW are used in root pass welding and semiautomatic/mechanized GMAW and orbital GMAW are added to those processes in root pass welding. In the welding of root pass with mechanized GMAW system, there is no possibility of using flux cored wire due to the potential for slag entrapment. Also, in root pass welding with orbital GMAW, precise fit up, uniform gap in whole joint, high operator skill, and tight fit-up tolerances are required [53, 79]. In automatic pipe welding system, welding parameters adaptation in real-time is a critical factor to maintain consistent root pass quality [9].

Fill pass welding is done after root pass and takes most part of the welding time. Fill welding is usually consisting number of layers and each layer consists of several passes [29]. Welding speed is no longer the leading factor, because the front-end laying speed is settled by the time required for the root/hot pass [80].

Cap welding is somehow covering of welded joint and should be performed in a way which gives a good cosmetic appearance to the joint. The cap welding procedure has similar requirements to the fill welding phase [30]. In circumferential cap welding different two ways are used to make this phase more reliable. First method is based on the use of a line marked on the surface a constant distance from the root of the weld and the second one is the use of combination of independent measurement of the horizontal position of the part with memorization [29]. Figure 11 (a) shows the hot and fill pass with Flux Cored Arc Welding (FCAW) which done by two operators and Figure 11 (b) shows a typical result of this process [81].

Figure 11 (a) Welding of hot pass (b) Typical weld appearance of a mechanized weld joint [81]

3.5. Various Welding Groove Types in Orbital Pipe Welding

Mechanized pipe welding compared to manual welding needs much accuracy of groove preparation and fit up [22]. Typically, welding groove used in pressure vessels are traditional V, butt, narrow or semi-narrow gap, and fillet profiles. In heavy industrial applications, U and fillet groove are used [29, 65]. In automatic welding of smaller pipes and tubes, a standard V-bevel with a small gap can be used, although J-prep with the pipe ends butted together is the most popular groove types for this welding procedure [1]. Also, girth-butt weld of pipes have been used widely in various applications, such as oil and gas pipelines, steam piping, boiling water reactor piping systems [82].

By using mechanized narrow gap welding the amount of filler metal in welding process reduced which leads to reduction of tensile residual in pipe [83]. Therefore, use of single bead technique is essential with the narrowest groove possible. There are two ways of narrow gap welds, first two stringer beads and second, the weaving technique. Figure 12 shows several types of narrow gap welding [84].

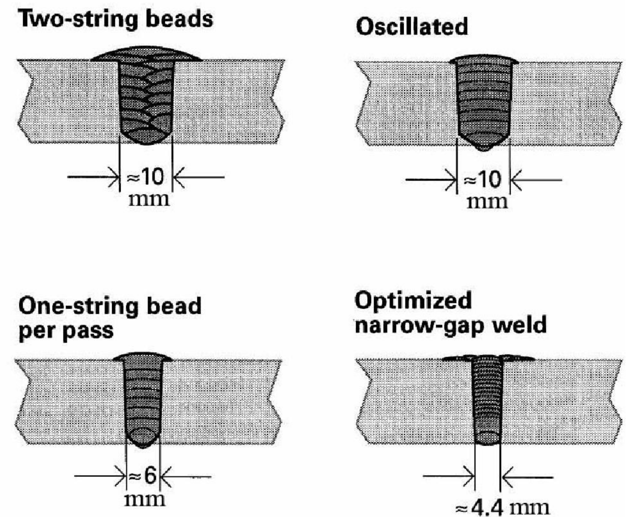


Figure 12 Various possible narrow-gap GTA welds [84]

In the experimental test done in [37], X80 steel welded by using of two solid SAW wires with different grooves, heat input, material thicknesses to see their influences on the microstructure and properties of the welded joint. The results depict that the number of required welding pass notably was reduced in the welding of small groove with high heat input.

In order to obtain a proper joint, it is important to look at the entire design of the facing tool. Tube ends must be square and flat. All burrs should be removed on the outer as well as the inner side of the tube. There should not be any chamfers during tube edge preparation to produce the best joint fit-up possible and subsequently, the best weld [3, 4, 14, 58]. Immoderate gaps will have a significant effect on the weld bead profile, which is caused by differences in tube diameter or out-of-roundness. Also, pipe wall thickness should be repeatable at the weld joint because most of orbital tube welding performed without the use of filler material [14].

3.6. Orbital Welding Parameters and Equipment

A welding quality is good when weld have enough penetration, desired microstructure, and right welding profile without any spatter [57]. Typically, pipe welding equipment manufacturers suggest a series of pre-calculated weld program for different tube wall thicknesses, diameters and materials [4].

Arc Voltage

In pipe welding, arc voltage which is directly related to the arc length depends on weld current, stability of arc, and concentricity of pipe [3, 4]. Arc length influences weld penetration and longer arc length leads to less penetration and too short arc length produces poor penetration in very low arc power. The distance between electrode and tube should be kept constant to avoid stubbing-out. In a constant arc length, by increasing feed rate, penetration and HAZ increased [57].

Welding speed

Using of automatic orbital welding is the most effective way to control welding speed [51]. The main goal of welding machine is to weld as fast as possible while the quality of weld stays constant. Weld speed depends on the tube wall thickness and flow rate of material [4, 49]. In the study [4] welding speed is suggested to be set at 1.7 to 4.2 mm/s, running faster on thinner-wall materials and slower on heavy-wall tube.

Welding current

Welding current affects the depth of penetration by influencing heat concentration in the weld pool [57]. The main goal in welding current controlling is to obtain defect free welds with full penetration. During of orbital pipe welding processes, usually multiple levels of weld current used to compensate for heat buildup in the tube. Factors influence the welding current are, weld speed, base material, wall thickness, and shielding gas [3].

Arc pulsing

In welding with arc pulsing, in a fixed duration of time the power source pulses rapidly between a peak and background current to reduce heat input and as a result, producing better and repeatable weld quality. This method may be used in welding of joints with poor fit up which are difficult to weld. The main advantage of using arc pulsing in orbital welding system is decreasing of the gravity effects on the molten weld. During welding of pipe in the position of 6 and 12 O'clock the gravity pulls molten materials and makes the welding process difficult. When the welding torch is in those positions by reducing the current to its background current (lowest) the molten materials can solidify before dropping to the ground [4].

3.6.1. Power Source

More recently, variable polarity welding power supplies have been introduced into the pipe welding world. In the pipe construction world, portability is the key. Developed power supplies used today in orbital pipe welding, tend to be at the top of the range. They record automatically the majority of required welding data for projects with a high level of microcomputer control of pulsing parameters and multi-schedule welding parameters [46, 85].

The physical size, weight, and input voltage of the power supply are important considerations [1]. The power supply controls the arc welding current and the power to drive the motor in the weld head. It switches the shielding gases on and off as necessary [4]. A power source output of 200 to 300 A generally suffices for conventional mechanical welding. An orbital welding power source integrates the controls that operate the various weld head functions with the power source. A standard power source can provide output power only and cannot be used for mechanized orbital welding. In addition, multipass welding requires multipass programming, which usually is done with an integrated microprocessor and custom software [1] .

For smooth welding, the power source must have a fast power switching device. A fast switch operation permits quick responses to changes in arc conditions. For example, a tight part fit-up or a narrow gap in a pipe joint forces the welder to push the rod close to the joint, often causing a premature arc and sticking. A fast responding power source can sense this through feedback circuits and boost amperage before the rod has a chance to stick. An inverter allows welders to make small current adjustments when welding to produce a smooth and stable arc and control over the weld puddle [86].

Inverters may offer higher power efficiency and a better power factor than other welding machines, making for lower operating costs. Control electronics allow manipulation of static and dynamic characteristics of welding power so that a single power unit may perform all welding processes. Inverters also link well to computers and microprocessors. Some inverters automatically accept primary input voltage without wiring changes or alteration to accept either 230 or 460 V, single or 3 phase, 50 or 60 Hz input. Inverters do the same work as transformer-rectifiers. A silicon controlled rectifier “chops” the alternating current (AC) output, or turns it on and off, and rectifies to direct current (DC) welding power at 20 kHz; inverters operate at 60 kHz, or 60,000 cycle per second [86].

One way to classifying power supplies is by how much amperage, or heat, the unit can generate at a given duty cycle. For thin work, look for low-end amperage control to prevent burn-through. Thick work requires enough amperage to ensure good penetration. For example, GMAW of 18 gage steel in a single pass takes about 70 A, where welding 12.7 mm steel in a single pass requires about 315 A.

Duty cycle is the number of minutes out of a 10 minute cycle a power supply can operate. For example, a machine that can deliver 300 A of welding current at a 60 % duty cycle can weld continuously at 300 A for 6 minutes, and then must cool down for 4 minutes to prevent overheating. Duty cycle and amperage are inversely proportional. Operating at 250 A, the same machine has a 100 % duty cycle- it can weld without stopping at this amperage. Operating at 400 A, it has about a 20 % duty cycle [86].

Analog power source

Analog power sources are programmed by entering the desired speed, amperage, and other parameters on dials and putting the machine into motion with mechanical switches. The units allow one pass (one orbit around the pipe) to be programmed. When multiple passes are required, welders must stop the machine, reset the dials for the next pass, and restart the weld. Analog power sources are easy to understand operation, good tolerance of environmental extremes, and simple maintenance requirements. However, analog power sources cannot lock out unauthorized changes in critical parameters, and they do not store programs [1].

Microprocessor based power sources

Microprocessor based units require a longer learning curve than do analog power sources. Most weld programming is done by the welder using the equipment and can store up to 100 weld programs, so most programs use simple prompts that require little computer literacy. These power sources have the features of, using many levels of programming for all parameters, possibility of multi passes without stopping, usability in automatic weld procedure, storage of weld program, simplifying the weld development process. Also, use of solid state data cards that allow program transfer between systems or off-line programming on personal computers [1, 46].

3.6.2. Filler Wire

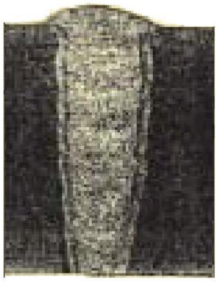
Filler wire manufacturers has been involved with different challenges since improving of pipe and welding manufacturing require new filler wire technology as well. Flux cored wires were invented in 1957 which consists of a metal sheath containing a core of flux [87]. The core is mixture of powdered ingredients, including fluxing elements, deoxidizers, denitriding compounds, and alloying materials to improve hardness, strength and as a result corrosion resistance. Two methods are used to produce flux cored wire, standard and all position. In all position wire, puddle freezed much faster than standard wire and should be used in orbital applications due to the nature of the welding [53, 88].

Using of wires containing a small amount of titanium first was tested in 1960s in the UK and USA on transmission pipelines. In this case, smaller grain size is obtained and the welding result was quite acceptable at that time and burn-off rate of the wire was reduced. Also, this type of wire increases welder's comfort, weld toughness, and the proportion of the arc energy available to melt the edges of the weld preparation. Further, this wire reduces defect rate and lack of fusion which is the most serious problem in semi-automatic pipe welding [7, 21]. In the study [7] two wires, first 0.8 mm without titanium and second 0.9 mm with titanium were used at 200 A and 25 V. The result shows more burn-off rate for the first one, while 33 % of the available heat was used to melt the wire; this number was 24 % in the second case.

Today, for pipe welding with mechanized system, both titanium bearing and titanium free wires are using successfully. But, carbon manganese wires without titanium are gaining in popularity due to the mechanized or fully automatic pipe welding users' feedback. Productivity, even with mechanized pipe welding systems is an important factor and manufacturers have begun using of metal cored wires instead of solid wires in mechanized downhill welding. In 2000s, metal cored wires were used for the first time in pipeline welding [7, 21]. Metal cored wires are a variant of flux cored wires, but differ in that the flux consists almost entirely of metal. These types of wires have the ability of using in welding either double up or double down due to the small isolated islands of silicon shaped on the solidified weld bead [47].

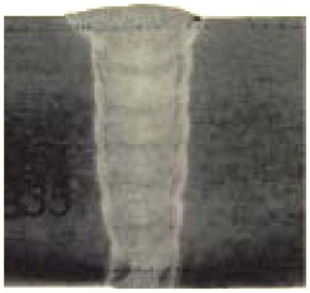
Table 1 and Table 2 illustrate procedures and mechanical properties for welding of X80 pipe with a carbon manganese solid wire and a 0.8 % nickel metal cored wire done in the study [21].

Table 1 Welding procedure for X80 pipe using carbon-manganese solid wire [21]

Welding procedure		
Pipe	X80, 1219.2 × 31.8 mm wt	
Welding consumable	OK Autrod 12.66, 1.0 mm	
Welding process	Mechanized GMAW	
Preheat temperature	108 ℃	
Interpass temperature	110-135 ℃	
Welding direction	Downwards	
Shielding gas	Root: CO_2 fill & cap: 30 % Ar, 70 % CO_2	
Polarity	Electrode positive	
Root	Copper backing, 240-295 A, 25-27 V, 0.9 m/min, 0.39-0.48 kJ/mm	
Fill runs 1-10	210-260 A, 24-28 V, 0.36-0.53 m/min, 0.49-0.85 kJ/mm, weave 1.5-6 mm at 1.8-5.8 Hz	
Cap runs 8,9	180-215 A, 20-23 V, 0.32 m/min, 0.63-0.87 kJ/mm weave 8.6 mm at 0.6 Hz	

Mechanical properties					
	Tensile properties			**Charpy toughness, J at -30 ℃**	
	PS (MPa)	TS (MPa)	El %		
Longitudinal	693	806	20	root:	110
Transverse		665-678	Broke outside weld	cap:	84
CTOD at -30 ℃, mm	0.25, 0.39, 0.25, 0.80, 0.80, 0.84				

Table 2: Welding procedure for X80 pipe using 0.8 % Ni metal-cored wire [21]

Welding procedure		
Welding consumable	PZ 6104, 1.2 mm	
Pipe	X80, 609.6 × 25.8 mm wt	
Welding process	Mechanized GMAW	
Preheat ℃	100 min	
Interpass temp, ℃	200 max	
Welding direction	Downwards	
Shielding gas	80 % Ar, 20 % CO_2	
Polarity	Electrode positive	
Root	Copper backing	
Fill runs 1-8	24 V, 260 A, 0.68 kJ/mm	

Mechanical properties

	Tensile properties			**Charpy toughness, J at -40℃**	
	PS (MPa)	TS (MPa)	El %		
Longitudinal	667	728	18	root:	87
Transverse		608-632	Broke outside weld	cap:	74

Analysis (%)

C	Si	Mn	P	S	Ni
0.08	0.59	1.68	0.012	0.008	0.73

As using of X80 pipe type has increased in pipeline, developing new welding wires is an urgent task [37]. Since successful use of carbon manganese solid wire in mechanized welding on X80 pipes in Canada, various wires have been tested for orbital pipe welding improvement [21]. The study [37] shows use of C-Mn-Cr-Ni-Mo WGX2 wire produce weld metal that can totally meet the current specification of X80 steel. ESAB offers OK AristoRod™ 12.65 and OK Autrod 12.66 solid wires for the mechanized downhill GMAW of pipelines in materials such as API 5L grade 52 to 70. The main applications involved with these wires are oil and gas industries, compressor stations, and pipelines [80, 89].

3.6.3. Shielding Gas

Both, solid and flux cored wires required proper shielding gas to have higher productivity. In orbital pipe welding system, equipments are mounted close to the torch and lower amount of spatter is a factor that should be considered. Selecting of shielding gas composition is highly depended on the wire manufacturer's recommendation. Arc stability, general weld ability, spatter, and metallurgy of the deposited metal are affected by shielding gas [53]. Shielding gas prevents the molten material from combining with oxygen in the ambient atmosphere [3].

Typically, more than one gas composition is suggested by manufacturers. CO_2 as a shielding gas for pipeline fabricators has the advantages of very secure weld penetration and less expensive. On the other hand, CO_2 shielding gas is not popular due to its unfavorable globular droplet detachment and the high amount of spatter [53, 80]. Argon is the most commonly used shielding gas in welding processes. In semi-automatic and fully automatic welding, the use of argon based mixed gases dominates. This mixture can be either, argon/hydrogen or helium and argon/CO_2 gas mixtures because of their advantages, such as fewer spatters, higher stability of arc, and possibility of using higher welding currents [3, 53, 80]. Argon is the most common root gas, but for duplex stainless steel and high-alloyed austenitics, nitrogen-based backing is recommended (e.g. 90 % N_2 + 10 % H_2) [90].

4. Adaptive Orbital Pipe Welding

In many cases of orbital pipe welding process, tolerance of the workpiece and pipe thickness are so precise that the weld joint can be welded without any problem while direction of welding is straight. In some cases, especially large diameter of pipes, due to some reasons, such as pre-machining tolerance of the workpiece, fit-up precision and unfitness of the joint, there can be significant variations in weld joint shapes and areas. This would result in poor welding appearance and possibly defects. Consequently, an orbital welding system without feedback and controlling of the welding parameters may easily result in poor welding quality, particularly, when the workpiece and welding joint are not prepared in good condition and are far away from ideal requirements [30, 91, 92].

Develop and improve intelligent technologies for orbital pipe welding, such as vision sensing, real-time intelligent control [93, 94, 95, 96, 97, 98, 99], and scan welding technique [100], may be an effective approach to overcome this problem. This controlling of parameters is so called adaptive welding which has been used with good results in industry for some time [95]. Adaptive welding systems have been called the Holy Grail of the industry [8].

Moreover, stability and accuracy of welding parameters controlling is very important to make sure penetration is consistent and predictable. Today's orbital welding systems offer computer controls that store a variety of welding parameters that can be called up as needed. Closed loop control of the welding parameters ensures stable, constant, and accurate values with less room for error or defects [4, 29]. Adaptive, practically means finding the center of the joint (dynamic joint tracking) instead of having a person always steer everything accurately. Also, in adaptive welding system, controlling the weld power, wire feed, rotation (speed), pulse time, oscillation width, torch motion and position, etc. are done automatically to help simplify operation and produce a high quality weld [8, 11]. Three following basic steps counted in the study [8] and should be implemented to have an adaptive arc welding process:

In the first step, entire of the joint observed precisely and possible defects or deviations in the groove walls are noticed. The system performs a comprehensive inventory of the joint to be welded. In this observation, measurements, such as temperature of the workpiece and the uniformity of the groove are considered. The system also keeps an inventory of previous welding passes and draws and uses it as a knowledge base.

Second step is recipe for decision making. The automated orbital welding system organizes the effect of the different process variables according to importance. And finally, integrating the rest of the system is the third step. Welding control system require coupling of power source, torch motion, and wire feeder. These three parameters, in some currently used welding systems are controlled separately for accurate control of heat. This is important especially in welding of different pieces with various asymmetrical or non-uniform heat capacities.

Recently, significant improvements have been obtained in adaptive orbital welding system. Different studies have done in weld pool geometry sensing, modeling and intelligent control of the weld quality and process monitoring. But still needs of more efforts on this topic is sensed due to the complexity of welding process, real-time and opening limits in orbital systems [9, 99, 101, 102, 103]. Today, multi laser vision sensors, thermal scanning, image processing, neural network model, machine vision, or optical sensing are used in various fully automatic orbital welding system to improve performance and reliability.

Generally, adaptive control of the welding parameters is not used in root pass welding to guaranty weld penetration. Adaptive control of the orbital welding process must be performed during the fill pass welding. There are two reasons for this: first, sometimes joint area/height in on side of groove is larger than the other, therefore to compensate this mismatch across the joint, weld parameters should be different on each side of the joint. Secondly, sometimes in forming process of pipe especially in pipes with large diameter, the joint volume on one side is much larger than the other. Consequently, travel and wire feed speed, current/voltage level should be adjusted to compensate for variations in the joint along the welding direction [29].

5. Most Used Welding Processes in Orbital Pipe Welding

Recently, high demands of automation of pipe welding process, with higher level of productivity and accuracy propelled welding manufacturers to produce newer orbital pipe welding systems. The choice of welding process is largely dependent on the steel grades to be welded [55]. Generally, welding process for pipeline consists of root pass and fills pass welding. The root pass by method of orbital GTAW is performed by the skilled workers due to the possibility for defect welded. STT, short circuit, modified short arc GMAW are other choices for root pass welding. Today, mainly for fill pass welding of pipe mostly GMAW method is used [104]. Therefore, it is completely necessary to be employed the automatic welding processes in order to improve quality, productivity and job environment [104, 105]. In this study, processes, such as GTAW (for process and pressure piping) [11], FCAW (for heavy-wall, large-diameter pipes) [11], Hybrid Laser Arc Welding (HLAW), GMAW and its variations (tandem, dual-tandem, double-electrode, twin wire, modified short arc, pulsed arc, Rapid arc, and STT) which can be used in orbital pipe welding system will be explained in details.

Also, there is possibility of using PAW in orbital pipe welding applications. This process has the advantages of smaller heat affected area, lower air porosity, higher aspect ratio (depth to width rate), and lower residual stress [106]. PAW compared to the GTAW is highly constricted and this feature leads to excellent linear relationship of arc length with the arc voltage under the same welding current [107].

Even with numerous advantages involved with PAW process, few investments have done for this process. Recently, some studies have done in the case of using PAW for pipe welding applications. In the study [107] the transferred arc PAW for pipe welding is investigated. This process typically operates in either keyhole or melt-in (conduction) mode. Usually, a common type of steel can be easily welded using keyhole mode of plasma arc welding process due to the contracted arc between the tungsten electrode and workpiece [108]. Keyhole mode can obtain much deeper penetration compared with other arc welding processes. Again, in the study [107] double-stage PAW process which is proposed to avoid problems and combine advantages in keyhole and melt-in modes explained. Due to the limited studies that have done in the case of orbital pipe welding with PAW process, the author would prefer not to go in more details for this process.

5.1. Gas Tungsten Arc Welding (GTAW)

GTAW process is an extremely important arc welding process [103, 109]. During the 1960s, to increase penetration of automated GTAW process, current extended to higher level. At currents above about 250A, the arc tends to displace the weld pool, this effect increased as the current increases more. Recent development in GTAW introduce new methods of welding, such as active fluxes (A-GTAW), dual shield GTAW, narrow gap GTAW, keyhole GTAW and laser-GTAW hybrid processes [110]. Today orbital GTAW is widely used for a variety of applications [111].

There are some limitations of using mechanized GTAW process, such as high heat input, low travel speed, low deposition rate, requirement of higher operator skill level, cost prohibitive on larger diameter pipe, requirement of machining of pipe ends in the field, and requirement of a special J-prep bevel geometry to make the initial root pass [77, 111, 112].

GTAW is known for its versatility and high joint quality. Generally, Orbital GTA pipe welding procedure practice, two passes are used for an acceptable pipe weld. Although several major welding processes can be used in root pass welding, GTAW is probably the most common choice for welding of this phase. The second or cover pass with filler material is used to obtain sufficient convexity on the outer side of the pipe weld. For welding of pipes with outside diameter less than 200 mm and under Schedule 10, enough GTAW should be done to have full penetration in wall thickness. For welding of pipe over Schedule 10, pre-machining of joints required to decrease the wall thickness that needs to be penetrated during the root pass. As a result, costs of welding as well as preparation time increase in orbital GTAW of large diameter pipes. Also, using of filler material turn into compulsory in order to produce weld bead contour with required positive reinforcement [110, 113].

Automatic orbital GTAW system is used in the industrial welding of tubes and ducts of diverse sized diameters and thicknesses. This process is used in situations where maximum leak integrity, high performance, or ultra cleanliness is of paramount importance. The minimal heat input permits distortion control and the retaining of dimensional accuracy [2, 48]. This process can be used in various industries, such as steam generation components for fossil power plants, process piping for chemical plants, and automotive exhaust gas system [111, 114].

It is widely accepted that orbital GTAW is the most suitable process for welding stainless steel tubes and can be used with a wide variety of materials, including highly reactive or refractory metals [4, 51, 110]. The mechanical, thermal, stability, and corrosion resistance requirements of the application dictate the material chosen. It is commonly used for welding difficult to weld metals such as aluminum pipe, magnesium, copper, titanium and many other nonferrous metals [4, 9, 45, 115, 116].

By using orbital GTAW at the Angra II Nuclear Power Plant in Brazil [24] the defects of using SMAW on type 347 stainless steel, such as micro-cracking eliminated. The orbital welds had a flatter, more uniform crown and required very little grinding due to better and uniform control of heat input.

Recently, orbital GTAW of narrow gap is an adapted process. Figure 13 demonstrates three different welding procedures on austenite steel pipe with thickness of 12 mm [100]. By narrowing the cross section of the joint, depending on the wall thickness, the joint volume is reduced by a factor of 2-3. By reducing the heat input and increasing the welding speed as well as reducing the gap width, axial shrinkage can be reduced to less than half of normal narrow-gap weld shrinkage. In the study [100] mechanized orbital GTAW were used in welding of austenitic steel pipes with different diameters to compare axial shrinkage results with conventional welding in various weld types (Figure 13).

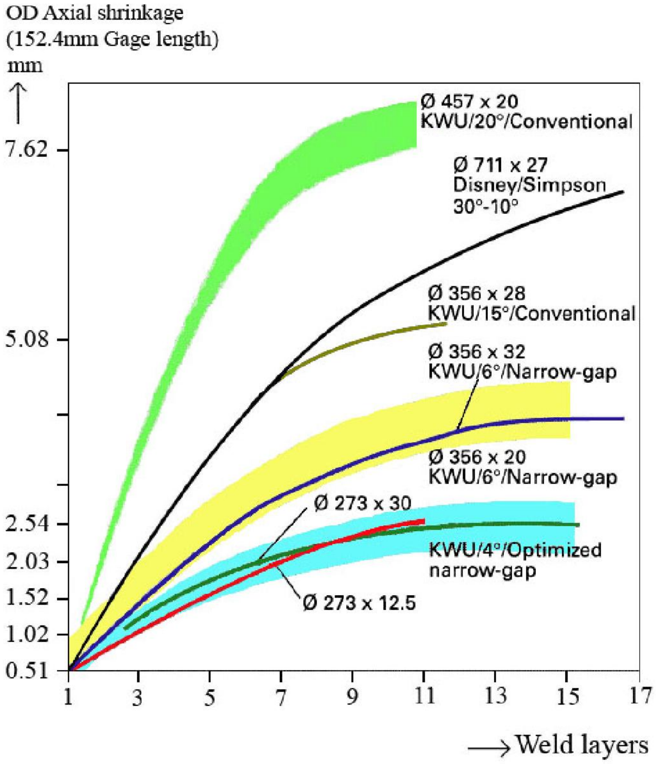


Figure 13 Mechanized orbital GTAW of austenitic piping; axial shrinkage at outer surface as function of number of passes and comparison of various weld types [100]

Figure 14 depicts comparison of cross sectional areas of pipe welding in normal and narrow gap grooves. As graph shows, growth of wall thickness in normal or conventional U groove results sharper growth of cross sectional area compare with narrow gap groove. A narrow-gap weld is usually made by welding “bead-on-bead” - so one run per layer [22].

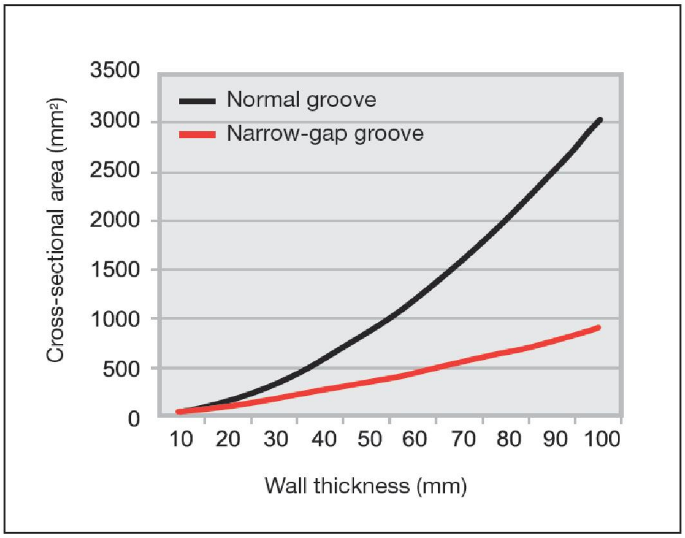


Figure 14 Comparison of cross sectional areas of pipe welding groove. Groove dimensions: normal U (included angle **30**°, radius 3 mm and root face 2 mm) and narrow-gap groove (included angle 4 degrees, radius 3 mm and root face 2 mm) [22]

Understanding of the GTAW process involves input from many disciplines. In this process, an electric arc is formed between a permanent, non-consumable tungsten electrode and the base metal. The arc region is protected by an inert gas or mixture of gases, such as argon or helium (or a mixture of the two), to prevent electrode degradation [26, 110, 117]. This process may be done with either, single or several electrodes [118].

Orbital GTAW process mostly is applied for applications ranging from single run welding of thin-wall stainless pipes to multi run welding of thick-wall pipes. This process even can be used for narrow-gap welding due to its precise control of heat input, repeatability of welding procedures, ability of equipment for using “on site”, higher operator productivity and duty cycle, consistent weld quality and so on [5, 22].

Power sources for orbital GTAW come in a variety of sizes and models. This process, as well as several other arc welding processes can be operated in several different current modes, including ‘DC’, with the electrode negative (EN) or positive (EP), or ‘AC’. Current from the power supply is passed to the tungsten electrode of a torch through a contact tube. To initiate the arc, high-voltage signal will ionize the shielding gas to generate a path for the weld current. A capacitor dumps current into this electrical path, which reduces the arc voltage to a level at which the power supply can then supply current for the arc. The power supply responds to the demand and provides weld current to keep the arc established. These different currents or power modes result in distinctly different arc and weld characteristics. The GTAW process can be performed with or without filler (autogenously). When no filler is employed, joints must be thin and have a close-fitting square-butt configuration [3, 4, 26].

In the study [78], GTAW and pulse Rapid arc GMAW were selected for orbital pipe welding with the view of optimizing orbital welding in butting bimetal pipes in duplex stainless steel. The main objective of this study was to improve a root pass procedure by combining two processes in the way that, high quality GTAW welds the inside of pipe and Rapid arc welds the outside. Additional attention should be considered due to the interface between the two passes in order to prevent gaps as shown in Figure 15. Result of this combination was high quality root welds with no welding defects in the inner layer in duplex stainless steel.

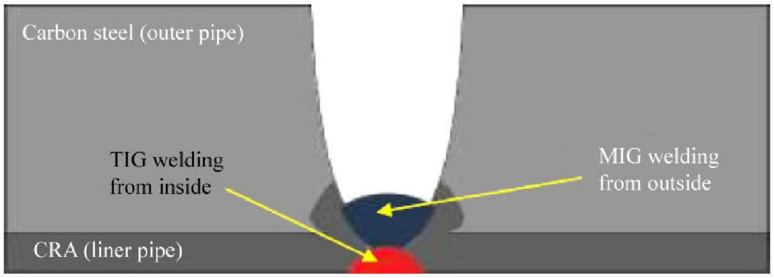


Figure 15 Schematic representation of the use of GTAW welds for inside of pipe and Rapid arc welds for outside [78]

Shielding gas in orbital GTAW process

Shielding gas is required on the tube and pipe during welding to prevent combining of molten weld pool with the oxygen in the ambient atmosphere. Chemical–metallurgical processes between the gases and the molten pool that occur during welding should be considered during process of selecting shielding gas [119].

Composition of a shielding mixture in arc welding depends mostly on the kind of material to be welded [120].

Density of shielding gas plays an important role on the efficiency of protecting the arc and molten weld pool. Argon and CO_2 are the densest shielding gas, therefore they widely use in welding industries. Argon is the most commonly used shield gas in GTAW process. In welding of stainless steels, nickel copper and nickel based alloys mixture of argon/helium typically used. Mixtures of 95/5 % argon/hydrogen are incompatible with carbon steels and some exotic alloys and can cause hydrogen embrittlement in the weld. Also, it is not recommended to use hydrogen for welding of other materials because of possibility of producing cracks in the welds [116]. Additional hydrogen into shielding gas allows higher welding speed. Also, it increases the volume of molten material in the weld pool due to the higher thermal conductivity of argon–hydrogen mixtures at temperatures at which molecules of hydrogen dissociate [121]. In most researches, the amount of hydrogen in argon is recommended in the range of 0.5-5 % [119]. Typically, helium is used for welding on copper materials [4] and aluminum.

Tungsten Electrodes in Orbital GTAW

This selection influences weld penetration, clean arc start, and arc wander. In orbital GTAW systems, the most typical used electrode materials are 2 % thoriated tungsten (contain thorium) and 2 % ceriated tungsten (contain a minimum of 97.30 % tungsten and 1.80 to 2.20 % cerium and are referred to as 2 % ceriated). Electrode tip geometry, such as electrode taper and tip diameter are very important in result of weld quality. Table 3 shows characteristics of both, sharp and blunt tapers as well as small and large tip diameter on weld result [4]. Figure 16 depicts effects of various tapers on the size of weld bead, their rate of penetration, the arc shape, and resultant weld profile [4].

Table 3 Characteristics of both sharp and blunt tapers as well as small and large tip diameter on weld result [4]

	Sharper Electrode	**Blunter Electrode**	**Smaller Tip**	**Larger Tip**
Arc starting	Easy	Usually harder	Easy	Usually harder
Arc stability	Good	More chance of arc wander	Good	More chance of arc wander
Weld penetration	Less	More	Less	More
Electrode life	Shorter	Longer	Shorter	Longer
Arc shape	Wider	Narrower	-	-
Amperage handles	Less	More	-	-

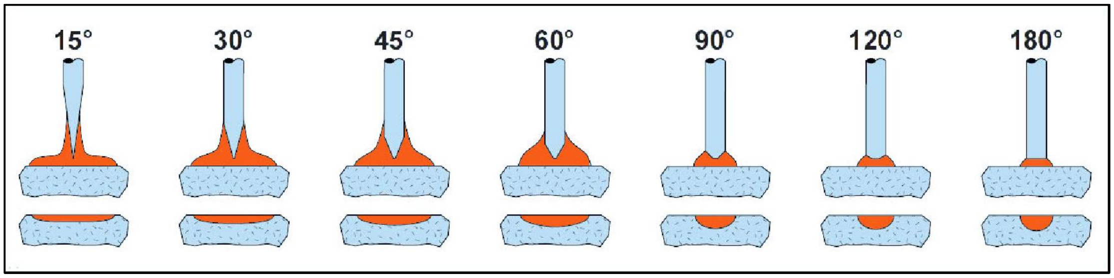


Figure 16 This drawing shows typical representations of the arc shape and resultant weld profile for various electrode tapers [4]

5.2. Flux Cored Arc Welding (FCAW)

Typically, in welding of pipe with orbital welding system, the GTAW or the GMAW/FCAW process are used. FCAW was invented to eliminate long time consumption due to the low speed of GTAW process on pipe welding. Also, this process compensates the greater volume of weld metal by higher deposition rate on the standard bevel [33, 111]. Automated FCAW is faster process compared to SMAW because of high duty cycle of mechanization and also, weld bead uniformity is improved in this process [122].

In this process, established arc between a consumable electrode and the weld pool joins workpieces by melting them. FCAW can be operated with 'DC' power supplies, with the electrode positive or negative, depending on the particular wire type and formulation. This process is similar to SMAW in such that it is self shielding, however the gas and flux-generating are contained in the core of a roll-formed and/or drawn tubular wire, rather than on the outside of a core wire as a coating [25, 26].

Recently, FCAW process has been used in different applications, such as shipbuilding, welding high-pressure piping in power plants or duplex stainless steel piping assemblies for offshore gas production, chemical plant/refinery construction and maintenance, and transportation. Although this process was approved several years ago in the nuclear industry of the United State [11, 53]. During the middle 1980s, this process found its application for large diameter and wall thickness pipes with deposition rate of 3.63 kg/hr. Figure 17 shows a sample of orbital FCAW for large diameter and heavy wall pipe [53, 111].

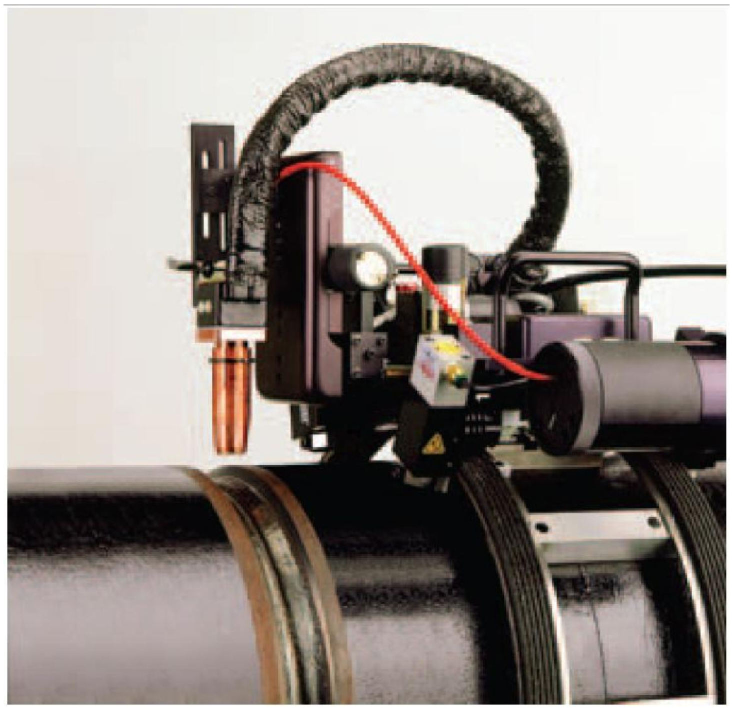


Figure 17 Orbital FCAW is a high deposition rate process (3.63 kg/hr), suitable for welding large diameter, heavy wall pipe [111, 112]

Orbital FCAW system is a technique increasingly being used. This process can be considered as the SAW process turned inside out. In SAW, solid wire electrode and weld pool covered by powder flux but in FCAW process, instead of solid wire a metal "tube" or sheath replaced wrapped around a core of flux. Orbital FCAW can meet the same quality standards as SMAW, SAW, and in most cases, GTAW. Welds will meet the American Society of Mechanical Engineers (ASME) B31.1 and B31.3 piping codes, Section IX, acceptance criteria. As a result, for those companies which still use semiautomatic GMAW/FCAW for out of position pipe welding, selecting of this process can be an economic and good decision. Also, using combination of STT/FCAW technique for standard V-bevel has been proven on many hundreds of thousands of welds worldwide for process piping, cross-country pipelines, and high-pressure piping in power plants (Figure 18) [33, 53, 112].

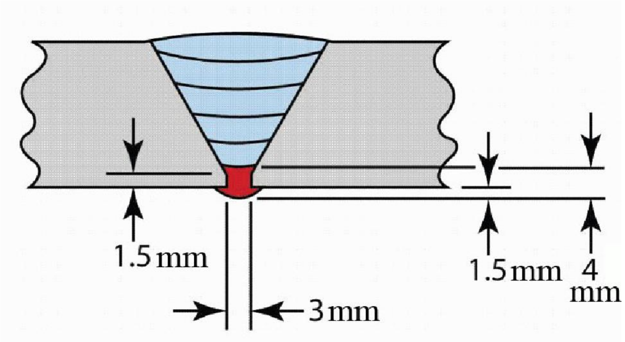


Figure 18 A standard V bevel is made with STT root and FCAW fill passes [111, 112]

Filler wire for FCAW is mostly available in two formulations: downhand (standard) and all position. All position FCAW wires uses a different flux chemistry and are formulated with fluxing agents that promote rapid pool solidification to allow pipe welding in all orientations including overhead. Rutile flux cored wire has been used successfully in either the spray or pulse spray modes of metal transfer for orbital FCAW system. Using of pulsed current is essential when metal core wire is used for all position welding. Orbital FCAW can be used in double down welding with relatively high average travel speeds in the 0.38-0.75 m/min range with a good machined and proper groove. Also, using of narrow groove bevel geometry helps in better control of weld pool at this high travel speed of welding [47, 81].

In selecting of shielding gas for FCAW process, parameters more than cost of the gas should be considered [123]. In FCAW steel electrodes process, CO_2 is certainly the most widely used shielding gas because CO_2 leads higher welding speeds, good weld penetration and lower welding cost. CO_2 is a comparatively inactive gas at room temperature but in the welding arc which temperature is very high, part of the CO_2 separated to form CO which is more stable. CO_2 can then further decompose into carbon (C) and oxygen (O_2) [88, 123].

5.3. Gas Metal Arc Welding (GMAW)

GMAW is one of the most used processes for metals joining in industry, both in manual and mechanized welding. This process was introduced to increase productivity and guarantee the desirable welding quality and integrity [78, 124]. By using an inert shielding gas, GMAW process can be as clean as GTAW with superiority of higher deposition rate which causes higher welding speed of thicker materials. Welding is possible by middle skill welders, although large size of torch makes welding of corners and small area difficult [25, 77, 125].

The GMAW is widely used in fabrication process in industries due to its inherent advantages. These advantages can be named as, high metal deposition rate, deep penetration, smooth bead, low spatter and ease of automation with better weld quality at permissible cost than other welding processes [57, 125]. One of the main advantages of this process is that, the mode of molten metal transfer from the consumable wire electrode can be intentionally changed and controlled through a combination of shielding gas composition, power source type, electrode type and form, arc current and voltage, and wire feed rate. There are three main types of metal transfer (welding arc) used in GMAW process which are: short circuiting, globular, and spray. New technologies from various companies lead to development of different types of GMAW in welding industry which will be explained later in this study [26].

The wire is fed to the arc by an automatic wire feeder, of which depending on the wire composition, diameter, and welding application, both push and pull types are employed. The arc is shielded from contaminants in the atmosphere by the shielding gas such as CO_2, argon, helium, etc. and this is why this process mostly in Europe is known as Metal Inert Gas (MIG) or Metal Active Gas (MAG) welding [25, 126]. In welding process which carbon dioxide CO_2 uses as shielding gas, GMAW is more proper name for this process [26, 27].

Normally, conventional GMAW uses Constant Voltage (CV) and 'DC' welding power supply. Either Direct Current Electrode Negative (DCEN) or Direct Current Electrode Positive (DCEP) may be used, depending on the particular wire and desired mode of molten metal transfer. But the 'DCEP' mode, in which the wire is connected to the positive terminal of the power source and the power source operates in the 'CV' mode, is far more common. The reverse polarity contributes to a stable arc, uniform metal transfer, and greater penetration. A 'CV' power source can adjust the welding current such that the wire melting rate is equal to the given wire feed speed, and the welding voltage, or arc length, is maintained constant [26, 124].

The main variables in all GMAW processes are, welding current, arc voltage, and welding travel speed. Other parameters, such as welding torch angle, workpiece to nozzle gap, welding direction, shielding gas flow rate and its pressure are auxiliary adjustable. Typically, there are some factors kept constant during welding, such as type of electrode and its diameter, polarity and its extension, workpiece compositions, shielding gas, and so on [127]. The arc energy, an indicator of heat content of the weld pool, is affected by the primary process parameters as per equation 1 [57].

$$E = \frac{UI}{v} \tag{1}$$

Where in this equation, 'E' represents the arc energy (J/mm), 'I' shows the welding current, 'U' and 'v' are arc voltage (V) and welding speed (mm/s), respectively.

Orbital GMAW

It is more than thirty years that mechanized GMAW has been successfully used for large diameter transmission pipelines with impressive record on improving productivity over that time. Mostly, in welding of fill and cap (final) passes of pipelines, orbital GMAW is used. All variations are fully developed, but they demand a 100 % compliance with the required conditions, if perfect welding joints required [7, 16, 128].

Variation of GMAW orbital welding is due to different technologies are used for the root pass welding, ways of mechanization and joint preparation, and finally in the number of welding stations used in the same time. Depending on the number of torches used during welding, deposition rate of orbital GMAW can be up to 6 kg/hr with typical repair rate between 3 % and 5 %. Figure 19 [128] and Figure 20 [129, 130] shows one the most frequently used variations of orbital GMAW which consists of different phases explained by details below [128].

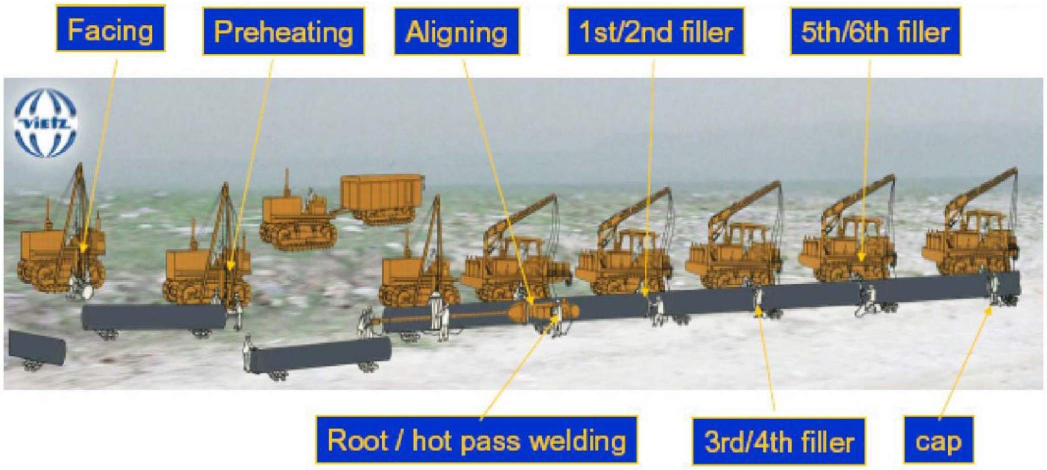


Figure 19 Required equipment for the economically efficient use of orbital GMAW [128]

Figure 20 The pipeline and welding cabins (a), the welding robots inside the cabins (b and c) [129, 130]

Welding investment costs is high for this method due to the requirement of a hydraulic power unit beveling machine. Pipes are lifted one by one and beveling machine starts to prepare their ends for welding. Generally, narrow gap J-shape is used for machining with approximately 2 mm root gap. This type of groove reduces the quantity of required filling material. Before welding of root pass, it is needed to mount the guiding band on the end of one side of pipe to leads the welding bugs [128].

Two GMAW orbital welding heads are used in root pass welding started from the 12 O'clock position to the 6 O'clock position. In order to obtain better result for root pass welding, a pneumatic internal line-up clamp with copper shoes is required. These copper shoes are used to back the liquid welding metal in order to reach a sufficient root. Pipes are centered together in such a way without any air gap, then the first head starts melting the gap from 12 O'clock position with high electric power and molten materials are backed by the copper shoes. When the first head reaches to the position of 2 O'clock, the second head starts welding of root pass. During of second head welding process, it helps to have a high quality root pass weld if a very constant power supply for the inverters or rectifiers to be served. Adjusting of power supply and wire feeding speed to the welding position is necessary in orbital GMAW due to the different position of head in different time (horizontal, downhill, uphill and overhead). In the new orbital welding systems, mostly it is done automatically, however semi-automatically and manually is also possible. Two welding heads with same parameters are selected for welding of hot and fill pass which is done downhill. The number of working stations is depended on the wall thickness of the pipe to be welded [128].

Mostly, in GMAW of carbon steel various mixtures of argon/CO_2 are used as shielding gas. The most typical mixtures are 75 % argon/25 % CO_2 and 90 % argon/10 % CO_2. Different factors, such as gas, labor, wire, and energy should be considered in the selecting process of shielding gas. Recently, the traditional mixture of argon/CO_2 is replaced with mixture of argon/O_2. This mixture has the advantages of saving cost, higher welding speed, higher deposition rate, lower spatter and fumes, usage of single tank system, spray arc at lower welding parameters, and excellent result of weld bead and mechanical properties [131].

GMAW Variations

Significant efforts have been made to improve the welding productivity and quality in GMAW process. These efforts can be listed as:

- Auxiliary preheating of solid filler wire [132]
- Multi-pass welding [133]
- Preheating of welding plate [134]
- Weld post-heating [135]
- An ultra-narrow gap GMAW [136]
- Optimization of shielding gas composition [57]
- Development of new waveforms and more efficient power sources [78]
- Unconventional welding process setting parameters control [57]

These mentioned methods have led to the development of many variants of GMAW process, such as T.I.M.E [137, 138], Rapid arc, STT, tandem GMAW [78], dual-torch and twin-wire GMAW [25], narrow-groove tandem gas metal arc welding (NG-TGMAW) [12], modified short circuit GMAW [104], and pulsed GMAW [104].

In oil and gas pipelines welding, as mentioned earlier root bead weld profile should be smooth and integrity. For welding of thin wall pipe, controlled dip transfer can be used with high depth of penetration and freedom from lack of fusion. A typical macro section of a root pass welding of X80 pipe with controlled dip process is illustrated in Figure 21. Also, this controlled transfer root and pulsed transfer fill passes were used for full pipes welds for X80 pipes [16].

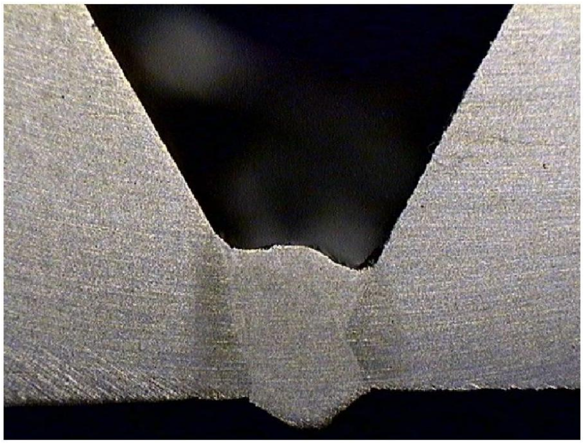


Figure 21 Root run in X80 pipe made using a controlled dip process [16]

In the study done by Edison Welding Institute (EWI) in Columbus, Ohio, USA, Variable Polarity Gas Metal Arc Welding (VP-GMAW) [16, 139, 140, 141, 142, 143] was investigated and has performed limited root pass welding trials on pipe. For VP-GMAW, liquid droplets still detached during the wire positive period, but the welding wire can be melted faster during the wire negative period [140]. They were able to produce a root pass without backing at travel speeds of 1.5 m/min [16] and base metal heat input could be up to 47 % less than the conventional pulsed GMAW [144]. Figure 22 shows macro section of a root run of this process [16].

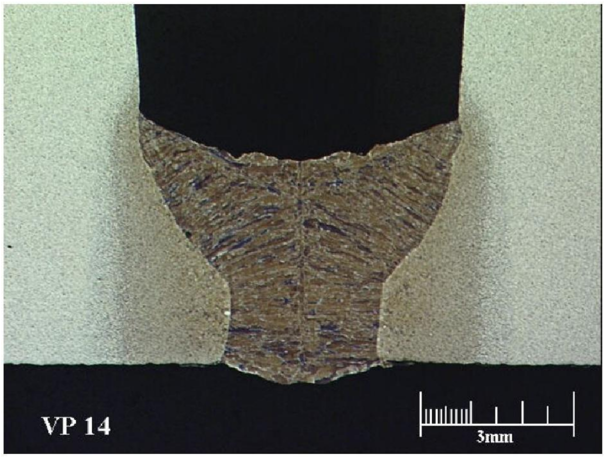


Figure 22 Microstructure of root pass of VP-GMAW process [16]

5.3.1. Tandem Gas Metal Arc Welding (T-GMAW)

T-GMAW is a variation of GMAW with difference that two welding wires are passed through the same welding torch and two close parallel arcs are adjusted by two GMAW power supplies independently [145, 146]. Synergistic interactions between the two welding arcs promote improved process stability and allow significant increases in deposition rate and travel speed. In this method, a single torch with two contact tips is used to feed both wires into a single weld pool. In essence, T-GMAW is still considered two parallel GMAW processes, but T-GMAW can alternate the maximum welding current to each welding gun [12, 16, 144].

In this process, the arc pressure remains unchanged, and the wire feed speed can be doubled. Hence, if arc pressure is the major concern, tandem GMAW can double the deposition rate [16, 144, 147].

Recently, EWI has developed new applications for T-GMAW to increase productivity and reduce welding costs compared with conventional techniques in shipbuilding, power generation, and heavy equipment [12, 147]. In this technique, possibility of welding in horizontal, vertical, and overhead positions are added to the advantages of conventional one. This is a special feature in welding of large structures where repositioning for welding is impractical or prohibitively expensive. Also, this system has deposition rates between 6.80 and 11.34 kg/hr for conventional joints in all position welding [148]. EWI technique has special application for welding of ship hull sections and others, such as field erection of pressure vessels, heavy wall pipe, and heavy equipment [12].

5.3.2. Dual-Tandem Gas Metal Arc Welding (DT-GMAW)

DT-GMAW technique is currently considered the most efficient method in welding of fill and cap passes due to its higher efficiency and lower welding cost by reducing the number of fill stations required in a pipeline welding spread. This process can be used widely in onshore and offshore applications and its applications in pipeline welding are still increasing [16, 149].

In the study done by Cranfield University's Welding Engineering Research center invested by BP Exploration and TransCanada, new generation of DT-GMAW developed. The system is shown in Figure 23 [16, 55]. This system meaningfully reduces the number of fill and cap welding stations to achieve a given number of welds per day and allows higher welding speed. These benefits lead to major saving in the welding costs (almost 25 %) and time. Figure 24 shows the macro section of X100 pipe with 14.9 mm wall thickness by the Cranfield automated pipe welding system [16, 55]. One of the main advantages of this system is that conventional radiography and automated ultrasonic testing can be used for defect detection. This system is suitable process in welding of oil and gas pipelines, such as X80 and X100 steels [16].

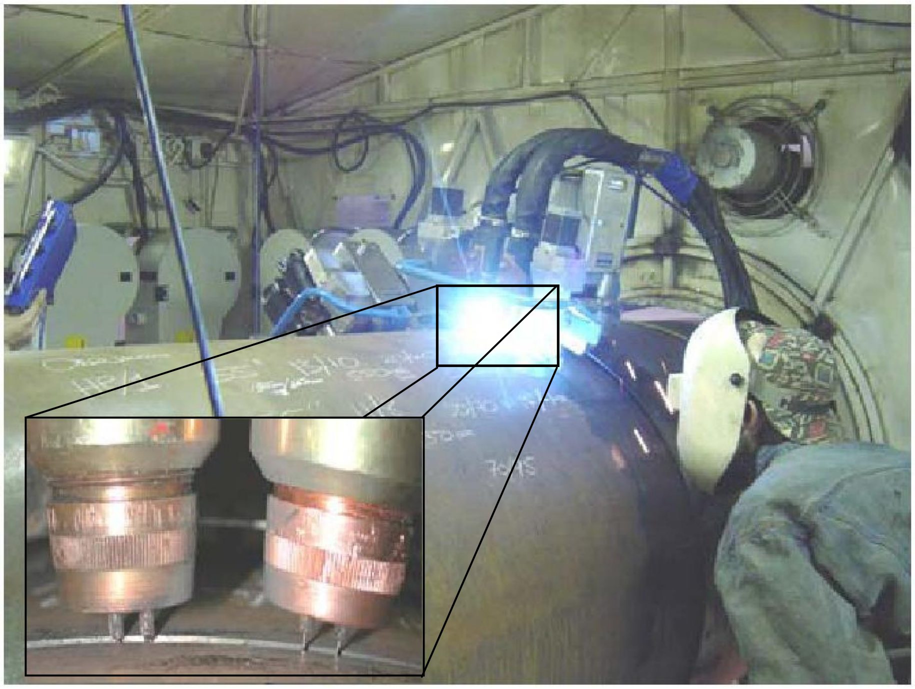


Figure 23 Arrangement of Cranfield automated pipe welding torches and system [16, 55]

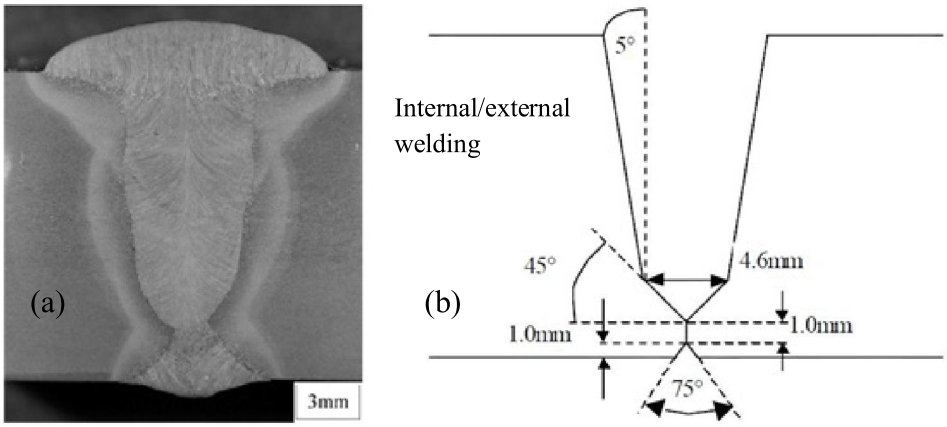


Figure 24 (a) Cranfield automated pipe welding system's macro-section and (b) weld bevel from weld in 14.9 mm wall X100 pipeline [16, 55]

In the study [16], by using thermocouple in different position of various orbital GMAW processes weld pool, cooling rate of each processes were estimated. All measurements were collected and presented as curves by the author of the study which are shown in Figure 25 and Figure 26. Each weld was made at the same calculated arc energy and the curves have been adjusted to align the 1400 °C point on each curve.

In the first test [16], a thermocouple plunged into the weld pool and for the dual-torch and dual-tandem processes, the thermocouple leaped into the weld pool of the second welding torch. As can be observed from Figure 25, the cooling rate of T-GMAW with one torch and single GMAW are almost the same.

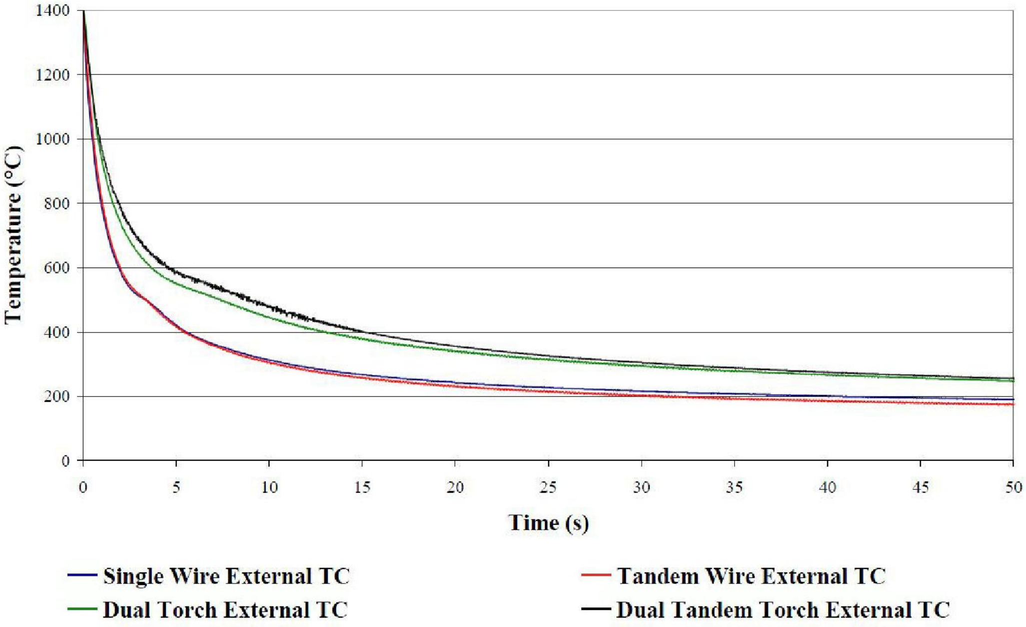


Figure 25 Cooling curves for an external plunged thermocouple with various GMAW pipeline welding systems [16]

In the second test, a thermocouple attached in a drilled hole immediately under the welding passes being deposited. As Figure 26 shows, the traces clearly show the effect of the second welding torch. As the travel speed in the case of DT-GMAW was twice of dual-torch GMAW, therefore the second torch passes gives point quicker than in the dual-torch process. However the heat input was same for both processes. This has a tempering effect on the weld metal. To show the difference in all-weld tensile strength between a single torch and dual-tandem weld with 1 % Ni, 0.3 % Mo welding consumable on X80 pipe, Table 4 is presented [16].

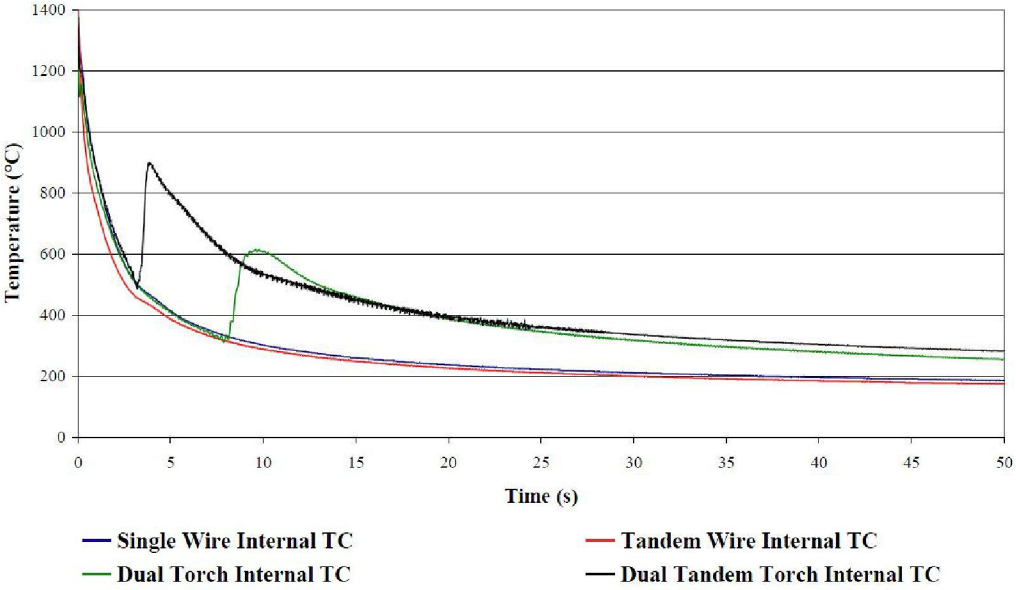


Figure 26 Cooling curves for an internal thermocouple with GMAW pipeline welding systems [16]

Table 4 Comparison of all weld tensile data for single and dual-tandem GMAW [16]

Weld Type	**Rp0.2 (MPa)**	**Rm (MPa)**	**Yield/Tensile Ratio**	**Tensile A (%)**
Single Torch Narrow Gap internal/external 1.0 % Ni / 0.3 % Mo	841	888	0.95	20.5
CAPS Dual Tandem Narrow Gap 1.0 % Ni / 0.3 % Mo	753	810	0.93	23

5.3.3. Narrow Groove Tandem Gas Metal Arc Welding (NG-TGMAW)

Generally, Welding processes with high deposition rate, such as GMAW and SAW are using in welding of thick section materials with conventional open-groove designs. High deposition rate does not mean of high productivity in these processes due to requirement of high amount of filler material and passes to fill a conventional single or double V-groove joint. The volume of conventional weld joints can be reduced by using narrow groove joint (see figure 24 b), however incomplete fusion into the sidewall is a common concern [12].

Using of narrow groove joints welding with conventional welding processes are risky, however mechanized GTAW has shown possibility of successfully use in this type of joint with relatively low deposition rate. Developed NG-TGMAW of EWI has succeeded in applying a high productivity process to narrow groove joint design, resulting in significant productivity growth. EWI system has been successfully used in welding of carbon steels, stainless steels, and nickel-based alloys, but not yet tried on aluminum and titanium alloys. The deposition rate of this technique (almost 4.11 kg/hr) is 3-5 times higher than the same welding situation with narrow groove gas tungsten arc welding (NG-GTAW). Excellent sidewall fusion and weld integrity were obtained, which demonstrated with ultrasonic nondestructive examination [12].

5.3.4. Twin Wire Gas Metal Arc Welding (TW-GMAW)

Initially, TW-GMAW was used in the welding of thick plates [150] but today, its application increased due to its high deposition rate. The main application of this process is in welding of thin plates with high travel speed (2 m/min) [151, 152]. To improve performance of the TW-GMAW process, pulsed current is used in the power source. In this case, two power sources are connected to each other named master and slave and commanded by the master power source in such a way that an out-of-phase current pulsing is established. During pulse period of the master power source the other one (slave power) is at the base period, reducing the magnetic attraction between the arcs (and conversely) [153].

5.3.5. Double Electrode Gas Metal Arc Welding (DE-GMAW)

Double Electrode GMAW proposes a way to change the fundamental characteristic of conventional GMAW so that the melting rate can be freely increased [124, 154]. For automatic and semiautomatic welding, the productivity is mostly determined by the travel speed provided that the welding performance criterion is met. Typically, the HAZ is desired to be small. While the most effective way to minimize the HAZ is to reduce the heat input, the deposition rate in GMAW would be proportionally reduced and the productivity compromised. Consumable DE-GMAW can solve this problem [154, 155].

In the non-consumable DE-GMAW process, a non-consumable tungsten electrode is added to conventional one in order to decouple the melting current into base metal current and bypass current (see Figure 27):

$$I = I_{bm} + I_{bp} \tag{2}$$

Where 'I' is the total current or melting current (A), 'I_{bm}' is the base metal current (A), and 'I_{bp}' is the bypass current (A). Therefore, deposition rate can be increased by improving of melting current while the base metal current can still be controlled at the desired level [144].

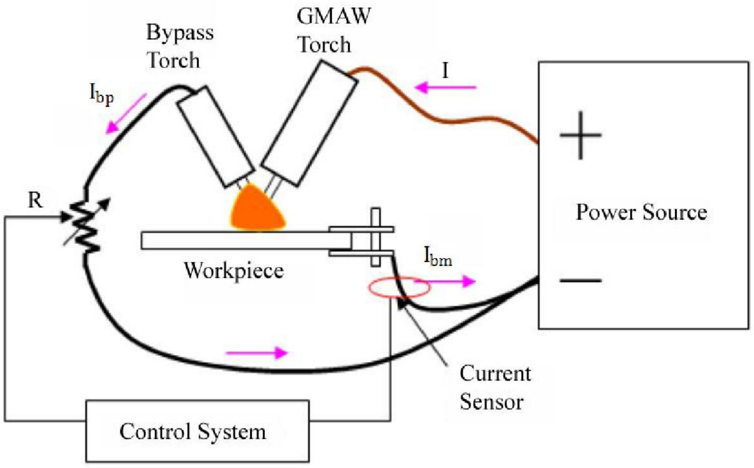


Figure 27 Non-consumable DE-GMAW system [124, 144]

If the non-consumable tungsten electrode changed with a consumable welding wire electrode in the DE-GMAW process, welding productivity can be further improved by increasing the melting current. This process is so called consumable DE-GMAW and a schematic of this process established at the University of Kentucky is shown in Figure 28 [144, 155]. This process has the potential to reduce the heat input without compromising the welding productivity [144, 154, 155, 156].

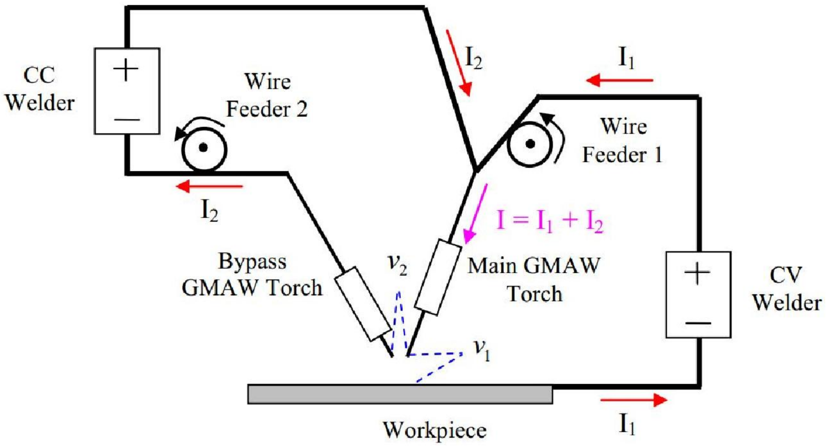


Figure 28 Proposed consumable DE-GMAW system [144, 155]

As illustrated in Figure 28, the bypass welding gun is powered by a constant current (CC) welder machine whose current can be adjusted. The main welding gun is powered by a ‘CV’ welder machine. The ‘CC’ welder provides the bypass current ‘I_2’ while the ‘CV’ welder provides the base metal current ‘I_1’. Two consumable wires are fed in by two welding guns. The displacement of welding guns is prepared by a motor. During welding, two parallel welding arcs are shaped, one the main arc established between the main wire and the workpiece, and another the bypass arc established between the main wire and the bypass wire. The total current ‘I’ which melts the main wire consists of two parts: the bypass current ‘I_2’ provided by the ‘CC’ welder machine and the base metal current ‘I_1’ provided by the ‘CV’ welder machine. Here like non-consumable, the below equation is valid:

$$I = I_1 + I_2 \tag{3}$$

As ‘I_1’ heats the base metal and ‘I’ melts the main wire, the consumable DE-GMAW provides a unique way to allow a large melting current ‘I’ be used to burn the main wire at a fast speed for high productivity without supplying excessive heat into the base metal. Single power source can be used for non-consumable DE-GMAW, although the bypass current energy was not effectively used. In consumable DE-GMAW process more than one power supply are required [144, 155, 156].

A stable consumable DE-GMAW process can be achieved with appropriate designed and originated welding gun configuration if the welding parameters are appropriately selected. A typical welding gun arrangement of consumable DE-GMAW is depicted in Figure 29 [144, 156]. As can be observed, the bypass welding gun is aligned before the main welding gun. The nozzle of the bypass gun is not essential due to providing of shielding gas by the main welding gun [144].

Figure 29 Welding gun arrangement of consumable DE-GMAW process [144, 156]

5.3.6. Modified Short Circuit Gas Metal Arc Welding

In pipe welding with traditional short circuit GMAW (S-GMAW), welding result was poor with lots of spatter on the sidewall of the pipe with lack of fusion. The new modified short circuit GMAW system has the advantages of uniform droplet deposition, more stable weld pool, far easier to create consistent tie-ins with the sidewall, easy control of weld pool, regular and precise of metal transfer [104].

In the modified short arc, the metal transfer occurs at a low current value, which results in a soft transmission to the weld pool. The modified short circuit process maintains a consistent arc length regardless of electrode extension. With the modified short circuit process, the software controls the electrode current during all phases of the droplet transfer. Once the droplet has been transmitted to the weld pool, the second current-rising phase begins and this initiates the arc stage. Subsequent to the two upslope phases of the modified short arc, the current is reduced to a desired base level. The use of a specified base current (BC) level ensures that the next filler drop will be transmitted during the next short-circuit. The highly controlled arc of the modified short arc process reduces spatter in the droplet detachment phase and decreases the heat input in the arc phase to be comparable with that in the conventional short arc process [104, 157].

This process does not require high operator skills. Also, hot pass welding is not necessary in this process due to fast freezing of the weld pool. Typically, SMAW, GTAW, and traditional GMAW create root passes 84.3 mm to 45.7 mm thick, depending on the operator. This requires a subsequent pass to add more metal so subsequent passes with FCAW or spray transfer GMAW do not blow through the root pass. Figure 30 demonstrates comparison of three different processes in root pass welding [104].

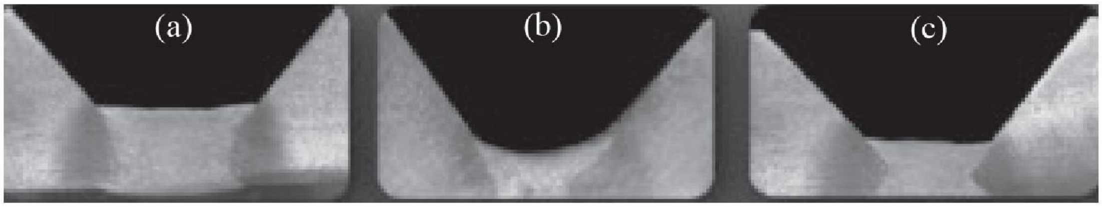


Figure 30 Comparison of root passes performed by modified short circuit GMAW (a), GTAW (b), and traditional short circuit GMAW (c) [104]

Modified short circuit GMAW process is a special design for the root pass welding (80.3 mm or greater) and can be replaced to the GTAW in many applications. Welding travel speed of this process can reach to 15.2 m/min to 30.5 m/min. The recommended fit up for this process includes pipes prepared with a minimum 45.72 mm root opening to ensure proper root reinforcement. The root face can range from a knife edge to 29.5 mm and the included angle is typically 75°. During welding process, the electrode is positioned in the center of weld pool and only in the welding of 5G fixed position [104].

5.3.7. Pulsed Gas Metal Arc Welding (P-GMAW)

In this mode of transfer, in a fixed duration of time, the power source pulses rapidly between a peak and background current. 'CC' is the most capable power source in pulse welding operation instead of using 'CV' [158]. This method is a variation of constant current welding which involves cycling of the welding current from a high to a low level at a selected regular frequency [159, 160].

Spray pulsed transfer occurs during the peak current period and the small molten droplets detach the electrode in a spray form. By increasing the pulse frequency, the size of droplets decreased and the metal transfer rate increased. Typically, the rate of frequency is between 60 to 120 Hz but this amount can go further [161].

The square wave graph of current versus time in pulsed arc is shown in Figure 31 [126]. During metal transfer the current reaches its higher value known as peak current 'I_p' and the lowest amount of current is known as background current 'I_b'. The other primary parameters of a rectangular current pulse are pulse duration or pulse time 't_p', pulse off-time or background time 't_b', and pulse frequency 'f '. The power supplies in this mode of transfer pulse the current back and forth between the globular and spray transfer current range to transfer the metal (see Figure 31) [126]. The arc is kept establish during background current typically at very low currents between 20 to 40 A. The metal transfer from consumable electrode in this mode is obtained in two ways depending upon the welding current: First, when the current is below, a certain critical current producing a globular mode (10 drops per second or low). Second, when the current is above the critical current, spray mode produced (a few hundred drops per second). The critical current as mentioned is so called transition current [104, 126].

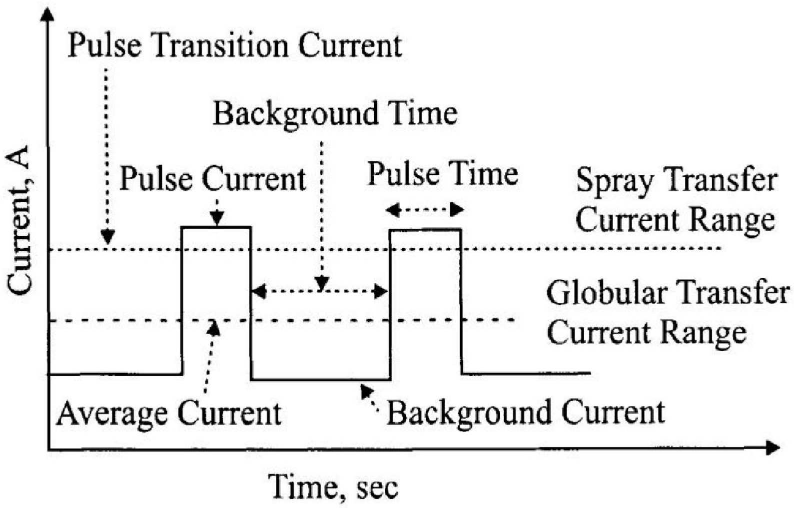


Figure 31 Pulsing current for metal transfer [126]

When the current rises rapidly by inverter pulse power supplies associated with higher current GMAW, the fume reduced. The reason is that, in very rapid growth of current the superheating of the molten droplets in the tip of electrode reduced. Consequently, the rate of fume generation decreased. Pulsed arc can be achieved by using argon and rich argon shielding gas and selecting appropriate parameter for background and pulsing current. By selecting most efficient parameters, one droplet from wire detaches to the weld pool per pulse [57].

The P-GMAW is versatile, and easily automated. Current pulsing has been used to obtain grain refinement in weld fusion zones, which has a positive contribution to mechanical properties. Optimum bead geometry with better penetration can be achieved by smooth spray transfer, through carefully selecting pulse parameters [162].

Figure 32 illustrates various welding process parameters and electrode parameters influence the process behavior in P-GMAW. The welding process sequence may be expressed as operational characteristics to thermal behavior to phase transformation and solidification of the molten weld pool. This affects the various weld quality features such as arc stability, bead geometry, weld microstructure and weld mechanical properties, respectively [57].

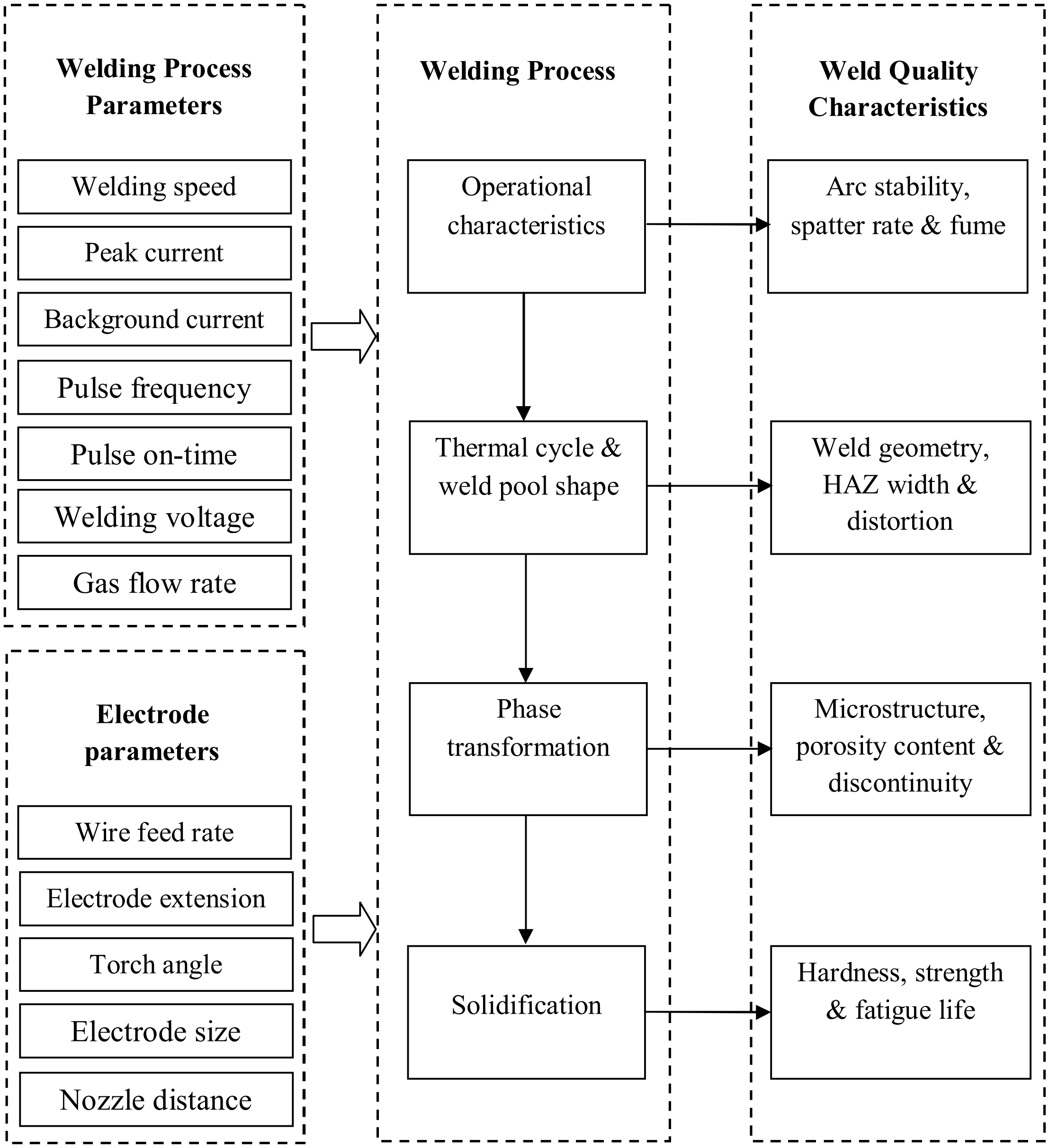


Figure 32 Schematic illustration of pulsed GMAW process [57]

In the project which was called P11, CMN Steel Fabricators of Miami, FLa., was contracted to weld 66 joints of chromium-molybdenum alloy. GTAW process was selected for the root and the first fill passes as its welding procedure specification (WPS) required. Also, 15 SMAW passes were needed to fill the joint but this process was replaced successfully with P-GMAW to speed up the project. P-GMAW is easy to learn especially for new welders and even easier for experienced welders to produce higher weld quality. Also, shorter arc can be made with this technique which helps eliminate undercuts and allows the operator greater control over the weld pool [104].

5.3.8. Rapid Arc

Rapid arc is a process close to the P-GMAW, planned to raise efficiency of welding by decreasing the cycle time in robotic applications. The arc stability in this mode is excellent due to the lower arc voltage and shorter arc length occurred during welding. Therefore, the spatter is reduced and torch travel speed increased almost by 10-30 % faster than conventional pulsed arc welding with similar bead appearance results. Lower heat input and as a result lower risk of burn through and reduction of incidence of undercutting by 75 % are other advantages of this method leading to cost savings [78]. Therefore, this process successfully can be used in orbital pipe welding system.

Rapid arc uses higher level of current and voltage. This mode is characterized by long electrode stick-out and high wire feed speed. Long electrode in Rapid arc causes current reduced but the resistance of the wire increased. Also, the voltage in Rapid arc is relatively low and force arc is obtained with high wire feed speed (up to 1.5 m/min). The power source can still be the conventional one in Rapid arc process [78, 163].

There are some factors should be considered during Rapid arc welding, depending on different applications. The place of electrode tip, torch angle, scale of mill, pollution, joint fit-up, joint firmness are some of those factors. In this mode of transfer, increasing the travel speed causes growth of spatter, reduction of penetration, low quality of welded bead, and more undercuts.

In higher welding feed speed due to requirement of shorter and tighter arc, mostly operators decrease the arc length. It helps puddle to follow the arc well. As a result, the wire travel speed cannot be exceeded too much but due to working in very low voltages and high stability of arc, it can be significantly raised.

Metal core wire can produce smaller weld beads and wire with diameter of 1.6 mm causes improvement of fit-up tolerance and growth of edge wetting. Short circuit in Rapid arc occurs in low current with the help of waveform controlling of arc adjustment. This waveform can be divided into the four main sections as shown in Figure 33 [78].

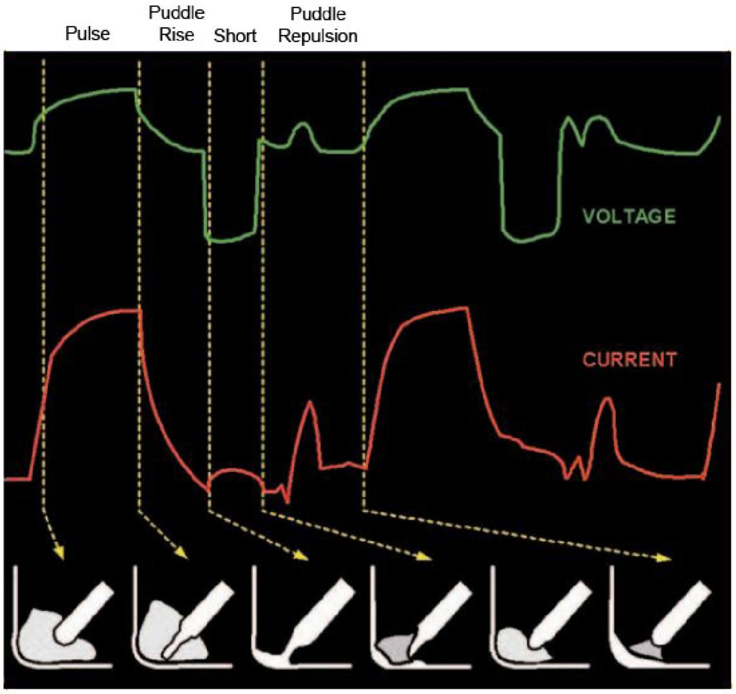


Figure 33 Schematic of Rapid arc’s waveform and its principle [78]

In section “Pulse”, the current rises rapidly and it increases the arc energy and molten droplet created at the tip of electrode. In “Puddle Rise” step, current decreased rapidly, the arc force is cut and it causes puddle raised up in the direction of droplet. In third step called “Short”, the arc suddenly falls apart and the droplet touches the molten weld pool. Finally, in “Puddle Repulsion” step, the electrode is conditioned due to the soft plasma rising which forces the puddle away. This makes guarantee that molten metal transferred to the weld pool in a stable rhythm in each period.

The cycle time decreased almost 10-30 % because of higher speed of the wire feed. Therefore, the process done faster and it causes higher efficiency, and as a result lower investment. Beside, this process needs lower post processing because of lower spatter level [78].

5.3.9. Surface Tension Transfer (STT)

STT is a controlled-current GMAW process invented by Lincoln Electric Company that uses high-frequency inverter technology and waveform control [62]. This process is quite close to the short arc with better control into the power source to increase the weld quality [158, 164]. One characteristic of this mode is slower deposition rate but higher weld quality with almost no spatters. Sophisticated controlling and electronic technical methods is employed in this process to have the best combination of short arc and GTAW process. STT has the ability of controlling the current without dependence on wire feed speed. During all phases of welding cycle, the welding current is adjusted to the heat requirements allocate by the arc [165].

The current is controlled in STT to make heat input independent of wire feed speed. As a result, electrode extension changes have no effect to heat. Distortion, spatter, and fume is decreased in this mode of transfer due to the less overheating of electrode, even with larger diameter of electrode and 100 % CO_2 shielding gas. Larger wire and 100 % CO_2 shielding gas together reduce the welding costs. Molten material of the electrode touches the weld pool before detachment occurred [166].

This job is done through a high speed inverter, during the whole shorting period to modify the output current waveform and well known as “Waveform Control Technology”. With this method in STT, power source can be programmed to improve efficiency of arc characteristics for each application [164].

The arc current range of all conventional transfer modes in FCAW are 90 to 400 A with voltage variation of 10 to 40 V. In STT process, current rate and wire feed speed are not related to each other. Current controller is used in this mode to adapt heat without dependence on the wire feed speed, so by changing the electrode extension nothing happens to heat [167]. Typically, waveform cycle repeated every 1/120 second [166] and Figure 34 demonstrates the waveform and metal transfer cycle in STT process [167].

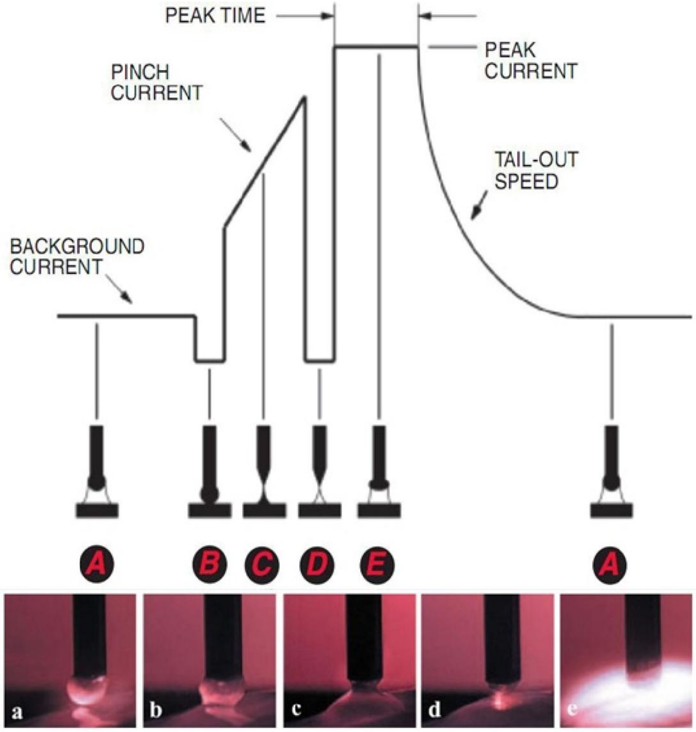


Figure 34 Schematic of STT wave form and principle of STT process in one cycle [167]

The rate of background current is between 50 to 100 A and keeps the arc existence and gives heat to the base material. The fundamental of STT process is explained below in brief with reference to Figure 34.

In the point (a) the current is in background level and a uniform molten droplet is shaped at the electrode tip until it touches the puddle. Point (b) shows the time that molten ball shorts the weld pool. In this point the current decreased to a level lower than background current and it lets the molten droplet wet into the weld pool. In next step point (c), accurate pinch current waveform is added to the molten metal which is connected to the weld pool. In this period of time, a special system of electronic circuit realizes that the short occurred in the weld pool is about to break and decreases the current to prevent spatter. The current reaches to its lowest level similar to point (b) to reestablish the arc, this point is point (d). Finally, in point (e), the electronic circuit system (circuitry) by sensing the reestablishment of arc, increases the current of arc to the peak current automatically, to produce the proper arc length. This peak current, goes to the background current by tail-out control. The rate that the current is changed from peak current to background current is adapted by tail-out control.

In STT welding, parameters such as background current, peak current, and tail-out influence the whole welding process. Good fusion is guaranteed by arc length which is depended on the peak current. Higher arc length is obtained by higher peak current. Too large arc length may cause globular transfer. Too small arc length may be occur arc instability and wire stubbing. The heat input to the weld is controlled by background current. When the amount of background current is high, the weld bead will be flat. Unlike, by decreasing this amount, taller rounded contour will be obtained. Additional power is provided by tail-out while the size of molten droplet does not go too large [167].

STT process is three or four times faster than GTAW to complete open root welds in pipe welding applications with better back beads and edge fusion without use of ceramic or copper internal back up bars. Also, HAZ is reduced in this mode. Distortion is minimized in this method compared to the conventional GMAW due to the low heat input. Operating of this process is easier than others, yet produces consistent, X-ray quality welds. The STT process results in a complete back bead without shrinkage from the 12 to 6 O'clock weld positions. Also, because current control is independent of wire feed speed, the process allows greater flexibility under all conditions [18, 19, 77].

Obtained weld quality of STT is higher in all position due to better position in poor fit up area. The input heat needed in this mode is lower and it makes less oxidization. By precise controlling of the amperage in every moment of welding cycle, better fusion is achieved. In STT process, because only required heat for weld is produced (lower heat input), so less material distortion occurs. Possibility of using larger diameter of wire, carbon dioxide shielding gas, and fewer spatters, all together reduce operation cost and increase the welding efficiency of this process [77, 164, 167].

The process is effective for welding stainless steel and related alloys, as well as mild and high-strength steels. 100 % of CO_2 and combination of CO_2 and argon can be used as shielding gas in power source for mild steel as well as combination with helium for stainless steel. Superior metallurgical properties can be achieved when welding duplex stainless steel and the “critical pitting temperature” (CPT) is significantly better with STT than with GTAW [18, 19, 77, 164].

The STT process has gained acceptance in open root pipe welding because it controls the welding current independent to the wire feed speed. This feature makes controlling of temperature or fluidity of the weld pool easier to guarantee penetration and fusion. Lower amount of spatter dissipated on the pipe and surrounding fixtures means more part of electrode spent into the weld pool and as a result this process is more productive. This process find by welders not only easy to make open root welds but also excellent mechanical and metallurgical properties [18, 19, 77]. Other advanced processes in this category are, Fronius’s CMT, EWM’s cold arc and Kemppi’s wise-process.

5.4. Laser Welding and Hybrid Laser Arc Welding

Hybrid welding refers to the combination of laser beam welding (LBW) with another welding process to further improve productivity. HLAW was introduced to eliminate drawbacks related to high-power pure laser welding. Laser beam welding has high welding speed, high power density, low distortion, narrow weld joints, low thermal load, single pass welding in large thickness, easy automation, and positive effects on the working environment [168, 169].

Compared to laser welding, HLAW has greater ductility, deeper penetration, higher bridgeability, higher process stability, lower laser beam power, lower fabrication time and welding costs, lower energy consumption, higher welding speed at constant heat input and distortion [168, 170].

On the other hand, advantages of arc welding process can be named as, higher tolerance to fit-up, low-cost energy source, better mechanical properties, good root opening bridgeability, and the facility for influencing the structure by adding filler metals [171]. Then, by combining the laser process an arc welding process the result is gaining broader acceptance within industry. This combination leads to advantages over other methods such as T-GMAW and Rapid arc welding, such as lower heat input, narrower weld joints, higher welding speed, higher thermal efficiency, better mechanical properties, and possibility of direct, single-pass butt-welding of pipes with little or no bevel requirement [149, 170, 172, 173, 174].

However, numerous advantages are involved with HLAW process; there are some limitations for this technology, can be listed as [175]:

- Almost new technology and risky
- Laser hazard and requirement of protection equipments
- To obtain high quality strict alignment and part fit-up are required
- Costly process compared to conventional automated GMAW due to expensive laser equipments
- Difficulty in welding of thick-section butt joints with a gap exceeding 1 mm, due to the small focal spot diameter of the laser beam

HLAW can be used to weld a wide range of metals, including steel, stainless steel, nickel, titanium, aluminum, copper, and other alloy systems. This process can be used in both, thin-section welding, such as automotive components [176], and thick-section welding, such as oil and gas transmission pipelines, boiler manufacturing, wind turbine towers, prefabricated steel beams, nuclear components, shipbuilding, heavy vehicles, construction and mining equipment, and rail cars [149, 177]. There is welding possibility of many joint designs with HLAW, such as butt, groove, lap, flange, and fillet joints [168, 170, 175].

Continuous-wave lasers are most often used for HLAW because they generate a constant laser power for the duration of the weld. The laser source is selected based on power and wavelength. The output power capability is chosen based on the desired weld penetration for a given application. Travel speed, power density, base-metal absorptivity, and joint design can also affect the determination of laser power [175].

CO_2 lasers and Nd:YAG (Neodymium-doped: Yttrium Aluminum Garnet), diode, and fiber lasers are main types of industrial lasers. CO_2 and Nd:YAG lasers have been used at high powers for deep penetration keyhole welding. The main difference between these to process in terms of materials processing is their wavelength of the light emitted. Only the Nd:YAG lasers wavelength which are 1.06 μm can be carried by an optical fiber to the workpiece, which allows circular geometries to be more easily welded. CO_2 lasers have a wavelength of 10.64 μm and this is not transmittable through glass. A series of mirrors or transmissive optical systems should be used to transfer laser beam to the workpiece. Nd:YAG lasers have been more limited in terms of power. Also, The beam quality of CO_2 lasers is better than that currently available with high power Nd:YAG lasers. To use high power Nd:YAG laser, The Welding Institute (TWI). Combined the beams from up to three Nd:YAG lasers to obtain one laser beam up to 8.9 kW power that can be transferred to the workpiece by using optical fiber with 1.0 mm diameter [16, 63, 171, 177].

Mostly, CO_2 laser welding systems are used in static and limited motion industrial environments. One CO_2 laser welding system has been field tested by Bouyges Offshore. This company developed a full production welding system based on a 12 kW laser. The system was introduced for welding of API 5L X52 pipeline with dimension of 254×12.7 mm in the 5G position. The system was easy to move and install on different pipe lay vessels. With filler metal additions, the process was tolerant to a maximum gap of 0.5 mm and a maximum internal misalignment of 2 mm [16, 63]. It should be noted that, in the welding of C-Mn steels for structural and shipbuilding applications, CO_2 lasers has been taken [178].

As mentioned, the most important aspect of Nd:YAG laser is its possibility of transfer by optical fiber. This feature as well as recent ability to produce high power Nd:YAG laser beams make this method much more attractive as flexible manufacturing tools and particularly for orbital welding of land pipelines [16, 177]. 1.5-2 kW Nd:YAG lasers have been successfully containerized [179] and 4 kW Nd:YAG lasers are the largest commercially available.

Nd:YAG laser is not a proper process for onshore pipeline welding applications due to the plug efficiency, physical size and cooling requirements Nd:YAG lasers. From the beginning of the "YAGPIPE" project this fact became well-known and it was assumed that new laser technologies would develop over the course of the project and that these may be suitable for pipeline applications [16, 177]. Also, weld bead shape of joints welded by Nd:YAG laser are wider and varies with different cooling times. This property of Nd:YAG laser system increase the risk of solidification cracking as well as ability to produce tough, fine grained, autogenous fusion zone microstructures [63].

Diode and fiber lasers are physically in small size with comparatively high wall plug efficiencies. Compared to Nd:YAG laser, this method is 30 % more efficient with 50 % lower operating cost. Diode laser is easy to transport and this feature makes this technology ideal for pipeline applications. The drawback of diode laser is their low beam quality which eliminates possibility of keyhole welding. However, manufacturers are working to increase power and improve beam quality and their research leads to those energy densities over 2.5× 105 $\mathrm{W/cm^2}$. With this new diode laser keyhole welding of steels up to 6 mm thickness is possible now [16, 180].

On the other hand, fiber lasers enables 50 % faster pipeline welding. Fiber lasers are similar in concept to the end-pumped YAG lasers, with different in the shape of optical fiber which is long. The core in fiber laser is doped with a laser medium usually ytterbium (Yb) for oscillators or erbium (Er) for amplifiers. The size of fiber core is generally lower than 10 μm with many meters of length, therefore beam quality of fiber lasers is excellent [16, 181]. In the last six years, fiber lasers have been used as a mobile application in shipbuilding and in the production of pipes [182].

Mostly, fiber lasers are used in micro-applications which need low power but recently 4, 6, 8 kW units have been manufactured. Yb fiber lasers are now commercially available with power levels of up to 10 kW. Yb fibers have special applications in pipe girth welds due to the use of single optical fiber to transfer beam to the workpiece. Also, their high efficiency enables the development of more portable welding systems. In fiber lasers, electrical to optical efficiency can be over 20 % and compared to Nd:YAG lasers lower input power or cooling is required [16, 177].

In the study [177] entirely feasibility of using high power laser welding of land pipelines were proved and it can be the most promising technology for pipeline applications in the future. This method used in orbital pipe welding for ensuring a good weld at the start/stop weld overlap position. As an example, [IPG Photonics, Oxford, Mass.,] claims that a 10 kW fiber laser that is part of a system for deep penetration laser welding of pipeline steel, enable 50 % faster welding than current technology. This process is used in welding of steel pipes like X70 and X90 thicker than 10 mm which is used in oil and gas industries in one pass with high speed (2.2 m/min for X70) [16, 177, 181].

HLAW process combines a gas or solid-state laser (e.g., CO_2 or Nd:YAG) with an arc welding process (e.g., GMAW, GTAW, or PAW) [183]. In the fully synergetic hybrid processes the plasma formed at the interaction point of the laser on the workpiece surface. Energy is transmitted from the laser to the arc by means of high-energy infrared coherent radiation using a fiber optic cable. The focused laser beam hits the workpiece surface converting its energy into heat. The arc transmits the heat needed for welding by a high electric current flowing to the workpiece via an arc column [168, 170, 184].

Figure 35 is a cross section of a penetration mode one pass hybrid weld conducted on a 12.45 mm carbon steel square butt joint. This weld was performed with 10 kW of laser power, a 333 mm laser spot size, and an 8.9 m/min wire feed speed for a 1.1 mm diameter steel wire at a travel speed of 1.52 m/min. Note that, the fusion zone resembles the superposition of a GMAW weld profile and a laser weld profile [175].

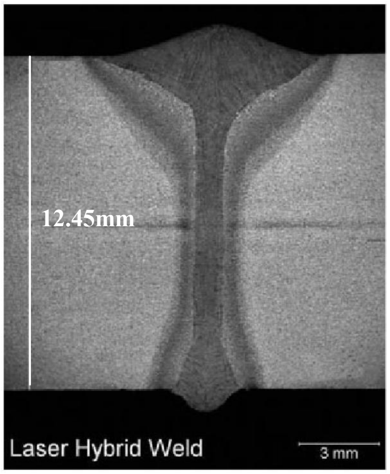


Figure 35 Cross section of one pass hybrid laser arc welding on a carbon steel square butt joint [175]

In the study [185], a machine for two-pass hybrid laser-arc welding of position butt welds, on main pipelines was developed and successfully tested. Moreover, the second pass was performed using arc welding, i.e. the laser radiation was used only to form a root weld. Also, in this study a hybrid tandem method of welding steels offered where two-arc tandem with consumable electrodes were combined with laser radiation located ahead.

Shielding gas for HLAW should be selected based on the material being welded, however additional considerations are necessary based on the laser wavelength and the desired GMAW characteristics [186]. Helium has a higher ionization potential than argon and it produces less dense plasma [175, 184]. Welding of carbon steels is normally performed by using CO_2 and in rare case, argon. [187]. In hybrid welding, however argon promotes a spray-rotational transfer of electrode metal, it increases the welding current and formation of undercuts in the upper reinforcement bead.

For laser and HLAW, it is desirable to use such gases or their mixtures. It makes possible to avoid their drawbacks, raise the welding speed, increase the penetration depth and decrease the sensitivity of the weld metal to porosity [188]. First of all as mentioned, such gases include helium and its mixture with argon. However, an important drawback of helium is its high cost especially for welding low-carbon and low-alloy steels. CO_2, also has a positive effect, as it allows growth in the efficiency of melting of electrode and base metals. The penetration depth in welding by CO_2 or its mixture with argon depends upon the laser radiation power and position of the beam focus relative to the specimen surface. To increase the penetration depth in hybrid welding of the butt joints, it is recommended to make the V-groove and deepen the focus closer to its bottom [188].

Variations of HLAW

So far, two variations of laser-arc hybrid processes have been used for industrial applications. These two processes are hybrid laser/GMAW and hybrid laser/SAW. The hybrid laser/GTAW method allows very high welding speeds in welding of aluminum sheets for tail-lifts with, at the same time, a very high surface quality of the weld. The hybrid laser/GMAW method is used for steel applications (shipbuilding) and also for aluminum structural designs (automotive engineering). For this reason, attempts to optimize the hybrid process have been made. Improved degasification possibilities are expected by substituting the GMAW process for the SAW process since after that the melt is maintained for a longer time [189].

Hybrid laser gas metal arc welding

In hybrid laser/GMAW, the arc process causes the lowering of the molten pool surface where, penetration depth is increased [190, 191]. The penetration depth is mainly determined by the laser beam power and shaping. The weld width is mainly determined by the arc, in particular, by the arc voltage. In contrast to the "pure" laser beam process, a welding speed increased up to 100 % at a constant laser beam power [189]. A schematic of Hybrid laser/GMAW process is shown in Figure 36 [149].

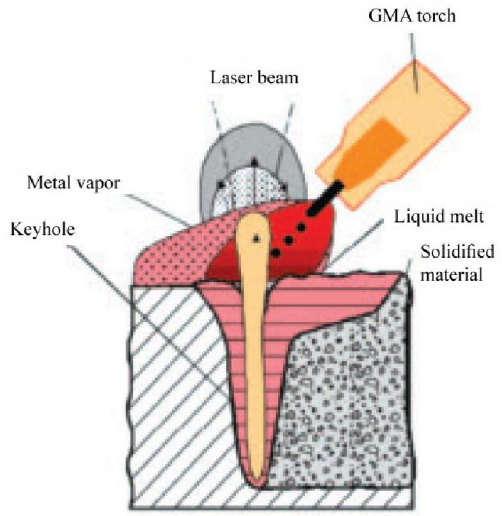


Figure 36 Hybrid laser welding combines the attribute of GMAW and laser beam welding [149]

The arc is pulsed via customary GMA welding power source [189] or it is applied as a 'DC' arc, in the most cases in the form of a spray arc. The shielding of the welding zone is just as in CO_2-laser beam welding, realized with pure helium [190] or with helium-argon gas mixture. A trail shield device is generally used when welding reactive metals such as titanium or in applications where discoloration due to surface oxidation is unacceptable [189]. A typical result of hybrid laser/GMAW of a sheet plate thickness of 8 mm is shown in Figure 37 [180].

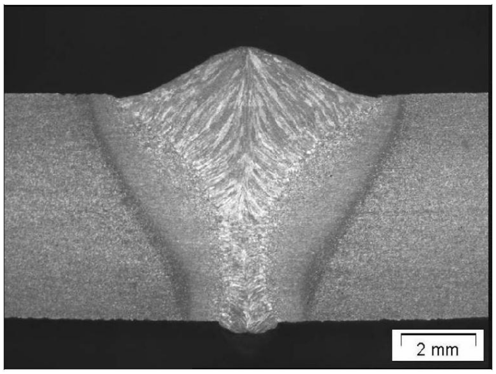


Figure 37 Formation of the weld in hybrid welding [180]

The mainly used welding filler materials are similar and customary solid wires, the same wires as used for “pure” GMA welding of the base materials [189]. However, metal cored filler wire gives a better arc stability in the hybrid welding process than solid wire [192]. There are more advantages of using metal cored over solid wire in hybrid welding, such as higher contents of oxygen and form of suitable insoluble oxide particles in the molten pool [171]. For thick-plate welding, mainly CO_2-laser beam sources are used since those provide higher powers than of Nd:YAG-laser [175, 189].

Apart from the square butt preparation, also V- and Y-groove shapes can be used which are, partially, results of blanking without any further edge preparation. In contrast to laser beam welding with cold filler wire, the laser beam energy must not be used for melting the filler material since the wire has been fed to the process in an already molten form, thus a reduction of the welding speed can be dispensed with [189]. The filler material allows exerting a defined met illogical influence on the welded structure.

While in laser beam welding mainly parallel welds with a high aspect ratio are produced (Figure 38, a), the upper part of hybrid-welded seams is particularly expanded (Figure 38, c), which results in a triangular weld shape [189].

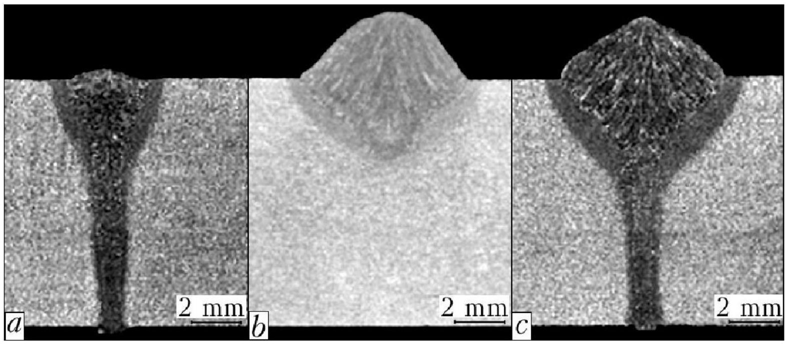


Figure 38 Welds: laser welding (a), GMAW (b), laser-arc hybrid welding (c) [189]

Hybrid laser/GMAW has been recently used in welding of 5G position and for girth welding of land pipelines for the oil and gas industry [193] with an acceptable geometric profile of weld bead [12]. Figure 39 shows welding head equipped with additional degrees of freedom and the equipments for hybrid welding of root pass and the integrated second arc torch for welding the cover pass during one vertical-down weld movement [180].

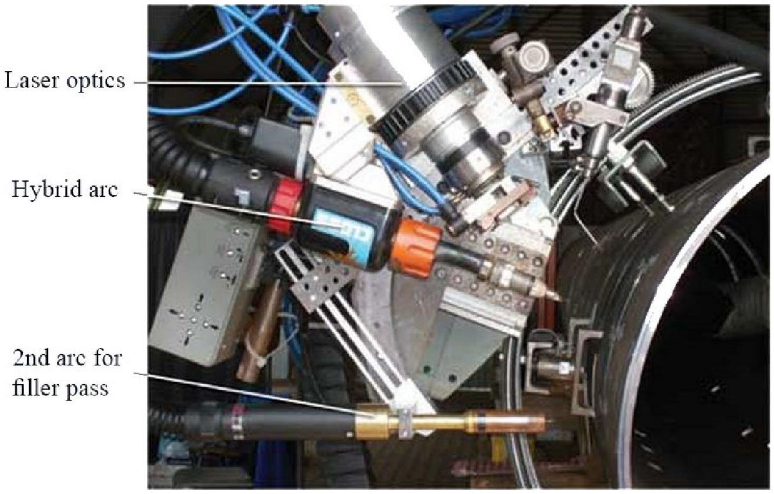


Figure 39 Welding head with hybrid equipment for root pass welding and arc torch for filler pass welding [180]

Figure 40 depicts excellent example of improper tolerance provided in the study [194] using 10.5 kW CO_2-laser/gas metal pulse arc hybrid welding. The experiment was welding of 10 single V-groove on X52 steel pipe with 10 mm thickness and 1 mm root face. Filler wire G3Si1 of diameter 1.2 mm and assist gas argon-helium mixture at wire feed rate of 5.2 m/min were selected for this project [195].

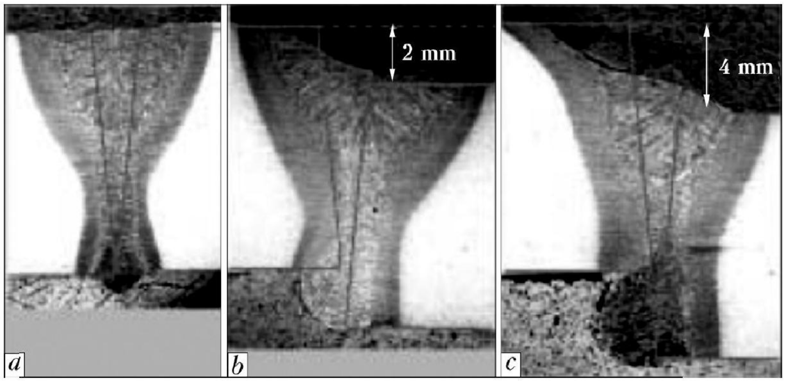


Figure 40 Macro-section of the pipeline steel X52 welded joints 10 mm thick at speed of hybrid of (a) 1.0 and (b, c) 0.8 m/min [194]

Today, new laser technology leads to produces 10 kW Yb fiber lasers with 25 % efficiency in a size like a refrigerator. It means this laser power source can be used outside of laboratory and practically in the pipeline welding applications. In the study [12], a 10 kW hybrid welding system were used in the welding of X80 and X100 root pass to achieve complete joint penetration welds with a 4 mm root at a travel speed of 2.3 m/min. The result of X100 pipes welding are demonstrated in Figure 41. While a throat thickness of up to 12 mm can be produced, the root pass hardness and associated Charpy V-notch (CVN) toughness requirements cannot be achieved (in X80 and X100 pipe) by the hot pass if the weld throat produced by the hybrid root pass is too thick.

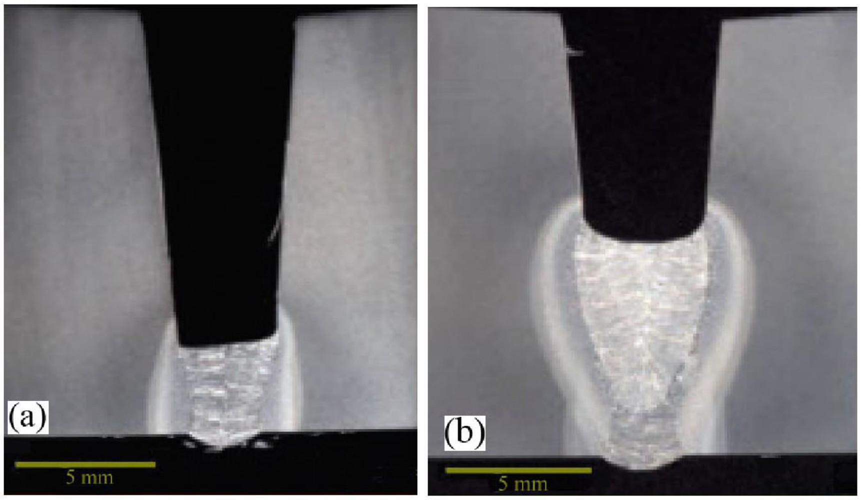


Figure 41 Cross section of hybrid welding at 0.0381 m/s (a) root pass welding (b) root pass plus hot pass welding [12]

In the case of using Nd:YAG laser power combined with GMAW process, the study [196] shows that this combination is more suitable for pipe welding than autogenous laser welding. Also, in the study [149] utilizing of this process for the root bead and relying on conventional mechanized GMAW for filling and capping were explained. Results in this study represented deposition rate of up to 4 m/min in 3 mm thick root beads which is doubled compared to conventional GMAW. Also, a new project done in UK has demonstrated the feasibility of producing root beads in pipeline girth welds at very high speeds. An example of typical section through pipe wall of autogenous 9 kW Nd:YAG laser is shown in Figure 42 [196].

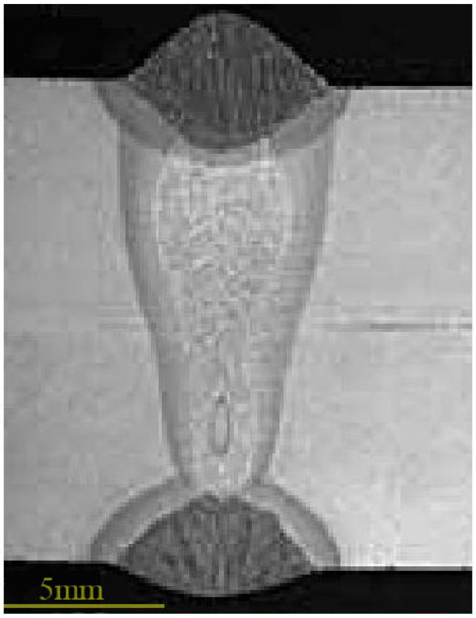


Figure 42 Section through pipe wall, showing internal GMAW root run, 9.0 kW autogenous laser fill and GMAW capping pass [196]

According to the study [16], it shown that hybrid Nd:YAG laser/GMAW of the root pass has the potential to increase welding productivity. Figure 43 (a) illustrates a typical macro section of such welding. By using 3 and 6 kW of laser power source, EWI and TWI have made 3 mm root passes at 3 and 3.5 m/min, respectively. Also, it has been investigated that hybrid laser/GMAW can be used in welding of the first fill pass completing an internal root using an Internal Welding Machine (IWM). A typical of macro section by using this method is shown in Figure 43 (b) [16].

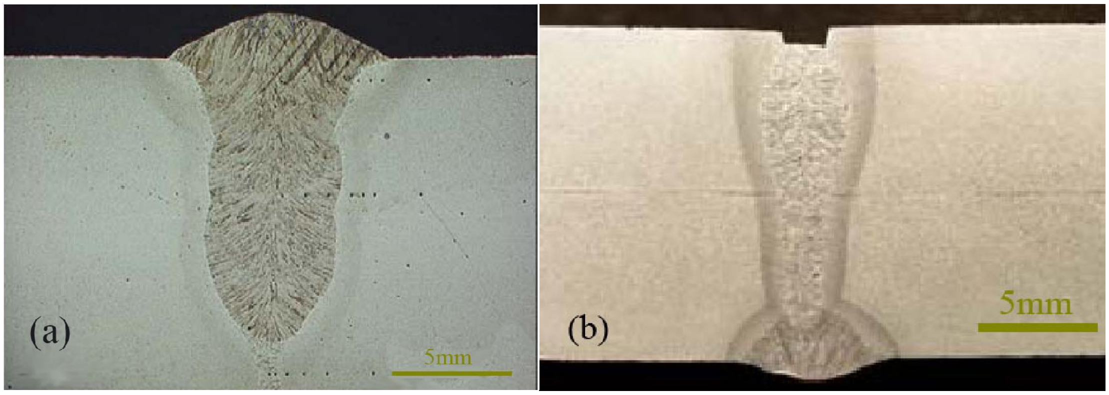


Figure 43 (a) HL-GMAW root with GMAW fill (b) IWM root pass with HL-GMAW first fill [16]

With Nd:YAG laser/gas metal arc hybrid welding process there is possibility of providing the carbon equivalents of the pipeline steel. Also, this welding process causes significant improvement on the microstructures and mechanical properties of welds in pipeline steels. Further, by using metal cored wire in a compound bevel joint on a range of pipeline steels in this process, predominantly acicular ferrite weld microstructures are resulted [171].

Hybrid laser submerged arc welding

SAW is a high-quality, reliable and productive welding process which has been successfully applied for years in shipbuilding, terotechnology (the technology of installation, commission, and maintenance) and pipe construction. As earlier mentioned, the method belongs to the group of arc welding processes and it is characterized by the fact that the arc is burning invisibly and, shielded from the atmosphere, inside a gas- and metal-vapor filled welding cavity. This cavity is surrounded by liquid slag from the molten weld flux. Beside a high thermal efficiency degree with good molten pool degasification, the slag effects also the forming of a smooth bead and notch-free surface. In connection with a suitable wire-flux combination which has been adapted to the base material the result will be high-quality welding [189].

According to the previous state-of-the-art, the variation "Combination of laser-submerged arc" has, as a method coupling, not yet been a matter of research. The investigations which have been known so far are restricted to the considerations of the process combination SAW and laser beam welding [197, 198]. As far as previous investigations are concerned, the spatial distance of both processes and the separation of the weld into a laser-welded and a SA-welded area have been noticeable. Those areas have, among one another, not shown any mixing of the weld material. It has just been the preheating, brought in by the laser beam welding process which resulted in the synergy effect of increasing the welding speed of the SAW process [189].

The coupling of the processes, both the laser beam welding and the SAW process in one process zone proved to be a problem since the flux had been falling into the keyhole of the laser beam and the laser radiation had been absorbed by the flux and not by the component. For that reason, a device which impeded this "falling forward" of the flux had to be designed and built. One starting point is the separating plate [patented by Aachen University] which is mounted between laser beam and flux feeder [189]. The shielding gas which is required for laser beam welding is directed against the welding direction onto the separation plate in order to blow the flux which might fall through the gap between workpiece and sheet out of the laser beam process zone [189, 195].

This arrangement requires some process-related parameters which have so far not been considered in the hybrid technology. The distance between separation plate and weld piece is of particular importance. The distance must be chosen short enough to ensure that smallest possible quantities of flux are falling forward and must be chosen large enough that a slag that might be running ahead does not jam to the sheet. The inclination angle of the sheet is also most important. If the inclination angle is too large the sheet might be captured by the laser beam, if it is too small the arc might burn between sheet and filler wire. The shielding gas flow, more-over, must not be too voluminous since then the arc of the SAW process might be blown off which would result in pore formation in the weld [189].

6. Seam Tracking in Orbital Pipe Welding

For joining one pipe to the other, girth arc welding, which consists of the root pass and the fill pass procedures, is prevalently performed. The welding process for manufacturing pipe structures can be accomplished with automatic equipments that have been partially mechanized only for fill pass welding and operated by a welding operator [199]. Due to machining or installation errors, it is difficult to ensure that the torch has always aimed at the groove center especially the large diameter pipe, which requires manual adjustment during welding process. This method not only reduces the efficiency of production but also cannot guarantee the quality of welds. Offline programming of industrial robots can completed this work well [200], but it is a time-consuming and a costly tool. Some approach using visual sensors are studied for tracking weld seams [201, 202, 203], which are not suitable for pipe welding when the question of the signal noise is taken into account. The pipe welding robot, using laser vision sensor which is not sensitive to noise and have high recognition precision [204], is able to recognize and track horizontal and longitudinal dimensions, and fully meet the pipe welding seam tracking and controlling demand [204, 205].

A weld pool control technique with the vision sensor system for pipe welding consisting of a laser vision sensor subsystem, a controller, an actuator, a charge-coupled device (CCD) camera, a long wave pass filter for lowering the arc intensity in bead-on-plate welding, and welding equipment [204, 206]. Block diagram of such system is shown in Figure 44 [204].

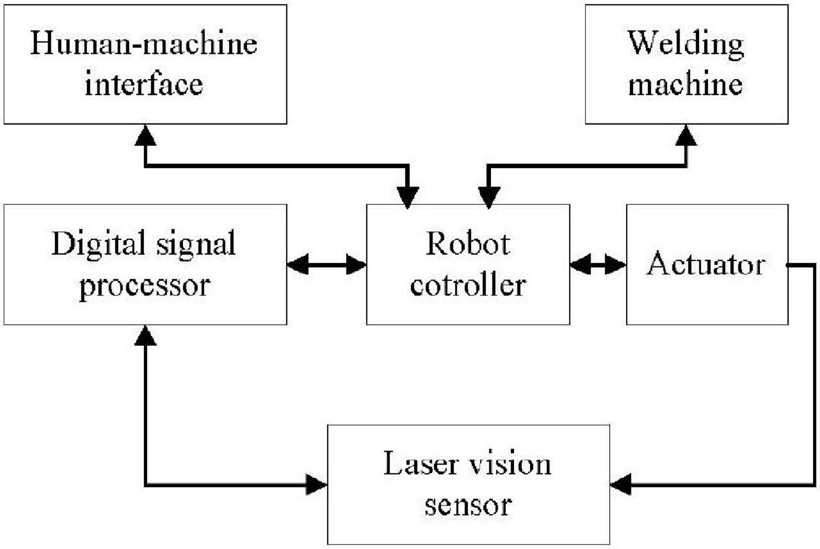


Figure 44 Block diagram of the pipe welding system [204]

In adaptive orbital pipe welding the great challenge is the position of welding torch during welding process. As shown in Figure 45 the welding of pipe is divided into four positions. The positions are the flat position, the overhead position, the ascending vertical position and the vertical descendant position. In each one of them the optimum parameters of the torch in relation to the welding pool are different [207, 208].

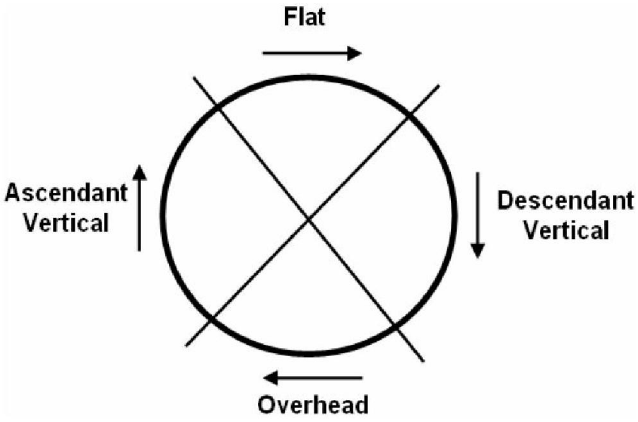


Figure 45 The four welding positions in the orbital pipe welding [207, 208]

On the other hand, to obtain desired result, precise control of torch angle in the displacement plane during welding process is required. The reason is requirement of pulling or pushing the welding pool by the torch, and in the perpendicular direction to the movement, to correct the trajectory and to control the stick-out. Also, the lateral angle movement in relation to the groove is an important factor in up or downhill pipe welding. By correct position of torch in lateral angle, the effect of force of the gravity can be reduced in the welding pool. Figure 46 shows a-four degrees of freedom in the manipulator to get all the possible movements to be executed by the hand of a human welder [208].

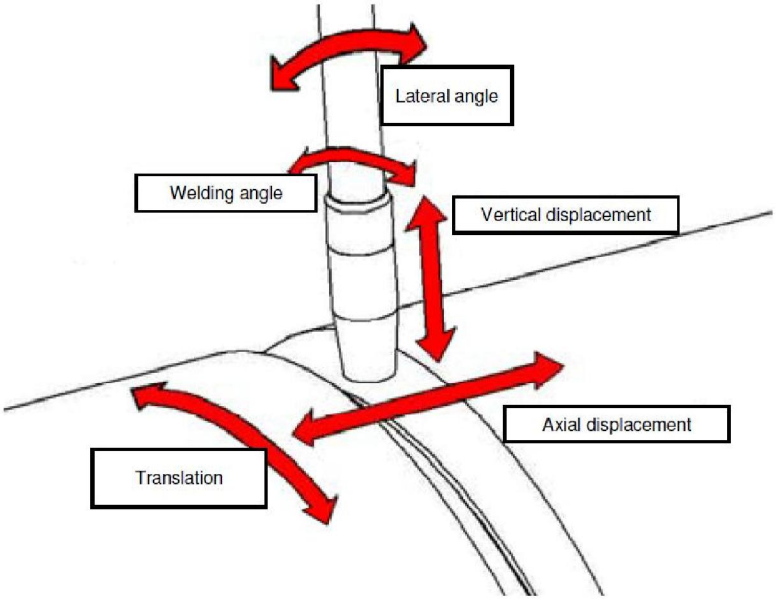


Figure 46 Welding torch degree of freedom [208]

There have been various studies in the field of adaptive welding with similar or different methods to improve welding productivity and quality. In the study [64], a fully adaptive automatic welding system fill control for multitorch and multipass SAW was developed. The study [208] developed a viable option of kinematic structure that is capable to easily fulfill all the necessaries requirements. In the study [130, 209] the angle variation effects on the metal transfer was studied on both transfer modes. Later the author improved his work in [129] by adding the effect of the input parameters on the drop detaching around the pipe in GMAW and compensation of the gravity force effect variation. In the field of using vision sensor in different welding and orbital pipe welding processes, there have been efforts and some of them are mentioned in this study.

Laser vision sensors are preferred method in noisy environments where automated manufacturing processes, like welding are used. The Studies [210, 211, 212] were primary studies that suggested using of laser vision sensors for seam and joint tracking. Since then study [213] applied a laser vision sensor in welding process control and automatic welding inspection. Recently, various kinds of high-speed welding processes have been introduced in an effort to improve productivity by using this system. In the study [214] a multiline laser vision sensor was developed that improved the tracking capability and reliability of conventional laser vision sensors so as to apply high-speed joint tracking. In the study [215] a system consists of CCD camera, lighting, image acquisition card, mechanical devices, host computer (IPC), ultrasonic probe, and pipes were investigated for image processing, as the structure of system is shown in Figure 47.

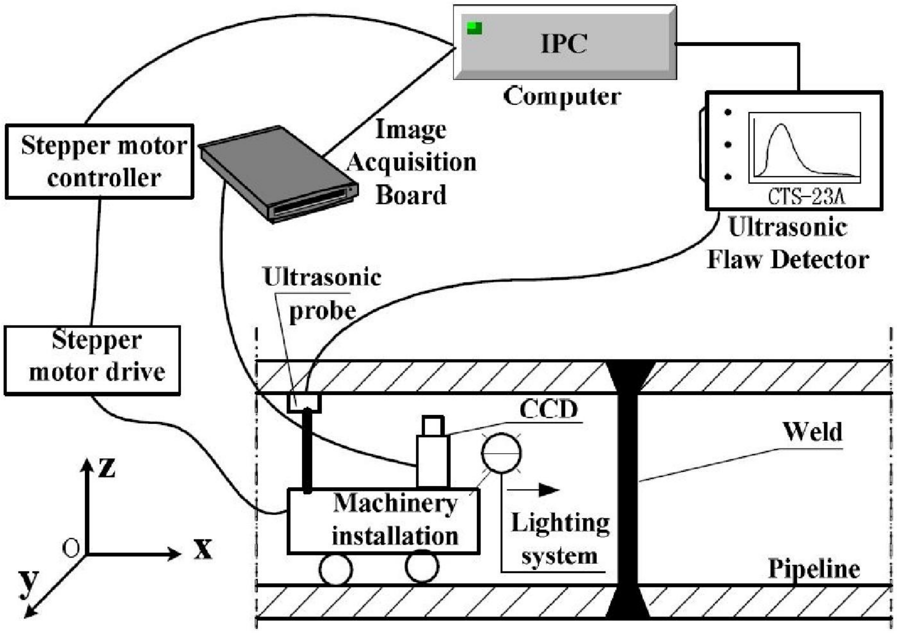


Figure 47 Visual inspection system [215]

In this system, as can be observed from the figure, machinery installation move the ultrasonic probe, lighting and camera into the pipeline, and CCD camera take the scene inside pipeline, then the taken images are sent to the computer. Next step is to analysis the weld image and processing. The images converted by the A/D of image board into computer memory. Further, these images processed by using variety of image processing methods available. Image processing requirements of a short time, can accurately extract weld information and accurately detect the location of weld, realize real-time automatic detection of weld [215].

In automatic GMAW welding, due to the nonlinear and multivariable feature of arc welding processes, intelligent control systems for modeling and controlling the welding process is needed especially in welding of pipes which is more difficult than plate welding. In the study [216] machine vision were used as sensor to monitor the welding pool image during GMAW process. The main reason of designing such system was to reduce welding process complexity and process time. The pipe welding system and the schematic of welding manipulator used in the study is shown in Figure 48 [216]. Different part of system, such as circumferential welding manipulator, CCD camera, the personal computer, GMAW machine, microcontroller and motor board are named in this figure. The task of motor board is to control stepper motor which is used for the revolution. CCD camera captures the molten pool images. These captured images are determined by image processing algorithm.

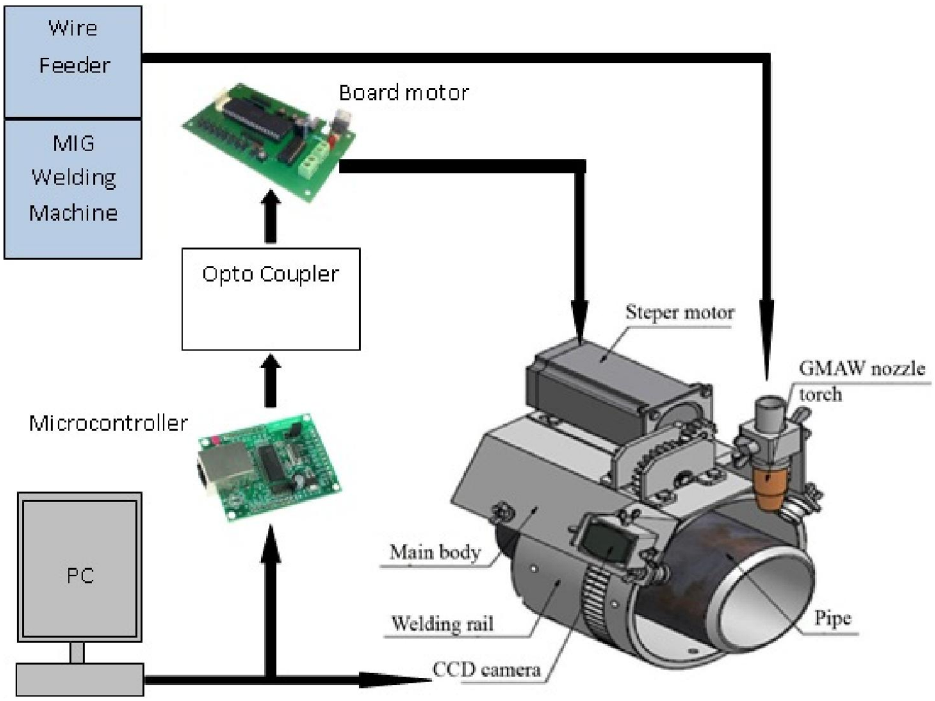


Figure 48 Schematic of welding system and manipulator [216]

Mild steel pipe with diameter of 101.6 mm and thickness of 8 mm and a ‘DC’ type GMAW machine with CO_2 shielding gas were used for the mentioned system and experimental study. The results of this experimental study shows that the error from image processing algorithm for detecting weld bead width id 0.1 mm with standard deviation of 1.3 mm. Also, the error from neural network simulation to detect weld bead width is zero with standard deviation of 0.4 mm [216].

In the most of studies have done, observing weld pool was with a top-side view. As an instance, in the studies [217, 218] control of the weld pool width in pulsed GMAW were studied by using vision sensor to measure weld pool during the base current period of the pulse. Further, [219] investigate the relationship between the observed bead width and the penetration depth in GMAW process. To eliminate the limitation of having information on penetration through the joints, some efforts have been done to give a front view of the weld pool [220].

Seam tracking of root welding is one of the key factors in improving productivity. In the study [199], this has been done on root pass welding of steel pipe in such situation that pipe is rotating and welding head is fixed. The system consists of visual sensing system composed of a CCD camera, lenses and filters, a frame grabber and image processing algorithms as well as five-axis pipe welding manipulator with its controller, the hardware logic for detecting the short-circuit and the visual sensing system.

Figure 49 (a) illustrates the way that seam tracking process of this system works [199]. As can be seen from the figure, the image needs to have the shadow of the wire indicating current position of the torch, and the center of the weld pool presenting the center of groove. First, to make finding of the center of groove possible, it is needed to identify the left and right boundary of weld pool. From the mid column between the left extreme column and the groove center to the mid one between the groove center and the right extreme column, the gray level of each pixel located between a pool start pixel and the pool center in the vertical direction for each column were then added. Afterwards, the differentiation for the summation along the horizontal direction was carried out to obtain minimal and maximal values, and their column positions, respectively. As a result, the center of the torch could be then determined to be located at the center of the two columns. An offset of the welding wire from the center of a groove makes shapes of the weld pool at both sides around the wire to be of asymmetry.

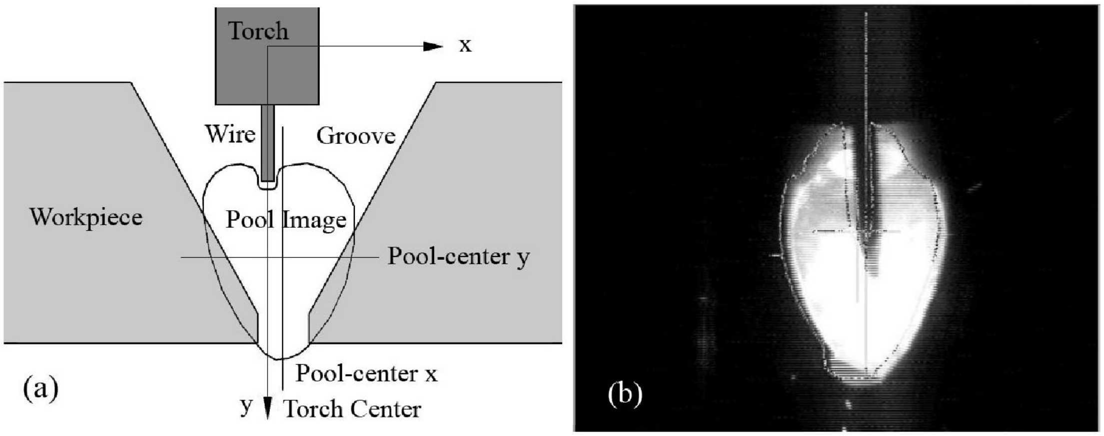


Figure 49 (a) Features extraction in weld pool image, (b) weld pool image [199]

Figure 49 (b) depicts a captured image of the weld pool during welding by CCD camera, offering clearly the boundary between the weld pool and the background and also the shadow image of the wire. Finally, in the study, the result of experimental welding with and without controlling of the weld pool is presented by Figure 50 (a) and (b), respectively [199].

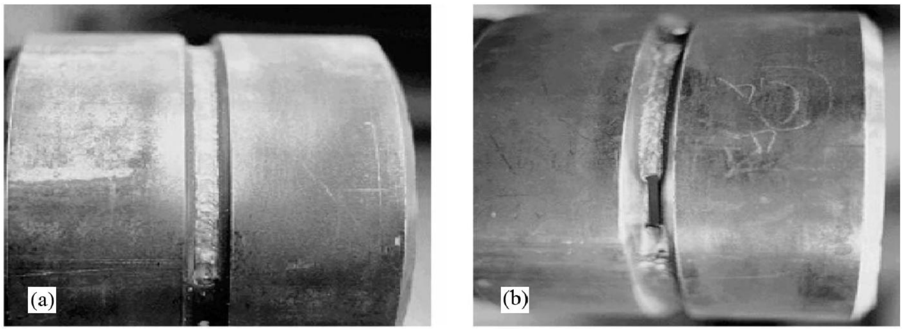


Figure 50 Result of weld pool control: (a) with control; (b) without control [199]

The GTAW system like GMAW is a highly nonlinear and multivariable welding process. Figure 51 shows an outline of the circumferential GTA welding of a pipe [9, 221].

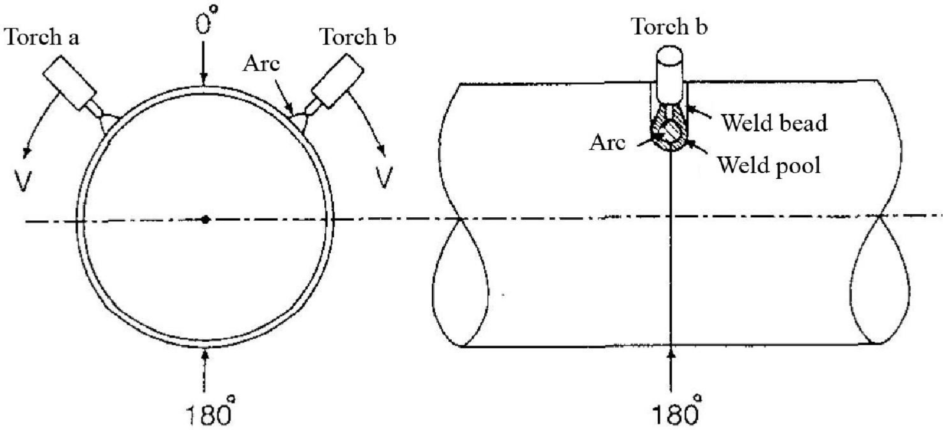


Figure 51 Outline of circumferential GTA welding of steel pipe [221]

In the study [222], a vision sensor used to take images from the welding joint and a universal approach were described for the implementation of a robust algorithm to analysis those images. This system can be used in commonly used welding processes, like GTAW. The approach permits real-time geometrical measurements of the upper surface or "weld face" molten weld pool width. Figure 52 illustrates an example of simplified arrangement of a vision sensor for orbital pipe GTA welding [222].

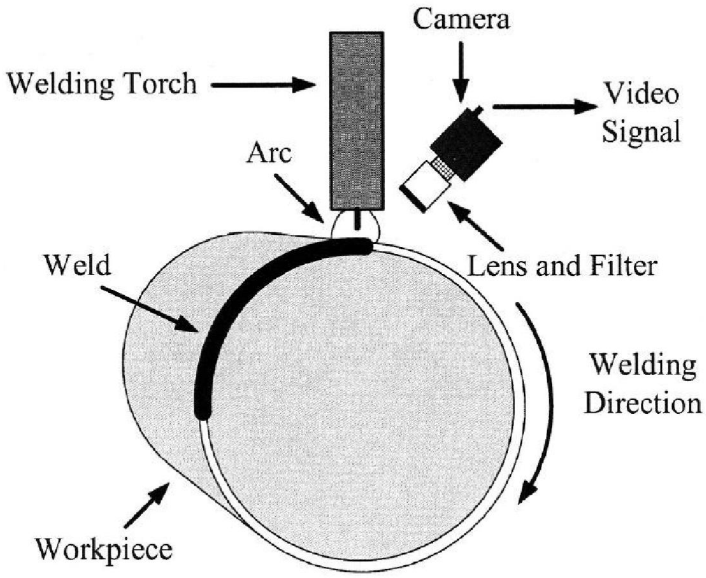


Figure 52 A simplified orbital welding arrangement [222]

Figure 53 shows the real-time pulsed GTAW control system for the automatic orbital pipe welding used in the research [9]. As shown in the figure, this system consists of a welding power source, welding machine and equipments, a personal computer, a visual feedback module with a CCD camera, and a pulse function generator circuit. The pipe material used for this research was a 304 stainless steel. The width of the root pass on the inner surface of the pipe is measured by the CCD camera, and the desired one was 3.5 mm. The width information is then used for closed-loop control of fuzzy pulsed current controller. The diameter of pipe in this experimental work was 210 mm, with welding travelling speed of 90 mm/min.

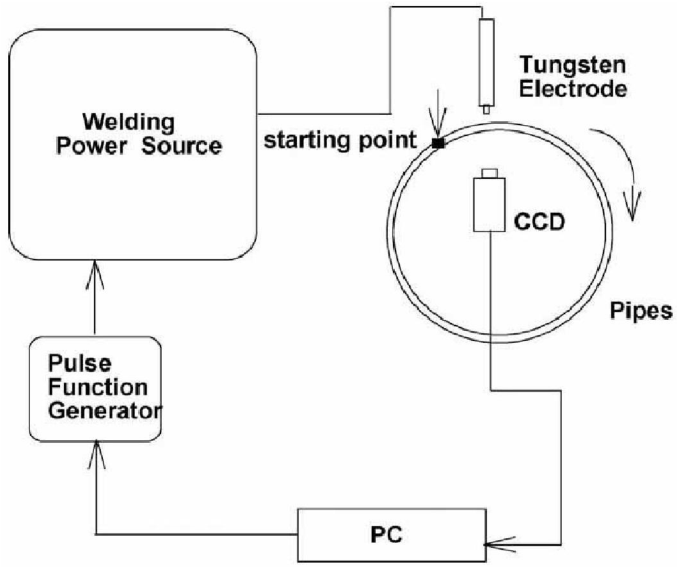


Figure 53 Process diagram of an automatic orbital GTA welding of pipes with CCD [9]

Figure 54 shows the result of welding. As can be observed, the heat input energy in full penetration of the pipe welding, can obtain the sufficient width of root pass, but improbably to melt more height of root pass.

Figure 54 Result of welding pool for pipes (front face) [9]

The following figures show the welding result in different position of 12, 3, 6, and 9 O'clock. At the first location (12 O'clock) as shown in Figure 55, the feature of welding pool is similar to the welding of flat plates, and the welding ripple is smooth. It mentioned by author that the width of root pass kept about 3.5 mm by fuzzy controller and the affection of heat accumulation has not formed [9].

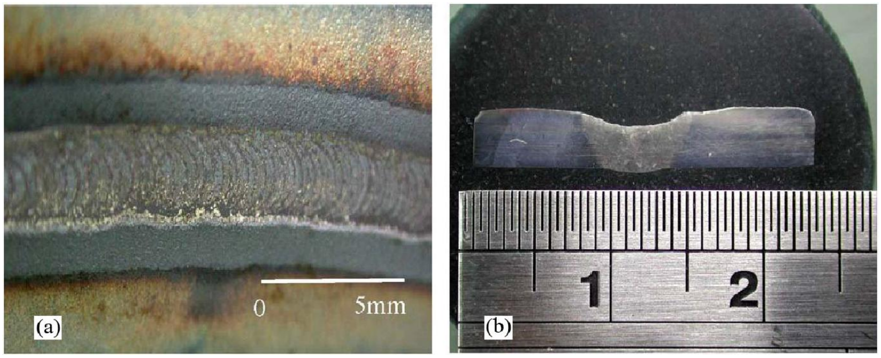


Figure 55 (a) Macrograph of a grooved weld at 12 O'clock location. (b) Fusion zone section at 12 O'clock [9]

At 3 O'clock location, as Figure 56 shows result of this location, again author claimed that fuzzy controller could keep the width of root pass about 3.5 mm. In this location the force of gravity influences more on the welding bead drops flow in the front direction of the welding torch due to downward (descendant vertical) welding position. This situation will increase the thick of welding torch. GTAW system must increase the electric current to melt the welding torch completely [9].

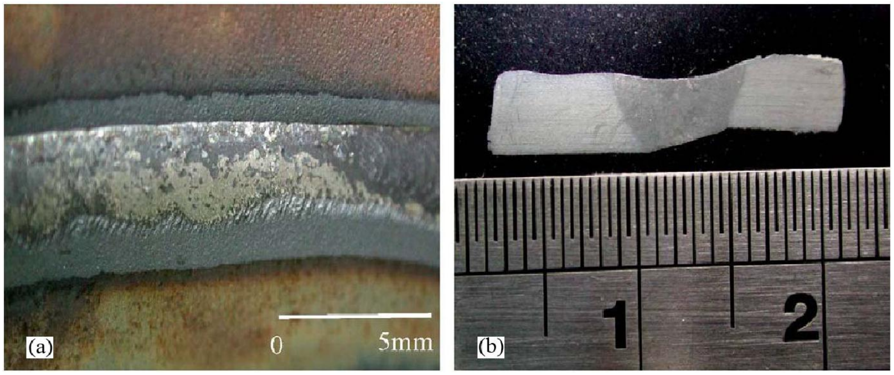


Figure 56 (a) Macrograph of a grooved weld at 3 O'clock location (downward). (b) Fusion zone section at 3 O'clock [9]

At 6 O'clock location, as Figure 57 shows result of this location, the welding position is overhead. Factors affected the forming of welding bead are: gravity, electric arc shock power, and surface tension. Again, in this position author claimed that the fuzzy controller of his GTAW experimental work could control and keep the width of root pass about 3.5 mm [9].

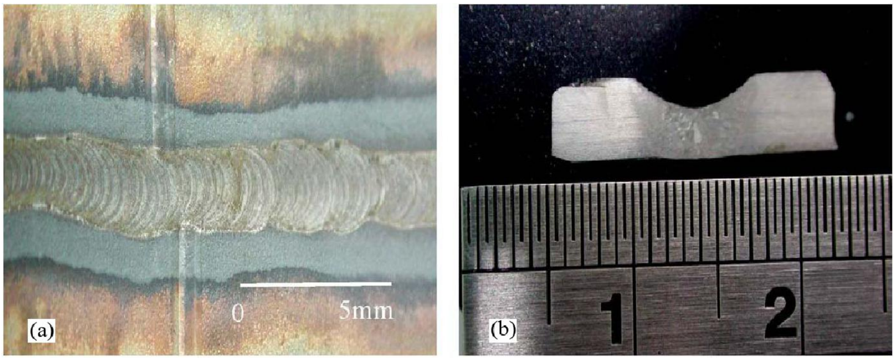


Figure 57 (a) Macrograph of a grooved weld at 6 O'clock location (overhead position). (b) Fusion zone section at 6 O'clock [9]

Finally, at 9 O'clock position, as result of this location shown in Figure 58, the welding position is upward (ascendant vertical). Same as 6 O'clock location, the welding bead formation is affected by gravity, electric arc shock, and surface tension. The welding bead formed will flow in the back direction of welding torch. To keep the stability of welding system in this location, electric current needs to be reduced by controller. Again, fuzzy controller shows good control in keeping the width of root pass constant. As a conclusion for this study, it can be said that authors by their experimental results showed that the fuzzy control technique for GTAW system is a useful and efficient way to obtain weld with good quality in various positions and conditions [9].

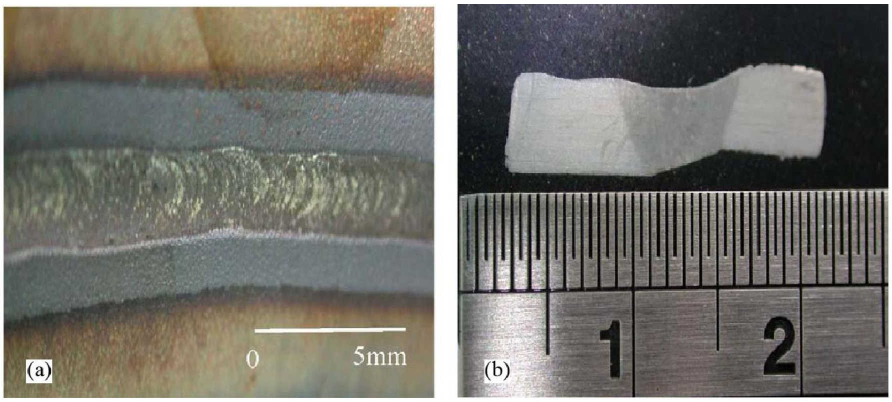


Figure 58 (a) Macrograph of a grooved weld at 9 O'clock location (upward). (b) Fusion zone section at 9 O'clock [9]

7. Weld Quality Test and Control

Higher weld quality is obtained with modern orbital welding system compared to the manual welding. The reason is that, the equipment of orbital system is designed for real-time monitoring of the affecting weld parameters [223]. To have an ideal welding result with orbital welding system, all the equipments and operators should be certified. Also, each weld should be tested and certified to the desired standard level [51]. In pipe welding, the following factors affect the welding joints result and should be considered [128]:

- Tube material, dimensions, and welding consumables
- Machines, equipment, appliances, tools
- Work preparation, welding parameter
- Pipe welder, working conditions, supervision
- Climate and environmental conditions
- Knowledge, experience

For quality test [128]:

- Inspection, examination of the surface
- Test welds (destructive testing)
- Ultrasonic examination and radiation tests
- Pressure tests with water or air

After or during welding procedure, there are possibilities of some defects on the weld, such as intergranular stress corrosion cracking, brittle fracture [15, 34]. One of the significant defects in pipe welding is deformation and residual stresses in welded structures due to a non-uniform temperature field. This non-uniformity of the pipe section is called ‘‘ovality’’ and is shown in Figure 59 [10].

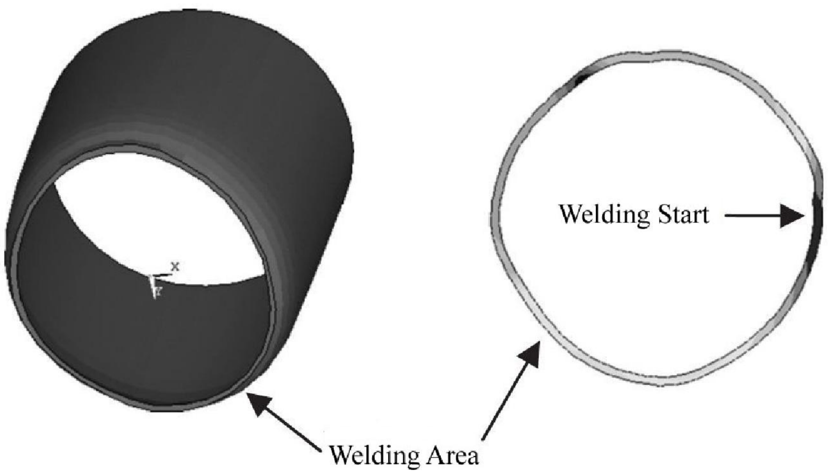


Figure 59 Ovality after welding [10]

Several factors influence the extent of deformations and residual stresses in the welded joints, such as geometrical size, welding parameters (like heat input), welding sequence and applied structural boundary conditions. Residual stresses can be determined, for example, using the so called ring-core as well as radiographic procedures. Several techniques are used to predict residual stresses, including stress-relaxation [82], X-ray diffraction [224, 225], ultrasonic [226] and cracking [10, 82, 100, 227].

When the weld is completed, the outside and inside of the pipe should be clean by welder and any burrs or sharp edges should be removed. In the study [228] a flow chart for orbital pipe welding/inspection/documentation of stainless steel welds is presented which can be used also for orbital pipe welding of other materials. This flow chart is shown in Figure 60.

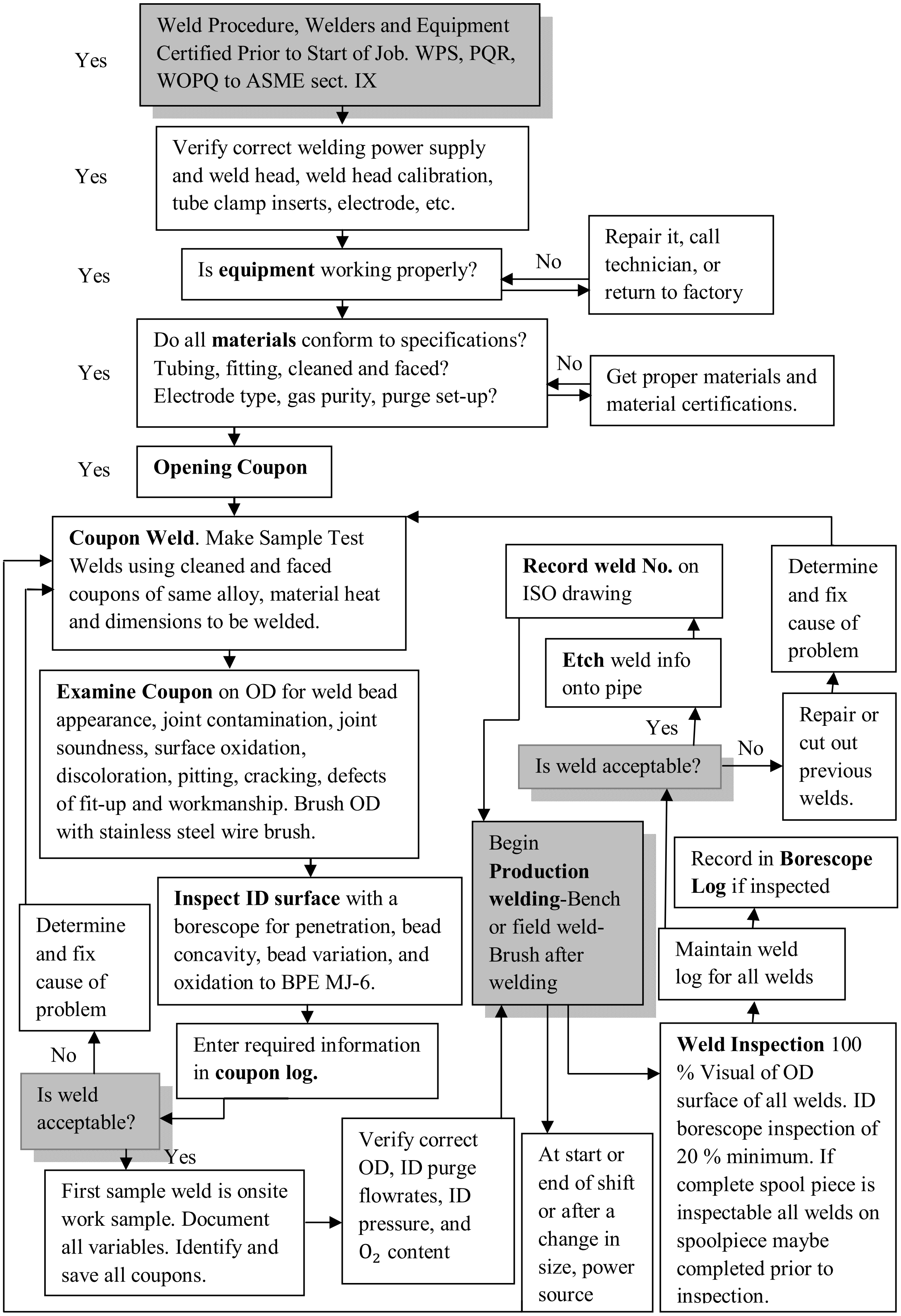


Figure 60 Flow chart for orbital welding/inspection/documentation of welds [228]

8. Investments and Economies in Orbital Pipe Welding

Two main aspects of pipeline welding have the most effect on economics of pipeline construction. They are root pass and fill pass welding. The speed of root pass welding is a key for cost reduction in pipeline application and it means the higher welding speed, the bigger saving of cost. Reducing the time for the root pass ultimately reduces right-of-way time and therefore cost. Fill pass welding deposition manages the number of welding stations required to maintain pace with the root pass [12, 16, 149].

In the study [3], it is reported that, orbital welding system can do the work of at least two skilled manual welders. From the study it can be concluded that, $71,000 can be saved per year by using just one orbital welding system plus advantages involved with using orbital welding system, such as weld quality, lower scrap rates, reduced skill level risks and so on.

9. Future Studies

Research and development activities for future applications, especially regarding metals which so far cannot be welded with current welding processes is going on [229]. This forces welding systems to be advanced. Advanced orbital pipe welding system consists of welding processes and sensing systems which together make the welding process adaptive. Adaptive orbital welding systems should not only have the ability to quickly be adapted due to new demands, but they are also expected to efficiently change and reconfigure their facilities and even location [230]. The future of adaptive orbital pipe welding is gained by more inventions on faster welding process as well as faster sensing system with cheaper mechanism. Downhill GMAW seems to be the process of choice for the next few years. Hybrid laser arc welding and FCAW are two processes required more investigations and attentions to obtain higher productivity. Also, use of multi-torch and welding heads with different processes at the same time can reduce the welding cycle time and consequently, more economical benefits will be obtained.

10. Summary and Conclusions

Stationary and orbital pipe welding were mentioned in this research work as two main mechanized welding systems in pipe welding applications. In the stationary pipe welding system, welding head has a fixed position while the pipe rotates. Various processes, such as GMAW, SAW and GTAW can be used in stationary pipe welding. SAW was mentioned as one of the main processes used for pipe welding in different applications, such as pressure vessels, marine vessels, pipelines and offshore structures. Using of T-SAW by twin arc mode or multi-wire was referred as a method becoming more popular in longitudinal seam pipe production which leads to higher proficiency.

In orbital pipe welding method, the welding head rotates around a fixed vertical or horizontal pipe. Orbital pipe welding technique could yield in significant reductions in the processing time, skilled welder, and welding costs but improvements in the joint quality. Other advantages involved with this method of welding mentioned in this report are, portability, accessibility, high speed, precision, and cost effectiveness.

Two types of orbital welding systems were explained in this study: closed head and open head orbital welding systems. For welding of tubes, mostly closed head machines are used and in the case of pipe welding with large diameters open head machines are used. There are standard sizes of closed head welding system between 1.6 to 203 mm. Arc length during welding with this system remains fixed and the process needs feeding of wire but controlling of arc voltage is not required. In welding of stainless steels with this system, it should be considered that inside surface of the pipe as well as outside should be protected from oxygen during whole process. Generally, open head systems are used for pipe welding with large diameters and wall thicknesses. Due to the complexity of this welding process, precise controlling of all parameters in welding head requires a state-of-the-art computer.

Properties of pipe used in orbital welding were explained especially in oil and gas applications. It noticed that, the majority of welded steel pipe is produced from coil or plate. Numerous pipe materials can be welded by using orbital pipe welding system, such as 300-series stainless steels (with the exception of the types 303 which contain high sulfur and 303SE which contain selenium), 400-series stainless steels, high strength low alloy steels, titanium and its alloys.

In crude oil transferring, there always has been possibility of corrosion in inner surface of pipe. Crude oil consists of a heterogeneous mixture of hydrocarbons with non-hydrocarbon components which includes alcohols, phenols, sediments, water, salts, sulfur compounds, acid gases, and carbon monoxide. Therefore, high level of safety and trust direct to reduction of cost, highest efficiency, and lowest defects, required in oil and gas pipeline distribution.

On the other hand, increscent demand of oil and gas leads to the requirement of high pressure pipelines. Higher pressures and flow levels, therefore towards using line pipe of larger diameter and/or special material. Therefore, pipes with higher level strength have been produced during ages, such as X70, X80, X100, and X120.

X70 is micro-alloyed steel consists of niobium and vanadium with lower amount of carbon. X80 steel is purer and consists of lower sulfur compared with X70 steel and can be adapted to different welding heat inputs. X80 steel were invented by combining Thermo-mechanical rolling and subsequent accelerated cooling. This leads to higher strength, lower Carbon content and as a result better field weldability rather X70 steel. X100 steel produced by adding molybdenum, copper, and nickel and is processed to plate by combining Thermo-mechanical rolling and modified accelerated cooling. The X120 steel, with yield strength of 827.4 MPa is 50 % stronger than standard gas transmission pipe. It means more and higher gas pressure can be transferred but requiring special welding procedure is its problem.

GTAW and SMAW are still using in root pass welding and semiautomatic/mechanized GMAW and orbital GMAW are added to those processes.

In the welding of root pass with mechanized GMAW system, there is no possibility of using flux cored wire due to the potential for slag entrapment.

Fill pass welding is done after root pass and takes most part of the welding time. Fill pass welding is usually consisted of number of layers and several passes included to each layers. Each pass positioning should be precise and relative to the current state of the weld joint. This requires the sensor to analysis the image of filled joint, especially the points on the joint sidewall where the previous passes are located.

Generally, in mechanized pipe welding, types of groove used in pressure vessels are traditional V, butt, narrow or semi-narrow gap, and fillet profiles. In heavy industrial applications, U and fillet groove are used. In automatic welding of smaller pipes and tubes, a standard V-bevel with a small gap can be used, although J-prep with the pipe ends butted together is the most popular groove types for this welding procedure. Also, girth-butt welds of pipes have been used widely in various applications, such as oil and gas pipelines, steam piping, boiling water reactor piping systems, etc.

It noted that, possible gap in orbital welding is 10 % of wall thickness but this number is risky and gap less than 5 % is preferred. Wall thickness variation has the same story which it can be 25 % of wall thickness but to minimize the risk of weak weld quality and repeatability this number is mentioned ±5 % of nominal wall thickness.

In this master's thesis, adaptive welding were explained as, finding the center of the joint (dynamic joint tracking) and also, automatic controlling of the weld power, wire feed, rotation (travel speed), pulse time, oscillation width, torch motion and position, etc. This helps simplify operation and produce a high quality weld. It can be done by, weld pool geometry sensing, modeling and intelligent control of the weld quality and process monitoring. Today, multi laser vision sensors, thermal scanning, image processing, neural network model, machine vision, or optical sensing are used in various fully automatic orbital welding system to improve performance and reliability. Adaptive control of the orbital welding process must be performed during the fill pass and not root pass welding.

The most used welding processes for orbital pipe welding (GTAW, FCAW, GMAW, and HLAW) were explained in this study and as conclusion it can be mentioned that: GTAW, STT, short circuit, modified short arc GMAW are the most useful processes used in welding of root pass. Mainly, for fill pass welding mostly GMAW method is used.

Orbital GTAW process mostly is applied for applications ranging from single run welding of thin walled stainless pipes to multi run welding of thick walled pipes. Even welding of narrow-gap can be done due to its precise control of heat input, repeatability of welding procedures, ability of equipment for using “on site”, higher operator productivity and duty cycle, consistent weld quality and so on. Argon is the most commonly used shield gas in GTAW process. In welding of stainless steels, nickel copper and nickel based alloys mixture of argon/helium typically used. Mixtures of 95 % argon and 5 % hydrogen are incompatible with carbon steels and some exotic alloys and can cause hydrogen embrittlement in the weld. In orbital GTAW systems, the most typical used tungsten electrode materials are 2 % thoriated tungsten and 2 % ceriated tungsten.

FCAW was invented to eliminate long time consumption due to the low speed of GTAW process on pipe welding. Also, FCAW compensates the greater volume of weld metal by higher deposition rate on the standard bevel. Automated FCAW is faster process compared to SMAW and can meet the same quality standards as SMAW, SAW, and in most cases, GTAW.

DT-GMAW technique is currently considered the most efficient method in welding of fill and cap passes. Modified short circuit GMAW process is a special design for the root pass welding (80.3 mm or greater) and can be replaced to the GTAW in many applications. Also, STT process were mentioned three or four times faster than GTAW to complete open root welds in pipe welding applications with better back beads and edge fusion without use of ceramic or copper internal back up bars.

CO_2 lasers are not suitable power source for orbital HLA Welding of pipe due to difficulty of transferring laser beam to the workpiece. On the other hand, high power

Nd:YAG has the possibility of transferring by optical fiber and using in orbital welding of land pipeline applications. Furthermore, diode lasers can be used in pipeline applications. Fiber lasers were claimed to improve pipe welding speed 50 % faster.

Nd:YAG laser power combined with GMAW process has been recently used in welding of 5G position and for girth welding of land pipelines for the oil and gas industry with an acceptable geometric profile of weld bead.

To ensure the quality of weld, precise control of torch angle in the displacement plane during welding process, and precise control of torch position to be in the center of groove are required. In this study, different studies have been done in these cases were reviewed and explained. Laser vision sensor for seam tracking during orbital welding is preferred methods in pipe welding industry especially in noisy environments.

Orbital welding system can carry out the work of at least two skilled manual welders in root and fill pass welding with higher quality and less defects. Also, with orbital system, speed of root pass welding is higher than manual welding and this is the key for cost reduction in pipeline application.

The improvement of orbital welding systems reach to the level that the invention of new welding machine and technology for pipeline applications is risky for constructor. On the other hand, improvement of pipe materials with lower cost, such as X80, X100, and X120 will continue in the future and this forces constructors for using new welding processes and machines. They will have an important part to play in the continuing improvement of the economics of pipeline welding.

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