Welding of pipes – Past, Present and Future

By

John du Plessis, Technology Manager, Southern African Institute of Welding

Abstract

Welding of pipe and pipe lines in Southern Africa and the rest of the world will grow over the next ten to twenty years. The growth in South Africa is driven by the expansion projects for the 2010 world cup, the need for energy and he installation of basic infrastructure.

The progression in the welding technology of pipes during the production of pipes, installation of pipes, and the fabrication and laying of pipelines since the beginning are discussed.

Welding during pipe production is mainly by submerged arc welding for larger diameter pipe and by electrical resistance welding (high frequency) for smaller diameter pipe.

Mechanised gas metal arc welding systems remains the dominant welding technique for the fabrication of large diameter pipelines. Small diameter pipe welding is dominated by manual and mechanized (orbital) gas tungsten arc welding.

The importance and the need for South African fabricators to adopt modern mechanized welding practice, especially with the current shortage of skilled welders are emphasized.

Current research and development into the so called one shot processes are discussed.

Introduction

Welding can be defined as 'the fusion of two surfaces to form one'. Welding is a precise, cost effective method for joining materials. Welding is widely used for the joining of ferrous, non – ferrous metals and other non metallic materials. More than a 100 welding processes are in use which makes welding technology complex, but extremely flexible as a joining solution.

Pipes and tube in various diameters, wall thickness and different materials form part of our daily existence in structures, pipelines and various other areas. Just for a moment, imagine what life would be like, as we know it, without pipes and tubes. Pipe and tubes are manufactured from a large variety of non metallic and metallic materials for a vast range of diverse applications. Each year, millions of tons of steel pipe are produced. Its versatility makes it the most frequently used product produced by the steel industry.

Pipes have been in use for thousands of years. Archaeological evidence suggests that the Chinese used reed pipe for transporting water to desired locations, typically settlements and for agriculture, as early as 2000 B.C. [1]. It has been discovered that clay tubes were used by other ancient civilizations. The first lead pipes were constructed in Europe in the first century A.D. In some tropical countries, bamboo tubes were often used to transport water. Colonial Americans made use of wooden pipes to transport water [2].

Today steel pipes are manufactured either by welding or by the extrusion of seamless pipes. This paper will focus on the welding of steel pipes during the pipe fabrication process as well as the welding of steel pipes for industrial application purposes.

Fabrication of Steel Pipe

Steel pipes are manufactured from a large number of different steel alloys with large variations in strength, ductility and formability. The size or the outer diameter (OD) can vary from a few to a couple of thousand millimetres. Wall thickness varies from less than a millimetre to tens of millimetres. This variety in pipe diameter and wall thickness ensures that there is a steel pipe or tube available for almost all conceivable applications.

Early manufacturing methods for steel pipes

The first production methods for iron pipe were introduced in the early 1800s, and these methods have steadily evolved into the modern processes we know and use today for the production of steel pipe. Initially, pipe was manufactured by hand. This was accomplished by heating plate until it became malleable. The malleable plate was then bent into a circular form with overlapping edges. The hot overlapping edges were hammered until a bond was forged between the overlapping edges. This process is known as forge welding.

In 1824, James Russell patented a method where tubes were created by joining together the opposite edges of a flat iron strip. [2]. The iron strip was first heated. The edges were then folded together by a drop hammer, and forge welded. The pipe was completed by passing it through a groove and rolling mill.

The Russell forge welding pipe manufacturing method was subsequently largely replaced by the butt-weld process developed in 1825 by Cornelius Whitehouse. The butt weld process forms the basis for modern pipe-making procedures. A hot iron plate was drawn through a cone-shaped die (welding bell) which transformed the flat plate into a cylinder. At the same time, the die brought the longitudinal edges of the plate together with sufficient mechanical pressure. The edges are then forge-welded into a butt joint.

In 1832 the first manufacturing plant using this process was opened in Philadelphia in the United States.

Gradually, improvements were made to the original Whitehouse method. One of the most important innovations was introduced by John Moon in 1911. He introduced the continuous process method in which a manufacturing plant could produce pipe in continuous stream. In 1922, a partnership between John Moon and Sam Fretz was formed. At first, only small-diameter pipe was made, but continuing development soon led to a full range of sizes up to 114 mm nominal diameter. This is the largest size that could be efficiently produced. The Fretz – Moon process is essentially a hot pressure welding process. Some pipe welding lines using the Fretz – Moon process are still operational today. [3].

Around 1890, the rotary piercing method for making seamless pipe was perfected. In 1898 a patent was granted to Standard Tool Company, USA, for electric resistance welding of pipe and tube.

Electric flash welded pipe was first successfully manufactured in 1927. In this method the steel sheet is formed into a cylindrical shape. The edges are then heated until they become semi – molten. The steel sheet edges are then forced together until the molten steel is forced out of the joint forming a bead. Today flash welding is no longer used to manufacture pipe commercially.

The next major breakthrough in the manufacturing of steel pipes is the spiral-weld seam process. Coiled sheet steel is cold formed into a helically form. This steel cylinder is welded to form pipe. With this process the length of a pipe produces becomes almost unlimited instead of relying on the length of the forming rolls or plate.

Current welded steel pipe manufacturing processes

Welding processes used for the manufacture of steel pipe falls into two main categories:

- Pressure / Electric resistance welding
- Fusion welding

The most frequently used pressure welding processes include the Fretz – Moon process, DC electric resistance, low frequency electric resistance, high frequency induction and high frequency conduction welding [4]. Fusion welding processes include submerged arc, gas metal arc, gas tungsten arc and combinations of these processes.

Welded pipes are manufactured with either a longitudinal or a spirally welded seam.

These processes are briefly described below.

Pressure / Electric Resistance Welding Processes

Electric resistance welded (ERW) pipe is manufactured by forming steel plate or sheet into a cylindrical shape. Current is passed between the two edges of the steel plate, heating the steel. The hot edges are forced together to form a bond without the use of welding filler material. It is now universally recognized as the most cost effective method of producing quality steel pipe for the available size range. The typical ranges of sizes for ERW pipe are:

- Wall thickness : 0.8mm up to 19mm
- Diameter: 12.7mm up to 660mm

Direct Current Electric Resistance Process

The direct current process was developed for the longitudinal welding of small bore pipe, typically smaller than 30 mm with wall thickness ranging from 0.5 to 2.0 mm [3].

An advantage of direct current welding compared to other resistance welding processes is that it produces minimal reinforcement resulting in a smooth bore. This is extremely important for re-heater and super-heater tubes.

The range of the DC process is limited by the electrical power which can be transmitted via the electrodes. Welding speeds vary between 50 – 100 m per minute.

Low Frequency Alternating Current Process

Alternating current is employed with frequency ranging from 50 to 400 Hz. Pipe forming and the energy for the welding process are supplied by the welding electrodes. Longitudinal welded pipe from 10 to 114 mm in diameter is produced. Welding speeds of up to 90 metre per minute can be achieved depending on the pipe wall thickness.

The low frequency process was used extensively from the 1920's until the 1970's [3]. Over time, however, the welds of low frequency ERW pipe were found to be susceptible to selective seam corrosion, hook cracks, and inadequate bonding of the seams. The low frequency process was therefore superseded by the high frequency ERW process, which produces higher quality welds.

High Frequency Alternating Current Process

The high frequency resistance welding process was introduced in the 1960s. Alternating current with higher frequency, typical 200 to 500 Hz, is used. Unlike the low frequency process, tube forming and the energy input operations are performed by separate units.

The current can be introduced into the open seam pipe either through induction by means of single or multiple coils or through conduction using sliding contacts. A typical manufacturing mill setup is given in Figure 1. [5].

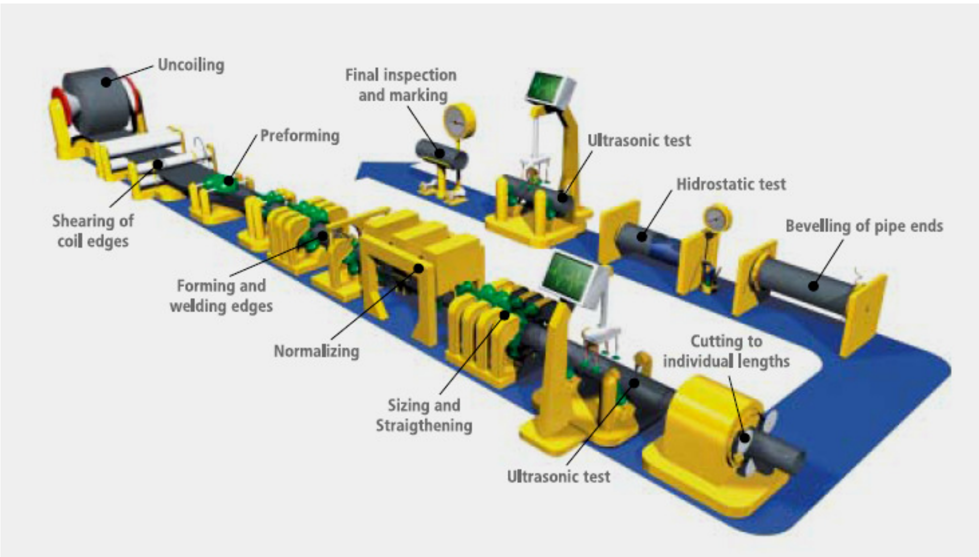

Figure 1. Typical ERW longitudinal pipe forming line

Pipe are produced with outer diameter ranging from 20 to 609 mm and wall thickness ranging from 0.5 to 16 mm. Welding speeds of up to 120 metre per minute can be attained.

Fusion Welding Processes

Fusion welded pipe is predominately manufactured in larger diameters typically in excess of 457.2 mm. A single welding process or combinations of welding processes are commonly used. The most common welding process is submerged arc welding with combinations of gas metal arc welding and submerged arc welding dominating the combined pipe manufacturing processes.

Submerged arc welding

Submerged arc welding is commonly employed to produce pipe. A number of variations on the basic process exist, mainly related to the number of welding wires used, welding heads and power supply characteristics. The welding process can be performed using either alternating current, direct current or in multi-wire systems combination of alternating and direct current.

Double Submerged Arc Welded (DSAW) Pipe

Double submerged arc welded pipe is welded pipe where the longitudinal butt joint is welded in at least two passes, one of which is on the inside of the pipe [3]. The steel plates are first formed into cylindrical shapes. The edges of the rolled plate are formed so that V-shaped grooves are formed on the interior and exterior surfaces at the location of the seam. The pipe seam is then welded on the interior and exterior surfaces. Some pipes have two longitudinal seams 180° apart. A typical manufacturing mill setup is given in Figure 2. [5]

Two different processes are used to manufacture DSAW pipe;

- The pyramid rolls method
- The U-0-E method

The main difference between the processes is found only in the method of forming the plate into a cylinder. In the pyramid rolls process, the plate is formed into a cylinder between 3 rolls arranged in a pyramidal fashion. As the name implies, the U-O-E method firstly uses a "U" press, and then an "O" press for forming, and finally “E”, where expansion of the pipe takes place. Other parts of the process, such as finishing and inspection, are similar [4]. Both processes use flat steel plate as starting raw material.

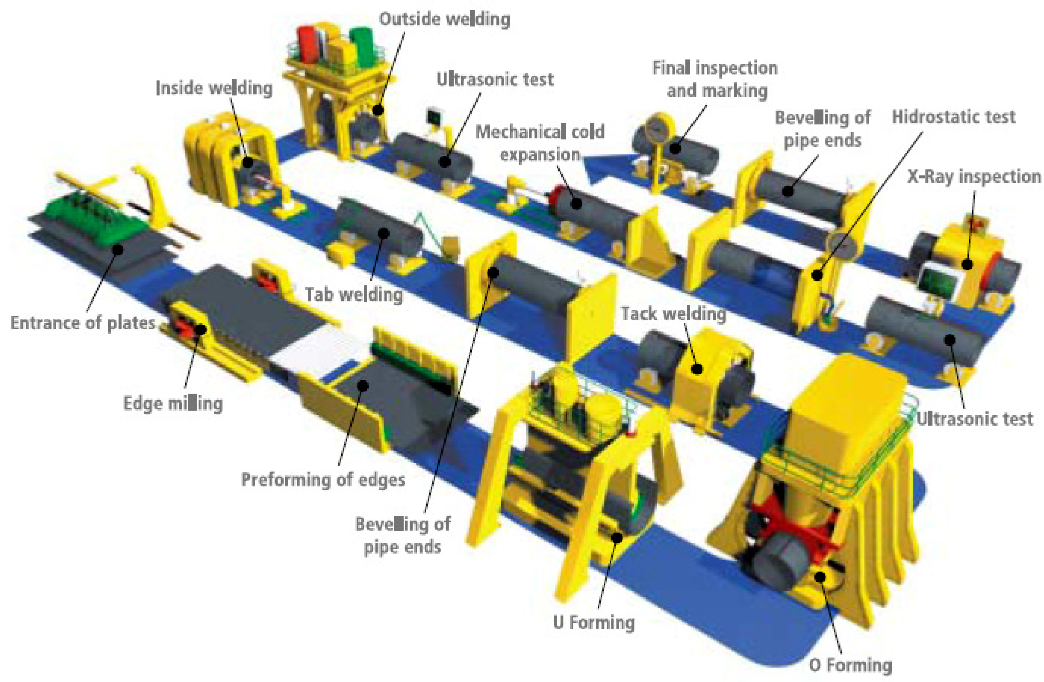

Figure 2. Typical SAW longitudinal U-O-E forming of steel pipes.

After forming, submerged arc welding is performed with either alternating or direct current. Single wire or multi wire systems (up to 5 wires) are commonly used. Welding speeds vary from 1 to 3 metre per minute with wall thicknesses of 20mm. Typically wall thickness ranges from 3 mm to 25 mm (governed by steel makers hot roll strip coil capacity).

Spiral welded pipe

Spiral welded pipe, as the name implies, is steel pipe with a seam running the entire length in a spiral form.

Spiral welded steel pipe is manufactured from coils of rolled steel. An automated mill unrolls the spool and forms the steel strip into a tube with a helical seam which is then welded internally and externally by submerged arc welding. The process is illustrated in Figures 3 and 4. [5].

This method of manufacture of steel pipe lends itself to the production of a wide variety of pipe outer diameters. The dimensional stability of the process is excellent with small variation, particularly with regards to pipe ovality. The pipe, due to its axial symmetry, has an inherent straightness. The length range is infinite as the process produces continuous pipe which can be cut to any length.

The pipe length is controlled only by the economics of transportation. The angle between the flat steel strip being fed into the machine and manufactured pipe leaving the machine, controls the pipe diameter in ratio to the strip width and the angle of the weld in the pipe.

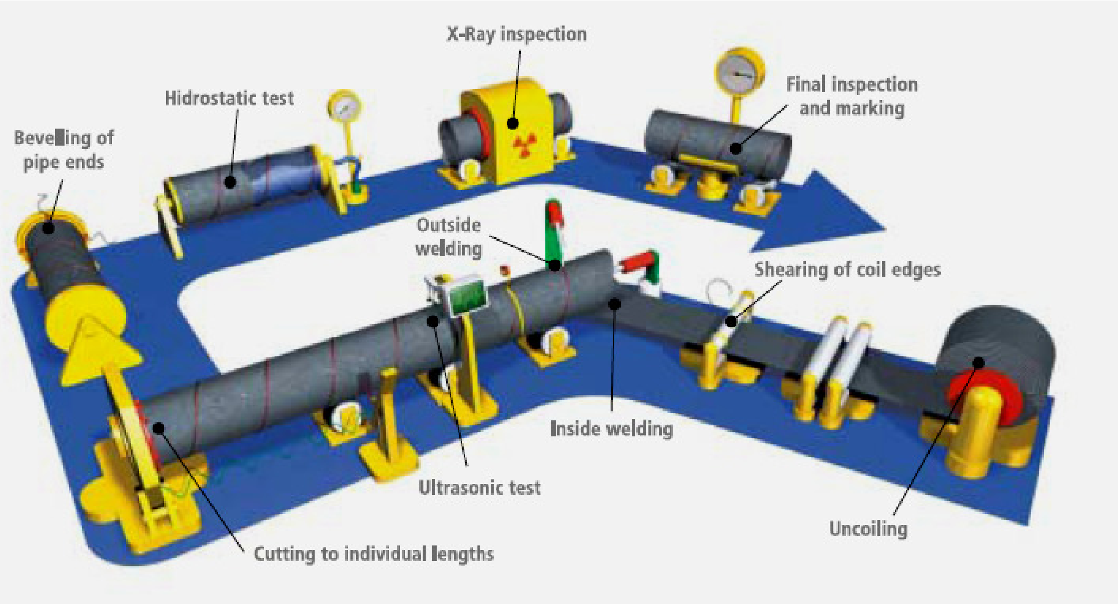

Figure 3. Typical SAW spiral continuous forming pipe line.

Pipe sizes ranges from 500 mm up to 2500 mm with wall thickness up to 25 mm.

Figure 4. Typical SAW spiral welding station

Future of steel pipe production

With the ever increasing changes and demands for higher strength, high quality pipe, the focus in future must be on product design technology to realize high strength, toughness, improved corrosion resistance and functionality; and on manufacturing technology to improve efficiency and quality.

Some of the drivers for future development in steel pipe production are:

- Increasingly higher strength and lighter wall thickness pipes.
- Steel composite pipes for aggressive environments
- Improved tacking systems in the pipe manufacturing process.
- Improved laser tracking systems during manufacture.
- More multi-wire welding stations for increased productivity.
- The increased use of hybrid welding processes including combinations of laser, plasma arc, gas metal arc and submerged arc welding.
- Replacement of submerged arc welding systems with software controlled inverter welding systems with compete manipulation of the waveform and electronic phasing for improved weld penetration control, less arc deflection and higher productivity.

The next section focuses on the processes used to join sections of pipe in industry.

Welding of pipe

Introduction

Pipe joining is one of the most critical yet inefficient processes in the construction industry. Pipes and pipelines have to satisfy increasingly stringent requirements, including higher service pressures, sour products, new high strength steels, more severe operating environments, tighter governing codes, and a host of environmental concerns.

Welding is the simplest and easiest way to join sections of pipe. The need for complicated joint designs and special threading equipment is eliminated. Welded pipe has reduced flow restrictions compared to mechanical connections and the overall installation costs are less.

Joining of steel pipes in the early days

The need to join pipe and line pipe existed since the first pipes were manufactured. The joining of iron and steel pipe initially was by means of mechanical joints and fasteners. Most small diameter pipe, even today, is joined by mechanical threading.

The first successful oil pipeline was built in 1863 from cast iron pipes. The pipes were hammered and screw coupled since welding had not been invented yet. The Dresser coupling was invented in 1891. It was the first time a mechanical joint could be assembled without excessive leaking. This joining method was extensively used for pipelines until the 1930’s when it was surpassed by welding.

In 1910 Chares Hyde issued a patent for joining steel / iron tubes using a copper ring as an insert between the two pipes to be joined. The pipes and the copper ring insert are joined by brazing. In 1911 Oxy-acetylene welding was successfully used for the joining of line pipe. The most common way to weld small diameter steel pipe was by shielded metal arc welding, oxyfuel gas welding and brazing.

In the early 1930’s gas tungsten arc welding was invented. The gas tungsten arc welding process is ideal for thin walled small diameter pipe and tube. The weld is of a high quality, and the joint can be made either by adding filler metal or autogenously.

Large diameter pipelines were mainly welded using shielded metal arc welding. Welding was performed with cellulosic electrodes as consumable. These electrodes allowed for rapid welding vertical down leaving very thin slag on the surface. This process is still used today.

Gas metal arc welding using solid steel wire and shielding gas found limited applications until the 1970’s. Flux cored arc welding was developed in 1950’s [6] and initially found limited application in the welding of pipe.

Current technology for the joining of steel pipes

Small diameter pipe and pipe for non critical applications are still largely joined by mechanical threads and fasteners. Pipe for critical applications is either joined by welding or brazing. Almost all welding processes can be used for pipe welding, however, with the choice of process based on availability, skill level, expediency and economy. Successful high volume commercial pipe welding is dominated by a few selected processes.

Shielded Metal Arc Welding (SMAW) and Gas Tungsten Arc Welding (GTAW) have been in use for years with a history of success in demanding pipe welding applications. Both the SMAW and GTAW processes need a high level of experience and skill to meet the critical requirements as demanded by high pressure and high temperature applications.

Orbital welding is a mechanized version of the GTAW process [7]. In manual GTAW, the welder manipulates the welding torch and controls the welding current. In orbital GTAW, the tungsten electrode is installed in a weld head that clamps on to the pipe. The pipe remains stationary while the welding head revolves around the weld joint circumference to complete the weld. The process is illustrated in Figures 5 and 6.

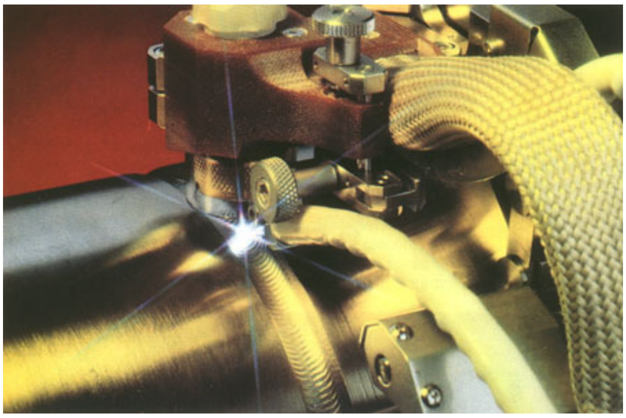

Figure 5. Typical orbital GTAW process

Figure 6. Orbital welding clamp and head

During the welding process the welding parameters are controlled by the power source. The welding parameters include welding current, travel speed, wire feed speed, weld bead overlap, delay of rotation at the start of the weld and current down slope at the end of the weld. A chamber filled with inert gas which encloses the entire joint during the weld is formed by the welding head. Each welding head can accommodate a range of pipe sizes, accomplished by changing the tube clamp inserts to fit the tube diameter on both sides of the head, or with the smaller heads, by changing the clamp assembly.

The ability of the mechanized orbital system to deliver repeatable welding variables, such as welding current, pulse times, and travel speed for fusion welding, as well as the precise control of wire feed speed, torch oscillation across the weld joint, and control of the arc gap for wire feed applications, make it possible to achieve consistency from weld joint to weld joint.

Orbital welding has become the preferred method of joining small diameter tubing in a variety of industries. Orbital welding has become both practical and economical, and in many cases is the only technology by which the necessary quality and productivity can be achieved.

The exponential growth in the use of orbital welding is driven mainly by advantages it can offer in terms of:

- **Productivity.** Being automated, these systems weld quickly. There is no change in speed from the beginning of a shift until the end of a shift.

- **Quality.** The weld quality produced with an orbital welding system and a suitable weld program is superior to that made by other methods.

- **Consistency.** An orbital welding system can produce the same weld hundreds of times without the variability, inconsistencies, errors, and defects associated with manual welding.

- **Traceability.** Orbital welding power supplies can record a real-time data log file of any deviation from set parameters. These data log files can be printed or saved for future retrieval.

- **Skill level**. Qualified welders are increasingly hard to find. A semiskilled welder can operate an orbital welding machine.

As technology advances and equipment and software become more sophisticated, orbital welding will continue to improve in productivity, quality, and consistency

Large diameter pipelines today are mostly welded using shielded metal arc welding, gas metal arc welding and flux cored arc welding. Mechanized systems for welding pipelines have been available for more than 40 years [8]. Mechanized GMAW is currently the most used welding process for joining large diameter pipelines.

The first and limiting step in the welding of pipe is welding of the root pass. This is the critical weld pass on a pipe weld as it is the most difficult weld pass to make. The root pass requires good welder skill, good process control and good alignment. The welding of the root pass limits the progression of welding and laying the pipeline. A major advancement was made by CRC, using an internally mounted clamp with multiple welding heads which achieves speeds of up to 2 metre per minute.

All mechanized systems weld vertical down using a narrow weld preparation. This has the drawback that the pipe ends must be re-bevelled using a bevelling machine which is fairly expensive.

Since the middle 1960's , every major pipe welding conference contained papers on novel and one-shot welding processes like flash butt welding, magnetically impelled arc butt welding (MIAB), laser welding, hybrid laser, homopolar welding and friction stir welding [8]. The holy grail of pipe line welding is the development of a cost efficient one-shot welding process, in which the whole circumference and wall thickness are welded in one pass. A number of these novel welding processes are described in the following paragraphs.

Magnetically Impelled Arc Butt Welding (MIAB)

The magnetically-impelled arc butt welding process (MIAB) is a solid state joining technique that uses arc heating of the components to be joined [9]. The arc is struck between the two pipe surfaces and then rapidly magnetically rotated around the circumference. The arc disrupts the surface oxides and softens the interfacial material without necessarily melting it. The pipes are forced together to forge the joint. Traditionally the technique was restricted to thin-walled pipe. The Paton Institute has developed MIAB machines for welding pipe up to 12 mm wall thickness.

Homopolar pulse welding

Homopolar pulse welding is essentially a resistance forge welding process. A Homopolar generator delivers a single high current DC pulse which essentially provides the energy to heat up and soften the material [10].

A typical weld is illustrated in figure 7.

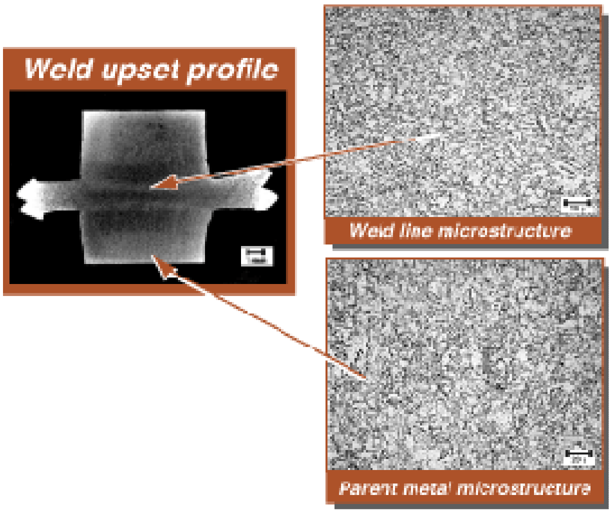

Figure 7. Homopolar weld upset profile

Radial Friction Welding

The Welding Institute (TWI) developed radial friction welding (RFW) for the specific purpose of welding pipe [11,12]. In this method a radial compression ring is rotated between two stationary pipes. Heat is generated, and a weld is created between the ring and the two pipes. Although this technology has been available for some twenty years, the RFW process has not been commercially exploited, partly due to the high equipment cost.

Flash Butt Welding

Flash butt welding (FBW) is a resistance welding process. At the E.O. Paton Electric Welding Institute, Kiev, Ukraine, this process has been improved and used for welding line pipe [9].

Flash butt welding uses a flash to provide enough heat to soften the ends of the pipes to be welded to near-molten temperatures. As the pipes are brought together, small areas come into contact, and through resistance heating, become overheated. These high-temperature areas burst out as tiny bits of molten steel.

The flash is generated by applying electric force to the ends of both pipes. Once pipe ends are hot enough, the joints are forced together to form a weld.

Laser Welding

The potential of laser welding of pipe and pipelines have been investigated by TWI, EWI and Cranfield University. The laser welding process have shown promise in welding the root pass as well as single pass welding of 12 mm thick pipe.

The Vietzs Pipeline laser system uses 20 kW laser connected to the welding head with a special fibre cable [13]. Welding takes place in a hermetically shielded enclosure. The welding process is controlled by integrated sensors. A 16 mm wall thickness 1016 mm OD steel pipe can be welded in less than 3 minutes.

A summary of pipeline applications and welding processes used in the 1980’s, the predicted technologies for 2000 and the current reality in 2007 is given in Table 1 [14].

Application	Past	1980's	Prediction	2007 Reality
Short Pipelines	SMAW	SMAW	SMAW	SMAW, Semi-GMAW
Tie Ins	SMAW	SMAW	SMAW	SMAW, FCAW, Semi-GMAW
Long Pipelines (Small diameter)	SMAW	SMAW, SAW (Pre-Fab)	SMAW, Flash, MIAB, Mechanical Joining	SMAW,GMAW,FCAW,Mech-GMAW,SAW(Pre-Fab)
Long Pipelines (Large diameter)	SMAW	SMAW, SAW (Pre-Fab), Mech GMAW	Mech-GMAW, Hot wire GTAW, Flash	SMAW,GMAW,FCAW,Mech-GMAW,SAW(Pre-Fab)

Table 1. Summary of welding technology.

From Table 1, it is clear that the conventional welding processes are still dominant. The main reasons for this is that few welding processes match the speed of multiwire mechanized gas metal arc welding systems. Some other reasons to consider include that much of pipeline welding today is done in remote areas with inhospitable climates, making use of local labour pools which are relatively unskilled. The required welding equipment must also be rugged, reliable, and durable.

Considering the aforementioned factors, two welding processes emerge as the leading processes: shielded metal arc welding and self shielded flux cored arc welding.

South African Reality

With the continued development in the chemical and energy sector currently experienced, we can deduce that thousands of pipes will have to be joined in the next couple of years. The Vaal Secunda pipeline is in progress and there are a number of other pipeline projects planned in Southern Africa in the near future.

The welding technology employed in welding small bore pipe is mainly GTAW. There is increasing use of orbital GTAW for small bore and tube to tubesheet applications.

For medium to large diameter pipe it is quite common to find SMAW, combinations of GTAW and SMAW, and combinations of GTAW and, GMAW. Few applications of FCAW are found in welding pipe.

The typical welding sequence is using GTAW for the root run. In small bore pipe GTAW would be used for the hot pass and capping runs as well. In medium to larger pipes GTAW would be used for the hot pass. Thereafter, filling and capping would be done either with SMAW or GMAW.

For large diameter pipelines like the Vaal-Secunda pipeline (1.9 metre OD) older technology is still employed. The tacking of the pipes, the root run, the fill and the capping passes are all done using SMAW. The electrode type used is cellulosic, AWS A5.5 E7010 or AWS A5.5 E8010.

No mechanized or semi automated welding processes are used, which is surprisingly considering the shortage of skilled pipe welders. In fact welders from foreign countries are employed on the project. The South African fabricators seem to be hesitant to use more modern mechanized technology despite the fact that it has been successfully implemented in various other parts of the world in the last 25 years.

What does the future hold ?

The future will not get any easier. Pipe material development is moving towards more complex and higher strength materials. Pipelines are now regularly built using X80, X100 and in a few cases X120 type material.

What welding technology can be considered the next big thing ?. We do not really know. Research and development are continuing into ‘one shot’ processes, hybrid welding processes as well as into optimization of existing welding processes.

The high probability developments are the increasing use of dual tandem GMAW technology, Hybrid laser / GMAW technology and friction stir welding of pipe.

In South Africa a move to mechanized systems, i.e. orbital GTAW and mechanized GMAW, will present the biggest single improvement in the efficient use of resources.

References

[1] 'History of steel pipe', Steel Plate Engineering Data, Volume 3, Welded steel pipe, pp 2 - 5.

[2] 'How products are made', Volume 5, Steel pipe history. www.madehow.com

[3] Brensing K.H.,Sommer B., Manessmanrakren Werke GmbH, 'Steel tube and pipe manufacture process', pp 35 -60.

[4] K. Masamura, Y. Nagahama, 'Manufacturing processes and products of steel pipes and tube in JFE Steel'. JFE GIHO Ni.9, August 2005, pp 1- 6

[5] CONFAB line pipe product catalogue, Version 01, 2002, pp 1 - 8.

[6] AWS Welding Handbook, Volume 2, Eight edition, 1995, pp 157 - 190

[7] Henson B.K., 'Practical applications of orbital tube and pipe welding', AMI internal publication

[8] Widgery D.J., 'Mechanised welding of pipelines', Svetssaren No.1, 2005, pp 23 - 26.

[9] Yapp D., Blackman S.A., 'Recent developments in high productivity pipeline welding'. Journal of the Brazilian Society of Mech.Sci. &Eng., Volume XXVI No.1, January – March 2004, pp 89 -98.

[10] Carnes R.W., Hudson R.S, and Nichols S.P., 'Advances in homopolar welding of API linepipe for deepwater applications'. Joining and welding for the Oil and Gas Industry, Proceedings, International Conference, London, UK, 1997.

[11] Blackman S.A, Dorling D.V., 'Technology advancements push pipeline welding technology'. Welding Journal, Volume 79, number 8, August 2000, pp 39 - 44.

[12] Dunkerton S.B, Johansen A., Frich S.; 'Radial friction welding for offshore pipelines. AWS Welding Journal, Volume 66, Number 7, July 1987, p 41

[13] Thomy C, Seefeld T., Vollertsen F., Vietz E. 'Application of fiber laser to pipeline girth welding'. AWS Welding Journal, Volume 85, Number 7, July 2006, pp 30 - 33

[14] Ames N., EWI, Private discussion March 2007