Approach to the hygienic fabrication of process plants subject to health legislation

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DECLARATION

I declare that this report is my own unaided work. It is to be submitted for the Masters of Science in Engineering at the University of the Witwatersrand, Johannesburg. This report has never been submitted before for any degree or examination in any other University.

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Abiola Ladenika

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ABSTRACT

Many products are commercially produced in process plants. Process plants include factory made entities linked by site-welded pipes. However, onsite welding is more difficult to control. Biofilms inside pipe surfaces, particularly on rough surfaces including welds, encourages bacteria growth and microbial influenced corrosion (MIC). Industries producing products intended for human ingestion are subject to increasingly onerous health legislation related to permissible microbial load. Presently, clean-in-place (CIP) methods are used to ensure hygienic products. CIP is limited in actual performance and, also, consumes much water, a scarce commodity. Over time a rise in product contamination due to increased surface roughness results in bacteria build-up and material failures is induced by MIC increases.

This study is aimed at improving onsite welding of pipes, leading to more hygienic welds, thereby reducing or eliminating local biofilm formation. This research describes various forms of pipe end modification accommodating the effect of manufacturing tolerances before clamped Orbital TIG welding. It considers the effects of no pipe-end modification, swaging only and transverse impact of the pipe end then swaging. The weld zones were subsequently examined. The study showed that the weld zone of the impacted then swaged pipes had the best surface topography and morphology results. This should lead to a reduction in bacterial load, the CIP required, and enhance productivity. The pipe-end modification process is easy to implement onsite. The welder should be expected to manage pipe orientation and alignment. Pre welding pipe-end swaging is a practical method to improve weld joint fit-up and, hence, hygiene.

DEDICATION

I would like to dedicate this to my beloved mother, Mrs. Titilayo Ladenika, my wonderful siblings, Debo and Oyin, also my good friend, Tendai Mugurungi who through God, have encouraged and blessed me with prayers and constant support. Thank you for always believing in me.

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1. INTRODUCTION

1.1. Research background and motivation

Urbanisation has become endemic. Technology has made life safer, simpler, and more expedient. What humans consume influences the quality of life. People ingest foods, beverages, drinks, and medicines daily. The human race has grown beyond subsistence living. Foods, pharmaceuticals, and beverages are commercially produced. Many products are produced in process plants.

The 20th-century focus on revenue (profit) has been replaced by the 21st century, triple bottom line approach. This addresses the needs of; people, planet, and profitability. This has led to health authorities enacting ever more stringent legislation requiring lower bacterial (and spore) count in the end products of process plants involved with the production of consumables (A. E. Paterson, 2014).

Industrial plants characterized by products meant for human ingestion must ensure consumer safety. Most plants are fabricated from stainless steels. Both structural integrity and health legislation requirements must be met. Many existing plants built at a different time under less stringent health legislation are also required to comply. The engineering intent is always to meet client needs effectively and efficiently. Compliance, therefore, must be achieved with reduced economical implication (Mamvura et al., 2017; Zottola and Sasahara, 1994).

Clean in Place (CIP) procedures are used to control the hygienic condition of equipment. However, CIP processes require both large volumes of water and the use of strong chemicals at high temperatures (Czechowski and Banner, 1992). The current strain on water resources is significant, especially as private sources of water have reduced, and process plants have to share municipal water, with decreased quality (Ainsworth et al., 2004). Also, the chemicals involved in CIP can be harmful to equipment with repeated use, inducing corrosion in stainless steel (Dominik, 2011; Mosteller and Bishop, 1993; Willcock et al., 2000).

Health challenges are associated with biofilm growth. These bacteria serve as a practical threat to maintaining hygiene in product quality and promote deterioration of plant equipment by releasing microbes from biofilms into the product stream in production lines. This leads to contamination and induces microbiologically influenced corrosion (MIC) in process systems (Busscher et al., 1995; Garrett et al., 2008; Liu et al., 2011; Medilanski et al., 2002; Pagnier et al., 2009).

Biofilms in process plants can also upset the operational heat flow over surfaces, increasing corrosion and frictional resistance to fluid flow. These can lead to efficiency losses in a system and overall deterioration of products. Thus, the number of CIP cleaning cycles required increases, raising costs. Repeated cleaning eventually leads to increased surface roughness and biofilms resisting sanitisation. This allows bacteria to spread across the produce, making the biofilms more resistant to disinfection (Kumar and Anand, 1998; Mizan et al., 2015; Srey et al., 2013; Tarver, 2009).

Most operating equipment in process plants such as tanks, heat exchangers and absorbers are manufactured from austenitic stainless steel as it has excellent resistance to corrosion, good ductility, and its high clean-ability. The equipment is built under a controlled environment and then transported to site for installation (Aneke, 2012; Lucet et al., 1996; Mamvura et al., 2017). The components are connected by austenitic stainless steel pipes onsite. The preferred method of joining pipes in a process plant is by orbital welding. Pipes are generally manufactured to a standard length, which necessitates onsite fabrication, which in reality, is more challenging. Pipe joints are therefore areas with high potential for contamination when inappropriately welded because of the associated discontinuities that may occur, as original material surface characteristics are modified (Ferrara and Nwaoha, 2012; Godwin, 1993). This leads to crevices, rough surfaces or stagnant pools where the product may be retained, serving as a prime locale for biofilms formation, compromising an otherwise hygienically designed plant (Henon and Brond, 2000; Shiozumi et al., 1993). Several factors can lead to surface-breaking defects arising in welds, leading to areas with retained product thereby preventing efficient cleaning. These include (Medilanski et al., 2002):

- Thermal cracks running along the weld metal (caused by either lack of penetration during the welding process or the presence of a wide gap during the joint preparation).
- Excessive inclusions from the welding process may also detach, thereby creating surface porosity which can lead to entrapment of impurities, which is difficult to clean.
- Incorrect penetration during welding may occur if improper parameters are used, ideally the joint and the surface should flush with just the right of weld metal used, however, under-penetration leaves crevices at the weld joint, while over-penetration can impede the product flow in pipework. Both conditions introduce hygiene problems.
- Inadequate inert gas shielding of the inner surface when welds after welding results in a rough heat-affected zone (HAZ), which enhances biofilms attachment to surfaces, thus making it harder to eliminate.

Further research has established that increasing surface roughness in stainless steel enhances bacteria cells ability to bond to the surface, initiating biofilms formation especially in aqueous media or humid environments (Godwin, 1993; Willcock et al., 2000).

Orbital welding is the preferred welding technique to ensure quality hygienic pipe joints of end matched pipes. It is an automated process that offers control over a variety of welding parameters required in fabrication. Therefore, the system is designed to incorporate excellent welding expertise, reducing the possibility for errors or defects in the weld area. However, this technique relies on the consistency and precision with which the pipes are fitted. The pipes have to be well aligned, with clean, square cut ends and a small, consistent weld gap (Mannion, 1999). This technique provides better results, as the programming can account for the pressure of the internal inert shielding gas and gravity. Misalignment however can occur due to several factors, such as incorrect fit-up prior to welding and/or a mismatch in diameters or thickness causing defects. When pipes are not correctly positioned, there is the possibility of cauliflowering and a lack of penetration occurring after welding. A factor affecting pipe alignment is pipe geometry (Godwin, 1993; Mannion, 1999; Raab et al., 2015).

Pipe diameter, thickness and ovality are fabricated within tolerance ranges due to differences in manufacturing procedures. When the research refers to ovality, it means the ‘out of roundness’ of pipes. The researcher realises that out of roundness and ovality are not the same. Whilst pipes are generally ‘out of round’ and the report has used ovality as a convenient description, neither may apply. For instance, an octagon is not round and if measured will not be oval. An oval is a loose description of an ellipse, both implying minor and major axes are at right angles. This limitation does not necessarily apply. The word ovality is used to describe situations where the maximum diameter and the minimum diameter angle measurements differ.

Bowing also plays a role. Bowing occurs due to thermal effects during the production of seam welded pipes. As observed during a visit to FischerSA by the researcher, two forces impact on bowing; residual stresses within the nominally annealed base coil material from the rolling/sheet forming process and from the pipe forming/seam welding process. Prior to pipe forming, edges are normally trimmed at an angle to facilitate an even welding gap. When pipes are formed and seam welded, the seam is initially held in position by forming rollers.

As the pipe moves down the line and cools, the thermal contraction of the HAZ induces stresses in the pipe. The release of forming roll pressure also results in local flattening of the HAZ, possibly contributing to minor axis formation. Whilst these stresses influence pipe bowing, residual stresses in the material also influence bowing. The bow is not necessarily aligned to the seam. Though pipe straightening is used to correct most of the bowing, it also induces residual stresses (which may affect pipe section tolerances), and it may be released during welding. When square cut pipe ends are aligned, using references along the pipe length to distinct pipe end centroids, the setup gap will tend to be affected. This can affect pipe end fit-up for welding. A wide variance in pipe tolerance dimensions affects the matching and alignment of pipe ends (Godwin, 1993; Liu et al., 2011; Mamvura, 2014; Tarver, 2009; Verran, 2005).

The effect of pipe tolerances leads to the question, "How do we manage the fabrication of new plants and maintain the old plants to accommodate the changing legislation and operating conditions?"

The welder has no control over pipe manufacturing tolerances. The welder must take responsibility for alignment. The degree of overlap of the adjoining faces affecting fit-up is a function of pipe orientation and tolerances. However, pipe ends can be reformed by permanently altering the diameter, via swaging of the adjoining surfaces well beyond the material's elastic limit. This will induce plastic deformation while eliminating residual stresses, improving pipe alignment and fit-up to facilitate onsite orbital welding. Swaging is a process used to modify the diameter of pipes. The process involves placing a die that applies a tensile or compressive force to the pipe by expanding or compressing radially. (Mannion, 1999; Samuel et al., 1993; Urband and Garrison, 2003). In the case of this research, pipe end expansion was tested.

The overall aim of this project was to create a procedure for site pre-welding operations to diminish the effect of manufacturing tolerances and achieve a good overlap of pipe ends. Pipe alignment and overlap prior to welding can be optimized by modifying its ends via swaging to achieve tighter tolerances. This is potentially a more effective way of achieving good onsite welded pipe connections. With better weld conditions achieved, better hygienic performance is anticipated. Swaging is inexpensive and could ease operational costs as clean in place procedures will be required less frequently. The strategic choice in business is value driven.

1.2. Research Aim and Objectives

There is a legislated demand for lower and lower bacterial (and spore) counts in consumables by health legislation. Welded joints in pipes, act as the locale for microbial build-up. Welded fabrication of pipes is more difficult to control onsite. The aim of this project was to determine if pipe end reformation results in a better end overlap by mitigating the effect of tolerance differences.

The hypothesis tested if pipe-end plastic deformation will achieve better fit-up between adjoining surfaces prior to tungsten inert gas (TIG) orbital welding resulting in better surface topography, thus inhibiting biofilm build-up.

This hypothesis was tested through the following steps:

- Secure a set of randomly sourced thin-wall stainless steel pipes.
- Measuring the minimum axis, maximum axis, and wall thickness.
- Evaluating the ovality of each end of the individual thin-walled stainless steel pipes.
- Calculate the typical range of deviation from standard manufacturing tolerances.

- Fabricate a swaging tool to achieve ≥ 2.0% plastic deformation.
- Retain a control sample of pipes, and expand the rest under two conditions; with and without impact
- Apply Orbital TIG welding to the different pipe groups using the same parameters.
- Assessing the pipe joints of the three pipe groups to examine the differences in their HAZ’s surface topography and morphology.

1.3. Contribution to knowledge

It is believed that through this research, a better understanding has been established on the effect of pipe end reformation on improving the nature and quality of the weld joint in thin-walled pipes, thus reducing areas prone to biofilm formation. This is expected to aid in reducing the microbial load in the final product of process plants as required by health legislation.

1.4. Layout of research

The thesis consists of five chapters and an Appendix that seeks to provide answers to the aim and objectives set-out to be achieved.

Chapter one provided a basic introduction to the research, the hypothesis tested, and the significance of the work undertaken.

Chapter two reviewed the published literature on process plant design, health legislation guiding the manufacturing of products for human ingestion, biofilm formation, and its composition. The chapter also considered the importance of water and its relationship to the formation of biofilms. Several methods to control biofilms formed on stainless surfaces were reviewed and why swaging was chosen for investigation. It also reviewed welding processes.

Chapter three presented the experimental procedure, the assessment of the pipes, and the pipe grouping selection process. It also covered the pipe end reformation and the tests carried out to determine weld zone quality.

Chapter four focused on the results obtained and provides the analysis of the obtained data in relation to literature.

Chapter five offered the conclusion made from the study as well as recommendations for future work, thereby closing the testing of the hypothesis.

The Appendix listed all the cited references and other appendices.

2. LITERATURE REVIEW

2.1. Process plants manufacture and design

Process plant engineering is a blend of the knowledge of chemistry and the expertise of engineering. The intent is to manufacture on a commercial scale products vital to life. Process plants execute operations from the laboratory bench to the manufacturing facility (Holloway, 2012). The same chemical process can be replicated at different process plants, with varying scaled capacities at each facility. Also, a chemical plant at a location may be utilised to run several chemical processes, with the same equipment to produce multiple products. Process engineering encompasses a vast range of industries, such as chemical, advanced material, agriculture, food, mineral processing, pharmaceuticals and biotechnological industries (Aneke, 2012; Lucet et al., 1996).

2.1.1. Dual Piping Systems of Plants

Process plants commonly include large vessels or sections called units or lines that are interconnected by material moving equipment, mostly pipes, which carry streams of material between process elements. Process plants often utilise a dual piping system with (Schaschke, 2014):

i. A cooling or heating line (hot water or steam); water does not need to be portable. It also includes water used for cleaning of plant.
ii. A portable water stream for material production.

This structure is implemented to prevent a mix of the streams as reclaimed water may not be safe for humans. Material streams can include fluids, sometimes solids or mixtures such as slurries (Schaschke, 2014).

2.1.2. Pipe interconnections between process entities

Process plants operating entities include absorbers, condensers, reactors, tanks, pressure vessels, distillation columns, heat exchangers, reformers, valves, pumps, cooling towers, conveyors, silos, and other stage operation equipment. Operating entities in process plants are usually built under controlled environments which are aseptic, before being transported to site for installation (Aneke, 2012; Ferrara and Nwaoha, 2012; Lucet et al., 1996). These entities are interconnected onsite using pipes (or other transport methods). Pipes are generally not manufactured in the lengths required for practical applications. Pipes need to be fabricated onsite to link manufacturing units and each other. Pipes in process plants are generally small bore, (not accessible from inside) and often thin-walled (having a wall thickness <3% diameter). They are interconnected for transporting materials such as water (liquid and steam), sewage, gaseous and liquid hydrocarbons from sources to local distribution centres. Pipes are crucial for any plant. Great importance is placed on their setup as the precision and efficiency of the plant depends greatly on material transport through pipes to various equipment that function collectively. The nature of the pipe's content determines its material of fabrication. All these factors must be considered for the safety of the plant, its personnel, and the public or consumers of the end-product (Kemp et al., 2016; Mamvura, 2014; Mamvura et al., 2017).

2.2. Health legislation guiding processed foods

Process plants involved in the manufacture of products for human consumption are subjected to increasingly onerous health legislation. The enhanced health legislation has largely emerged post-1990 as part of the triple bottom line environmental response of people, planet and prosperity. Affected sectors include brewing, pharmaceutical, dairy, beverage, and food industries. Hygiene is paramount to ensure product safety and eliminate food contamination. Stringent health legislation restricts acceptable bacterial levels in the final product. Sterilisation is no longer adequate or acceptable, as dead bacterial cells are undesirable in the end product (Cluett et al., 2003; Paterson, 2014; Shi and Zhu, 2009; Stier, 2012). In South Africa, section 15(1) of the Foodstuffs, Cosmetics and Disinfectants Act, 1972 (Act No. 54 of 1972),("Foodstuffs, Cosmetics and Disinfectants Act," 2017) legislates microbial content in processed foods, and has been amended over the years (1998, 2001, 2008, 2011,) to incorporate increasingly stricter regulations on allowable microbial content on a wide range of consumables. International regulations require much stricter limits than South African standards. The European Union's Microbiological Criteria Regulation 2073/2005 (modifications made in 2006, 2014 with an upgrade expected in 2020) establishes the microbiological criteria for micro-organisms, providing rules on food safety criteria and process hygiene criteria. As a trend, International standards serve as a template for South African legislation. Also, for local goods to qualify for export purposes, it is critical that these strenuous limits guide local process plant technology to ensure cleanliness, and limit access of microorganisms in products (Lelieveld, 2005; Maroulis and Saravacos, 2003; Shi and Zhu, 2009).

2.3. Biofilms in process plants

Research has shown that the presence of biofilms in process vessels and pipework limits the ability to reduce the bacterial count in end products (Cluett et al., 2003). Production material residue (which may have been imported and shipped to site), water (which is increasingly drawn from municipal sources and is, whilst potable, of varying quality) together with the production process or surrounding logistics lead to the development of biofilms on equipment surfaces (Cluett et al., 2003; Sauer et al., 2007; Stier, 2012). ‘Biofilms are a well-organised and banding community of microorganisms attached together to a surface with the help of extracellular polymeric substances (EPS) formed by the microbes to develop a single layer or three-dimensional’ (Mamvura et al., 2017).

In ideal situations, microorganisms such as yeast cells and bacteria in the stream feed on organic matter, this can be observed under a scanning electron microscope(SEM) as shown in Figure 2.1. As the microorganisms grow they form colonies which morph into biofilms.

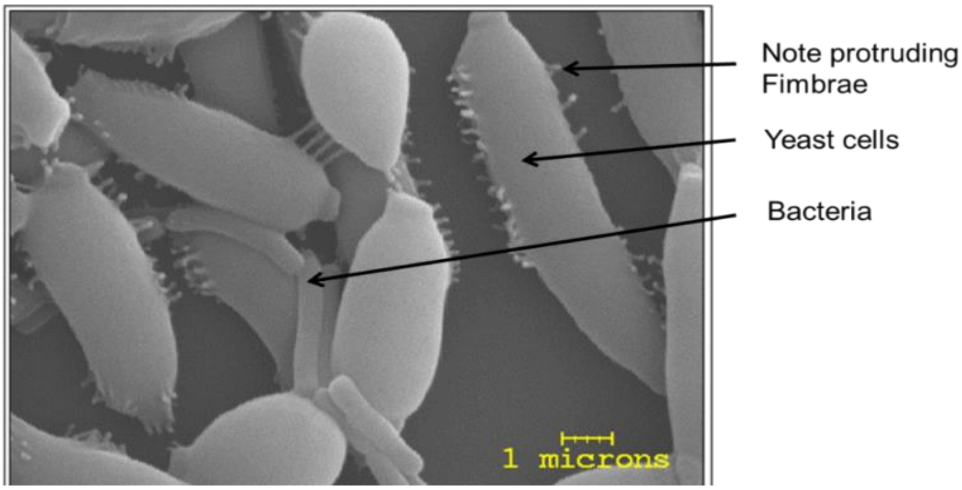

Figure 2.1 SEM of microbes fusing to form biofilm matrix in a dispensing line (Francolini and Donelli, 2010).

To limit the presence of biofilms and eventually eliminate them, it is important to understand how they develop and their effects on the process plant. In Figure 2.2 below, we see the gradual formation of biofilms from microbe deposits.

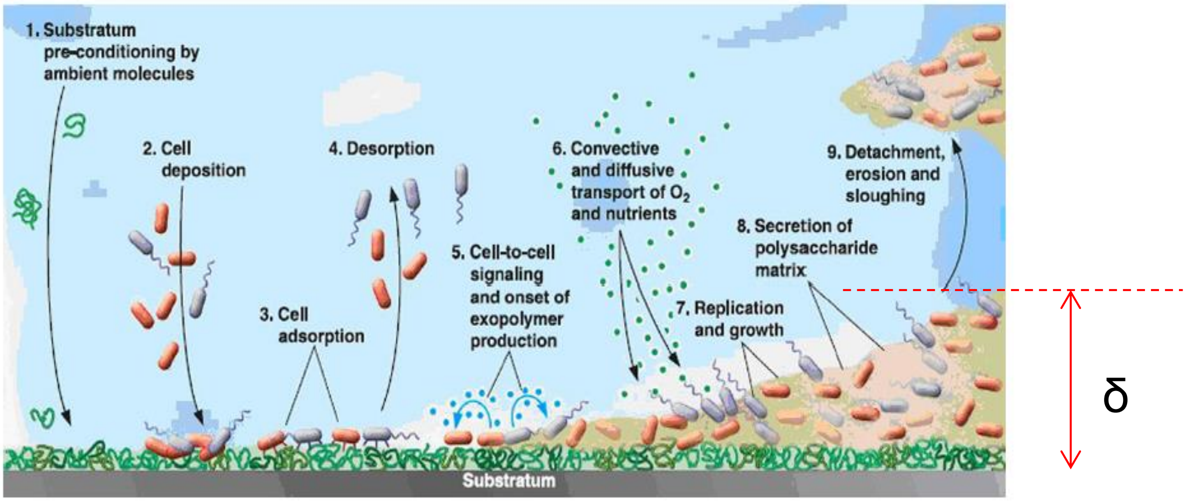

Figure 2.2 Series of events leading to biofilm formation (Francolin and Donnelly, 2010) (Depth δ added by Paterson 2014)

1. Molecules attach to material surface (step 1 in Figure 2.2)
2. Accumulation of microbes creating a layer (steps 2–4 in Figure 2.2)
3. Cells develop hair-like exo-polymers called fimbriae, and absorb organic material (Step 5 in Figure 2.2)
4. Biofilm layer expands and replicates (steps 6–8 in Figure 2.2)
5. Erosion of sections off the expanded biofilm layer (step 9 in Figure 2.2)
6. Eventual accumulation of a large film matrix with depth δ

A combination of increased surface roughness, reduced flow speeds, rising temperature and the presence of obscured areas lead to the depth δ increasing.

This irreversible process can occur within 20 minutes to 4 hours at 4–20°C. Stage 9 of Figure 2.2 shows the gradual degradation, erosion and eventual sloughing of the biofilms leading to contamination of the produce in process plants (Chmielewski and Frank, 2003; Mamvura et al., 2017).

Biofilms can either be formed from single specie or from diverse species held in a matrix material. Single specie biofilms are not as dense or resistant to environmental strain as multiple species biofilms due to the variation in their EPS material (Chmielewski and Frank, 2003; Donlan, 2002).

2.3.1 Bonding forces in biofilms

Bonding in biofilms can be analysed as bacteria cells acting as colloidal particles due to their size range, (about 0.2µm) inferring that reversible adhesion with bacteria can be calculated via colloidal factors (van Loosdrecht et al., 1989). However, the magnitude in which bacteria can be viewed as colloids is reduced since bacteria are capable of growth, metabolism, and independent motion i.e. their biological properties will be a major factor in their active adhesion (Škvarla, 1993).

Depending on the method of attachment, many trends can occur when microorganisms bond with a surface and grow (van Loosdrecht et al., 1989):

i. There is a reversible attachment between the cells and the surface, which leads to an equal distribution between separated and attached cells.
ii. The cells attach just to the surface, but not to individual cells, thus there is just a single layer of cells on the surface.
iii. There is an irreversible attachment of cells to each other and the surface, leading to development of biofilms.

Microorganisms attached to a surface, only achieve temporary equilibrium because additional chemical reactions may take place causing a change in the internal and external molecular structure of the microorganisms; ions and molecules can permeate the interface (cell wall) as microorganisms are regarded as thermodynamically open systems (Škvarla, 1993).

Naturally, microorganisms and surfaces tend to be negatively charged, leading to repulsive electrostatic forces. Initially, the effect of the long-range and short-range forces involved in the reversible attachment of the microbe to the surface, are different. The transport of bacteria to the surface is via long-range forces, however as the bacteria and surface interact, short-range forces play a more important role (Katsikogianni and Missirlis, 2004). Several forces come into play in biofilms adhesion. At distances greater than 10nm, majorly van der Waals forces and long range (DLVO) forces have an effect. However at distances shorter than 10nm, short range DLVO forces dominate. However, at close proximity (<1nm) DLVO theory is no longer effective due to the presence of hydrogen bonding and steric repulsion (Škvarla, 1993; van Loosdrecht et al., 1989).

The interaction between the total interaction Gibbs energy (G_{tot}), electrostatic (G_E), van der Waals (G_A), in relation to the separation distance (H) of a microbe and a solid surface, at various ionic strengths is shown in Figure 2.3.

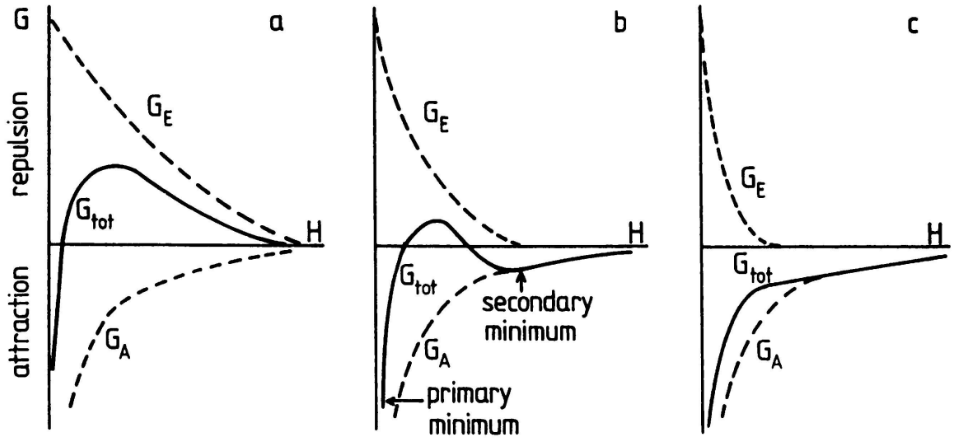

Figure 2.3 Gibbs energy of interaction of an equally charged sphere and a flat plane according to the DLVO theory represented under ionic strengths (a) low (b) intermediate (c) high (van Loosdrecht et al., 1990).

In describing the net interaction of a cell with a surface (G_{tot}), the DLVO theory is used to explain how there is a balance between the van der Waals forces and repulsive forces which are as a result of the solid surface meeting the electrical double layer of the cell. Although the DLVO theory justifies experimentally the observed low attachment of bacteria to surfaces which have a negative charge, it cannot account for the different patterns seen in other kinds of surface adherences or with substantial electrolytes in solution (Katsikogianni and Missirlis, 2004).

Generally for (van Loosdrecht et al., 1989):

a) low ionic strength:

A barrier for adhesion in the primary minimum is created due to $G_{tot}(H)$ having a positive maximum. An increase in ionic strength reduces the maximum $G_{tot}(H)$ as a result of decreasing of repulsion of G_E.

b) At some intermediate values of the ionic strength:

The maximum $G_{tot}(H)$ is low, thus there is the slow development of irreversible attachment as some of the particles contain adequate thermal energy bridging the barrier

c) At a higher ionic strength:

All particles attain the primary minimum resulting in irreversible adhesion.

Generally, reversible bacterial adhesion takes place in the secondary minimum (Busscher et al., 1984). Reversible adhesion infers a non-stop exchange between loose and adhered cells, making it difficult to differentiate their different activities with the exchange rate reducing with increasing adhesion strength. To prevent this exchange between surface and suspended cell populations, irreversible connection between bacteria and surface must occur for biofilms to form (Hermansson and Marshall, 1985).

2.3.2 Effects of Chemical Accumulation on Surfaces

The build-up of nutrients over a surface can lead to biofilm attachment (Garrett et al., 2008). Figure 2.4 shows how the cells can fuse with the material surface.

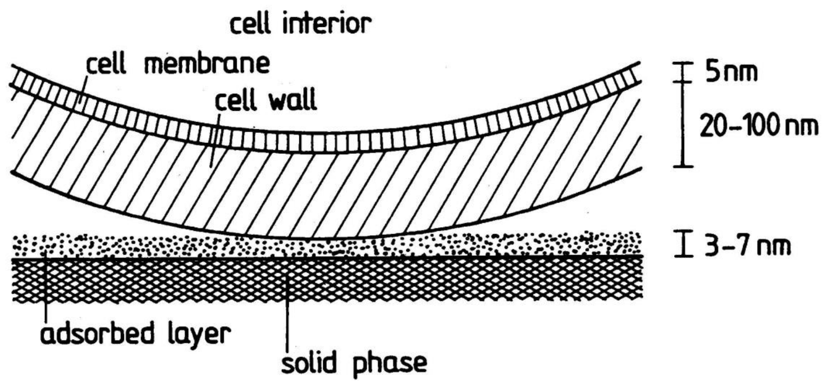

Figure 2.4 The interaction of an adhering cell and a surface at the reversible stage (van Loosdrecht et al., 1990.

Usually, the bacteria cell walls are small with 1–2µm and 20–100 nm diameter and thickness respectively. Only a minute section of the surface directly contacts the absorbed material layer. Thus the nature of the surface impacts adhesion indirectly (van Loosdrecht et al., 1990).

Plants are made up of different materials that fuse at different points. The high surface free energy of a surface affects biofilm attachment. Stainless steel surfaces have high surface free energies and are hydrophilic unlike rubber which is hydrophobic, generally allowing high probability of bacteria attachment. Also for hydrophilic surfaces, there tends to be a uniform attachment of the microorganisms forming a monolayer (Chmielewski and Frank, 2003).

The attachment of microbes to surfaces varies with roughness. As shown in Figure 2.5 an increase in surface roughness average translates to an increase in surface energy thus increasing the probability and strength of the attachment of biofilms to the surface. It is therefore ideal to make surfaces as smooth as possible (Cluett et al., 2003).

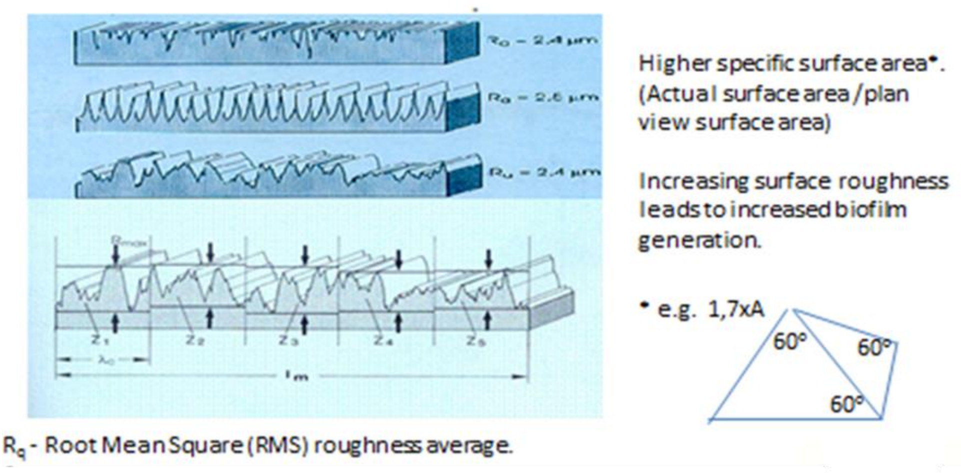

Figure 2.5 Biofilm build up in relation to surface roughness and roughness average (Cluett et al., 2003).

Another effect of biofilms attachment is microbiologically influenced corrosion (MIC). This is as a result of extracellular electron transfer (EET). EET is the electron transfer between microbes and the host solid material. For certain microorganisms, energy is obtained through the transfer of electrons with extracellular solid compounds. Research has also discovered that various microorganisms, such as sulphur reducing bacteria (SRB) , methanogens, acetogens and nitrogen reducing bacteria (NRB) can stimulate iron corrosion via their EET as shown in Figure 2.6 (Kato, 2016; Richter et al., 2012). The presence of these microbes lead to the release of metabolic by-products which damage the underlying surface layer (Sreekumari et al., 2005).

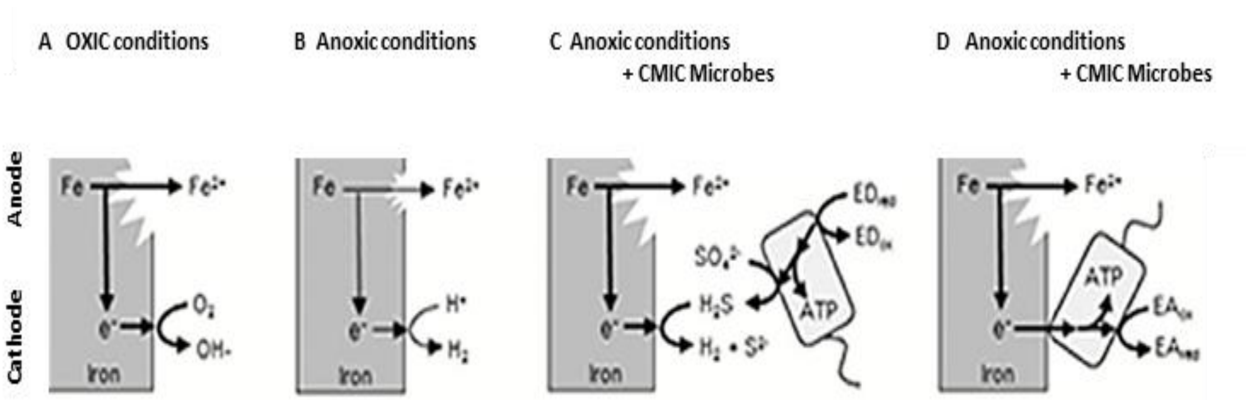

Figure 2.6 A representation of the oxidative dissolution of the iron corrosion mechanisms: from metallic iron into ferrous iron (Kato, 2016).

The following occurs in Figure 2.6 as follows (Kato, 2016):

a. Under oxic conditions:

   The Oxygen reduction process consumes electrons derived from iron oxidation (a cathodic reaction).

b. Under anoxic conditions:

   Hydrogen ion (H^+) is reduced to into hydrogen (H_2). Process is a cathodic reaction with a low corrosion rate.

c. Chemical MIC:

   Iron corrosion is initiated via SRB reducing sulphate into corrosive hydrogen sulphide (H_2S). This is a result of SRB requiring exogenous electron donors such as hydrogen ion to reduce sulphates to gain energy (a cathodic reaction).

d. Microorganisms inducing electrical MIC use electrons directly from the iron thus stimulating iron corrosion.

2.4. The impact of water (major raw material) in the context of biofilm formation.

Water is an essential raw material in almost all processes of consumables production. Also, it is used in the heating, cooling and cleaning of process plants. Process plants such as breweries can require water volumes up to 11 times the beer produced (Feng et al., 2009). Previously sourced from private reserves, due to scarcity, plants now get water from municipal sources. Municipal water, whilst potable, is of inconsistent quality (Braeken et al., 2004). Water shortage has led to an intensified effort on recycling waste water and ensuring that it is useful for agricultural or other industrial purposes.

Water can be classified based on its range of hardness. Water is considered to be soft when there is a low concentration of mono salts such as calcium or magnesium dissolved in it. In the case of hard water, complex salts such as Calcium bicarbonate ($Ca(HCO_3)_2$) or Calcium sulfate ($CaSO_4$) are dissolved in it, at high concentrations (Krottenthaler and Glas, 2009; Veríssimo et al., 2007). Boiling hard water containing $Ca(HCO_3)_2$ leads to the precipitation of the carbonate, thereby 'softening' the water, however, water with mainly $CaSO_4$, is considered to be permanently hard because it does not precipitate below 100^0c (Kemp, 1971). Precipitates developed from hard water can lead to the introduction of inorganic substances which can then be incorporated into the biofilm structure, thereby forming much larger three-dimensional structures protecting the microorganisms from shear forces or CIP chemicals, making them difficult to control and ultimately eliminate. (Ainsworth et al., 2004; Mamvura, 2014).

2.5. Strategies employed to control biofilms

The most important control is the removal of contaminants as early as possible, preferably before introduction into the process. Some of the methods used in biofilm control and elimination involve the use of:

(i) Silver ions

(ii) Ultrasound waves

(iii) surface modification

(iv) Clean-in-place systems

2.5.1. Silver ions

For a long time, plating and painting of instruments and equipment has been a source of protection, with the aim of producing an antimicrobial plane limiting the attachment of biofilms (De Carvalho and Da Fonseca, 2007).

A research (Dong et al., 2010) showed that silver is an active antimicrobial for several bacteria, yeast, fungi and viruses. An alloy of titanium and silver displayed good biocompatibility and high antimicrobial characteristics. In comparison to normal stainless steel, antimicrobial steels with 0,042% silver reduced the number of adhering bacteria by 99%. However, the low solubility of silver in stainless steel (<0,03%) leads to formation of a thin silver layer (<0,2µm) which limits effectiveness. thus, antimicrobial effect declines with time (as the silver depletes).

2.5.2. Ultrasound waves

High frequency ultrasound waves are used to eliminate biofilms due to their ability to release high bursts of energy via cavitation within liquid systems. It is however expensive to solely use high ultrasonic waves alone on a large scale. There is research on combining it with cheaper techniques such as temperature (thermo-sonication), pressure (mano-sonication) or a combination of pressure and temperature (mano-thermo-sonication) (Piyasena et al., 2003). These combinations lead to the medium absorbing ultrasonic energy creating heat causing to the thinning of microbe cell walls as shown in Figure 2.7. Research as shown that the effect of ultrasound is determined by the frequency used, with low frequencies causing mechanical effects, high frequencies introducing chemical effects and intermediate frequencies giving a mix of mechanical and chemical effects (Wu et al., 2012).

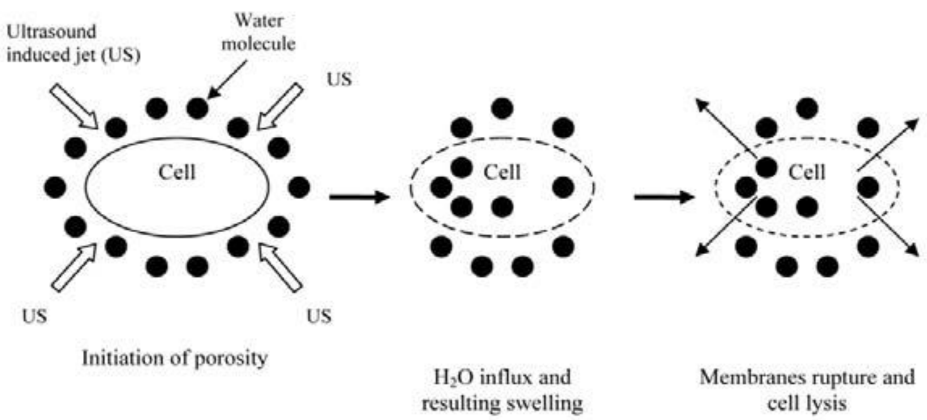

Figure 2.7 Process of ultrasound waves rupturing cells (Joyce and Mason, 2008)

2.5.3. Surface modification (Biomimicry)

Biomimicry is the use of naturally occurring systems to develop an engineering device. There are animals with natural antifouling surfaces such as mussels, crabs and sharks or body parts such as the endothelium in a healthy artery. These surfaces use physical and chemical properties to naturally prevent the build-up of biofilms. In shark, their skin has placoid scales with cellular enamel surrounding a vascular core of dentine similar to the human teeth, and these prevent biofilm formations. There is research (Carman et al., 2006) which worked on making microscopic designs of the shark skin called Sharlet AF™. This bi-surface contained rectangular-like ribs 2μm wide, periodic features (4, 8, 12 and 16μm) in length with 2μm spacing and it successfully reduced ulva build-up by 86% when contrasted to a smooth surface. Further research showed that the spacing and width of this bio-scale in relation to organism/surface size is vital to biofilm prevention. These engineered surface features have distinct structural features fashioned to the critical dimensions of the particular fouling microorganisms (Schumacher et al., 2007). In designing these surfaces, it is essential that the microbes do not fall between the ribs but over the protruding part or stabilize its total mass on a single rib (Scardino et al., 2006).

Surface modification systems have significantly improved with the ability to produce a micro to nano-scale biological surface which inhibits microorganisms settling. However, dimensional differences make species specific fouling control difficult because systems containing diverse microbes require varying features (Schumacher et al., 2007).

2.5.4. Clean-in-place systems

Currently, the most utilised method of controlling and limiting biofilms in process plants is the use of Clean-In-Place (CIP) systems which involve the introduction of antimicrobial agents or biocides into the process equipment to control and eliminate biofilms (Mamvura, 2014). CIP is a process of cleaning the inner surfaces of pipes, fittings, and general equipment in process plants without disassembly, with the elimination of loose biofilms with water (Ferreira et al., 2010). It is usually a computerized reproducible system which uses a mixture of heat and chemicals to clean and disinfect. The cleaning solutions are captured and recycled to limit ejecting it into the sewage system (Loeffler, 2006). The processes of cleaning and disinfection are vital, and the effectiveness of these operations greatly impacts the quality of the final product.

It incorporates an internal scrubber which applies mechanical energy for biofilm removal, however this should be limited, as too much of this may damage the surface, causing more areas to be prone to microbial attachment, and/or lead to a higher rate of microbial dispersal due to agitation creating more hygiene problems (Meyer, 2003; Van and Te, 2005).

The nature of biofilms found in particular sections of the plant determines the type of CIP solution used. Areas with aggressive biofilm formation will require the application of caustic solutions at high temperature while sections with mild microbe infestation can be cleaned with an acid rinse occasionally. Generally CIP systems follow a general five-step sequence: pre-clean rinsing, clean, post-clean rinsing and sanitise (Lewis and Bamforth, 2006). For effective mass transfer and overall removal of loose biofilms the CIP has flow velocity from 1,5-2ms^{-1} with a Reynolds number ranging from 10 000 to 30 000 to guarantee uniform heating and avoid soil sedimentation (Chisti and Moo-Young, 1994; Czechowski and Banner, 1992; Lorenzen, 2005).

There are several factors that lead to an effective CIP process. Firstly all areas to be cleaned must be in contact with the cleaning solutions, with no dead spaces. Long T-sections in process plants usually become dead areas as there is a decrease in flow of the cleaning detergent as it is channelled from the main pipe (Lorenzen, 2005). Thus, bends should be minimised to encourage free flow. Also the sanitising chemicals selected should be inert to the cleaned material surface (Briggs et al., 2004; Loeffler, 2006). The cleaning agent's temperature is an important factor as high temperatures can reduce the need for harsh chemicals but at 80^{o}C, biofilms containing proteins or starch will undergo chemical changes as proteins coagulate, resulting in an increase in fouling instead of a decrease. It also requires more energy to elevate the temperature and a hot environment may facilitate corrosion leading to equipment damage (Carpentier and Cerf, 1993; Chmielewski and Frank, 2003; Lorenzen, 2005; Van and Te, 2005).

To eliminate microbes, the plant is then disinfected after the initial cleaning process. The process of disinfection involves the extermination of microbes using antimicrobial chemicals with the aim of reducing the number of viable microbes on the solid surface after cleaning (Maukonen et al., 2003). It is important because cleaning can remove 90 % of microbes in the system, but cannot totally eliminate them. Disinfection is important because the microbes left can get redeposited at other locations eventually leading to biofilm formation (Gibson et al., 1999; Mamvura et al., 2011). Research also shows that after cleaning procedures, disinfectants still fail to breach the biofilm matrix, and thus some microbes still survive after CIP is completed (Holah, 1992). Water quality, especially its degree of hardness, also affects its effectiveness. Disinfection can also be limited due to the presence of organic matter such as food residues which can impede by reacting with the biocide, leaving a reduced concentration of antimicrobial agents to attack microorganisms (Van and Te, 2005). CIP is limited by the presence of extracellular polymeric substances (EPS) in the microorganisms, making them less vulnerable to antimicrobial agents (Chen and Stewart, 2000; Mamvura et al., 2011). Figure 2.8A shows how the bacterial initially deposits in the crack. In Figure 2.8B, it is observed that CIP fluids only affect the microbes on the outside lip of the crack, while the microbes in the crack, grow into a biofilm causing loss of material and increasing weld defect porosity. Whilst the intent is that CIP processes are not to compromise the pipe material, this is not always achieved. This results in a rougher pipe surface, facilitating further biofilm build-up (Carpentier and Cerf, 1993; Gibson and Ashby, 1999; Mamvura et al., 2011).

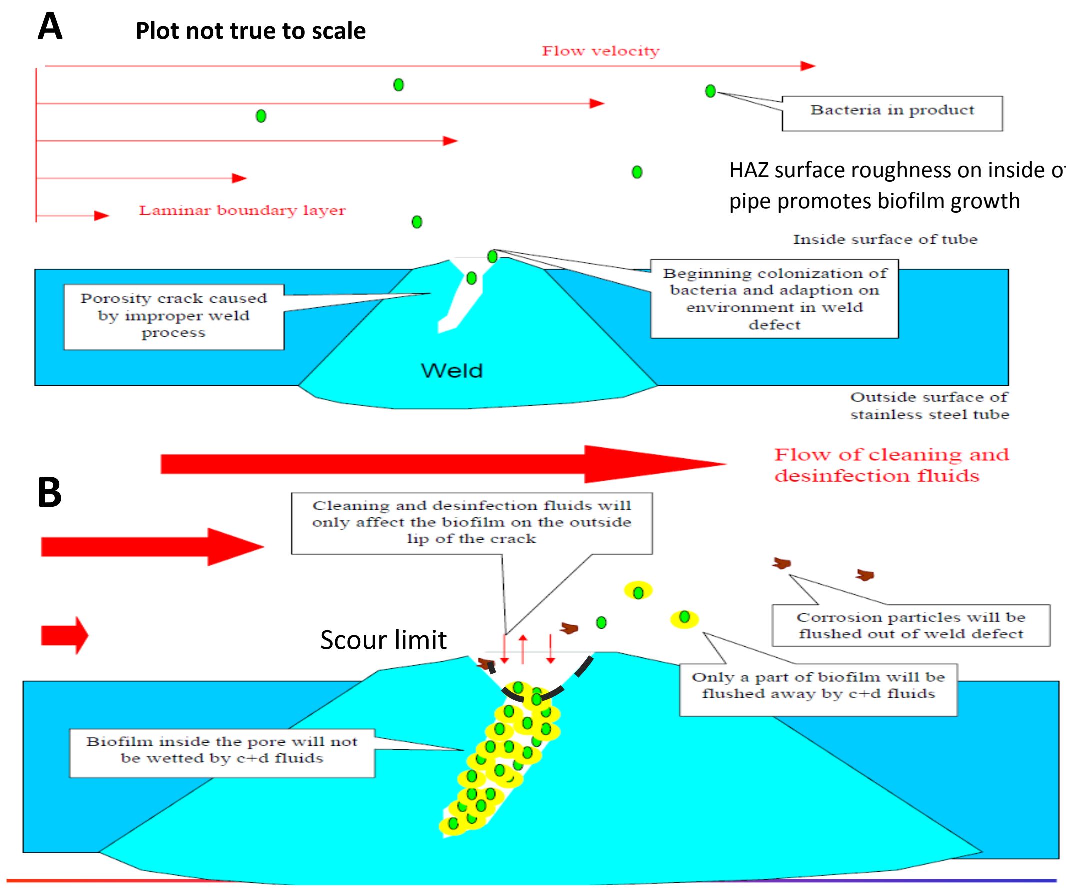

Figure 2.8 Progressive Microbial impacts of imperfections during CIP process (A) Bacteria hiding in weld defect (B) Effect of CIP on weld cracks (Lorenzen, K. 2007).

2.6. Welding in process plants

Process plants have several vessels and equipment which are factory built but require a significant level of onsite interconnection via pipes. These pipes are measured, cut to size, fitted and then joined. The most commonly used method for linking is welding. It offers high strength joints with minimal restriction to flow. There are several methods of welding but for small bore, thin-walled pipes, orbital welding is commonly used. Orbital welding is an automated form of tungsten inert gas (TIG) welding with the welding head rotating round the pipe joint. The process automatically offsets known variables such as travel speed, gravity, internal inert gas pressure and gravity via appropriate pre-programming. With this method, good welds are easily reproducible, thus eliminating errors and defects (Godwin, 2015; Mamvura, 2014; Mathers, 2015).

For plants required to maintain high hygienic parameters, the inside of welded pipe joints must be smooth and continuous to allow proper cleaning. For small bore pipes, good onsite welding is especially difficult and as they cannot be accessed from inside (Godwin, 2015; Van Houdt and Michiels, 2010). Defects in welding must be avoided as incorrectly welded pipes, makes an otherwise hygienically well-designed plant get compromised. While the total welded area is a minute section of the whole plant, many incorrect welded joints will present a great problem as they will support biofilm development and corrosion leading to damage. Examples of good and bad welds are shown in Figure 2.9(a, b, c, and d).

To obtain excellent welds, it is important that matching pipes are selected, taking into cognisance pipe tolerance and ovality. Also pipe fit up and alignment is paramount, as the pipe ends must be sharp-edged with square cuts. It is also important that the weld is done in an inert environment to limit oxidation and contamination.

(a) (b)

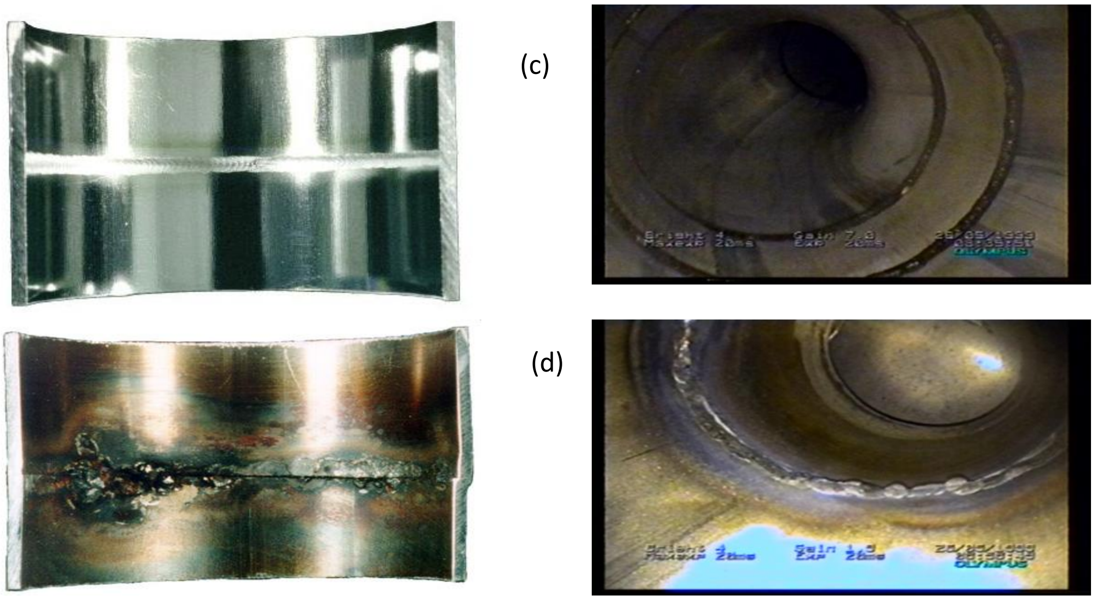

Figure 2.9 Examples of good and bad welds (Folkmar Andersen et al., 2006).

a) An ideal orbital weld on electropolished stainless steel purged with argon and no defects

b) A poor weld caused by either or a combination of poor penetration, misaligned edges, a huge crevice, and poor gas purge. This weld is considered unacceptable by any sanitary standards

c) Good weld with sufficient gas protection with no discoloration and a flat unvarying weld root,

d) Poor weld with inadequate gas protection (blue colour around weld) showing “cauliflowering”.

2.7. Pipe manufacture and fabrication

Pipes are generally used to channel materials to process operations. Pipes used in process plants are often fabricated from stainless steel. Stainless steel can be fabricated to meet different design conditions. It is generally inert to most chemicals, has very high resistance to corrosion, exhibits great durability at extremely cold temperatures, and is easily fabricated. Austenitic stainless steel is the easiest to weld in the stainless steel family. Their mechanical properties to a great extent are unaffected by welding, their properties remain the same even in extreme conditions and they can be fabricated by conventional processes (Ainsworth et al., 2004; Mathers, 2015).

Pipes are long, hollow products. They are two distinct types of pipes, welded and seamless pipe. Both types require the casting of the raw metal into a more practical material.

In the case of seamless pipes, a solid cylindrical billet is produced. This particular rolling stretches out the billet, forming a hole in the centre. A pellet shaped pointed barrel is driven into the centre of the billet while rolling to correct the irregular shaped hole. However, the pipe may still have an irregular thickness and shape, leading to the introduction of tolerances. The base product is progressively reduced in external diameter and increased in internal diameter using internal and external mandrals whilst length increases. Intermediate anneals are required to maintain workability (Jeffus and Baker, 2016; Mathers, 2015; Onyewuenyi, 2012; Younan, 2012).

In seamed pipes, an initially rectangular section billet is heated until white-hot, then progressively rolled and coiled to facilitate intermediate anneals to maintain workability and reheating into a sheet of thickness equal to the intended wall thickness. For seamed pipes, a flat sheet is formed to the desired thickness and coiled. The coil is then slit to widths slightly wider than the desired pipe circumference. Sections of the slit coils are then stretched to remove (most of the) residual stresses before the process of pipe manufacture begins (Group, 1996).

Seamless pipes are the strongest of the pipe types due to its homogenous structure throughout its pipe length and are generally used to make pipe fittings such as elbows, tees, and bends. Most pipe products are formed from seamed pipes. The slit coil mentioned above is edged and an angle to ensure an even weld width, then formed into the desired shape (generally circular) and seam welded. The longitudinal weld is then scalped to remove the weld profile both inside and outside. The resultant pipe is not straight as a result of unresolved residual stresses. Consequently, pipe straightening is required (Onyewuenyi, 2012; Paterson, 2014; Younan, 2012).

As a result of the difficulties of manufacture, mass produced pipes have a range of manufacturing tolerances for their diameter, wall thickness and ovality. These deviations in pipe measurements are incorporated due to one of, or the combination of the following factors (Godwin, 1993; Romantsev et al., 2009):

1. Slitting operations: either setting tolerances or prolonged use of tools, leading to wear resulting in width differences at setting.

2. Rolling operations: problems arise in keeping the sheet perfectly flat or maintaining a specific thickness, also the sheet may bulge slightly at the centre. Therefore, rollers control sheet flatness. The reason for using four or six high rolls is to maintain the alignment of the middle rolls forming the plate or sheet by counteracting against the roller's tendency to bow under stress.
3. Pipe forming operation: changes in pipe width and edge on cutting with machines.
4. Pipe forming operation: variations in pipe dimensions can occur during seam alignment, seam welding effects and springback due to residual stresses.
5. Effects of transporting pipes: introduction of additional stresses during packing and transportation of pipes to locations of use The preferred method of connecting thin-walled pipes in the process plant is by welding. Poor welds lead to crevices and rough surfaces. These act as zones for product entrapment, with these regions serving as areas that inoculate sound product with micro-organisms thereby compromising a hygienically designed plant.

Even when standard procedures are followed onsite, there are deviations in pipe weld quality. One major factor for this is pipe geometry. In pipe production, its diameter, wall thickness, and ovality are manufactured to varying tolerances, also bowing, which occurs as a result of thermal effects in seam welded pipes. These affect the matching and alignment of correctly square cut pipes ends. A poor pipe end fit-up can affect welding, this is illustrated in Figure 2.10, such as not having a sharp edge when pipe end is cut with a pipe cutter, when the end faces are not parallel/having unequal circumference, also when the pipe end is misaligned (Godwin, 1993; Mamvura et al., 2017).

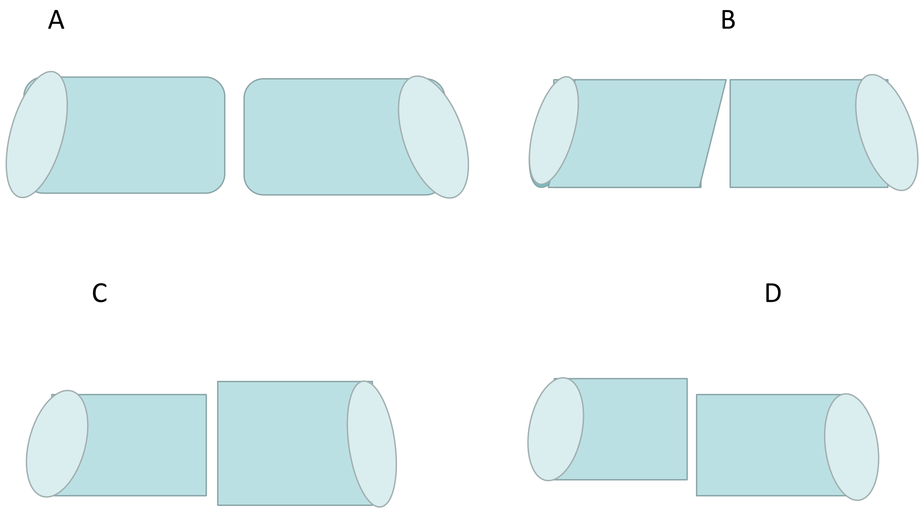

Figure 2.10 How poor pipe end fit-up affects welding (Paterson et al., 2014)

(A) Pipe with rough edge **(B)** Not parallel faces

(**C)** Pipes not of equal circumference **(D)** Misaligned faces

The primary description of pipes always indicates its wall thickness, diameter, and material grade. It is important that the wall thickness selected takes into account the interior forces (such as hoop's stress) and the exterior forces(thermal expansion, transportation, dead loads etc) each particular pipe will be subjected to over its design life (Group, 1996) . (Kawaljitsingh, 2017)

Products manufactured from the base material include standards related to tolerances connected to deviations from the theoretical thickness or shape used by designers. These tolerances are a practical trade-off between manufacturing cost and end use criticality. Tolerances are significant in their impact on fit-up and, particularly regarding hygienic connections. Tolerances include wall thickness, ovality and bowing (the degree of out of straightness along the length). Acceptable pipe tolerances vary depending on the end application intended. Hence a range of end-use specific tolerance standards exist. In pipe production, the diameter, wall thickness, and ovality tolerances vary with different manufacturers due to variations in their production processes (Godwin, 1993; Kemp et al., 2016; Mamvura et al., 2017).

‘Ovality is defined as the difference between the maximum or minimum diameter to set diameter, expressed as a percentage of the nominal internal diameter’(Kawaljitsingh, 2017) . Ovality is a common defect during manufacturing of pipes. It affects many post-manufacturing operations as it limits the adjoining of pipe ends before welding because of surface mismatch (Kawaljitsingh, 2017).

Ovality arises in pipes partly because of thermal effects during the production of seam welded pipes. Prior to pipe forming; the rolled product is annealed, stretched to remove internal stresses, slit and rolled into coils (Buckshumiyan et al., 2014; Kawaljitsingh, 2017; Mamvura et al., 2017). In the pipe production cycle, strip edges are angle trimmed both to ensure a constant circumference and to facilitate an even welding vertical gap prior to roll forming. During seam welding, the seam is initially held in position by forming rollers. As the pipe moves down the line after welding and cools, the thermal contraction of the HAZ induces stresses in the pipe. In the HAZ of the weld, the release of the forming roll pressure may also result in local flattening of the HAZ, contributing to minor axis formation. After welding, the pipes are straightened using rollers, but the process does not only not eliminate all internal stresses; it introduces new stresses which could be relieved during transport so affecting the delivered pipe bow. Other factors that lead to ovality in pipes include: a misalignment in the proper angle of inclination for the rollers at the pipe mill with respect to each other; after slitting and edge trimming, improper welding of the seam weld and the rough handling of pipes during transportation to site. The pipe straightening requirement arises partly from residual stresses in the parent material sheet after stretching and annealing. It may be exacerbated by springback associated with seam welding. Ovality can make onsite pipe fabrication difficult (Buckshumiyan et al., 2014; Kemp et al., 2016).

Based on the specifics of the process, the plant designer determines the acceptable pipe ovality. Generally, 5% ovality is accepted. However ASME allows for 8% ovality.

International design codes such as ASME B31 codes, API RP 1111, and DIN EN ISO 1127 standards, guide the tolerance and other (e.g. seam weld smoothness) requirements for wall thickness selection (Kawaljitsingh, 2017; Kemp et al., 2016).

2.8. Pipe end modification to improve pipe end fit up: Why swage

There are many factors contributing to poor welds in process plants. This research is focused on mitigating against pipe geometry tolerances. Pipes are manufactured within a range of tolerances for their diameter, wall thickness and ovality (Mamvura et al., 2017b). Another issue is bowing (within tolerances) over the length. This means that square cut ends will not present as parallel faces when pipes are aligned along the length. Due to this combination of bowing and ovality, apparently correctly cut pipes are affected in their matching and alignment before welding commences. However, welding only relates to pipe ends, not the full pipe length. Therefore, flaring or swaging well beyond the elastic limit of pipe ends aligned to the pipe length accommodating the bow can aid in achieving a good fit up (considered to be at least 80% overlap of adjoining surfaces). In addition, a fabricator controlled pipe centroid alignment may be important (Kawaljitsingh, 2017; Kemp et al., 2016).

The preferred method of onsite welding of pipe joints is automated tungsten inert gas (TIG) orbital welding. It produces high quality welds, offers superior regulation, more uniform control of the heat input while ensuring that there is no overheating and adequate penetration during welding so as not to reduce the corrosion resistance of the final weld zone. Orbital welding an automated process hence it is extremely sensitive to setup accuracy and it cannot rectify pipe end irregularities, such as misalignment or variations in pipe diameter. It, as is the case with other automated processes, is highly dependent on a repeatable, reliable fit up. For a proper overlap of pipe end for welding, a small consistent gap between square cut ends and precise alignment and adjoining surface fit up is paramount (Godwin, 1993; Mannion, 1999).

Misalignment in pipe welding occurs if the two faces of the pipework to be joined are not correctly matched. This causes a step to form at the weld junction. Such a feature can cause build-up of the product and make CIP more difficult thus, increasing the risk of poor hygiene. It may also increase the risk of corrosion due to microbial attack. Several factors can lead to misalignment of pipe ends before welding. Even if the pipes have parallel, correctly spaced, square cut ends, its end face geometry and bowing over its length have a major influence. Whilst designed and designated as circular, pipes are generally marginally oval (within specified tolerance limits) (Godwin, 1993; Jeffus and Baker, 2016; Kawaljitsingh, 2017; T. Paterson, 2014).

An extensive study based on thin wall pipe measurement for the Okahandja brewery project in Namibia was conducted. 90 pipes with different external diameters ranging between 29mm and 152mm were randomly chosen and measured. From these, a sub-group of 27 pipes of equal internal diameter was selected. These pipes were divided into two categories, wide tolerances, and narrow tolerances. A minimum overlap of 80% of pipe ends was selected as the standard for effective orbital welding. A mathematical algorithm was created, to contrast an overlay of arbitrarily selected pipe surfaces, point by point around the pipe circumference under diverse parameters. The algorithm was applied 1000 times over each test configuration as shown in Table 2.1 below (Paterson et al., 2014). The profile of each pipe was categorized by measuring the minor axis, major axes, and its inner wall profile.

Pipes were grouped into six categories for testing.

I. High tolerance pipes randomly aligned

II. High tolerance pipes randomly aligned by major axis,

III. Low tolerance pipes randomly aligned

IV. Low tolerance pipes randomly aligned by major axis

V. Full set of pipes randomly aligned and

VI. Full set of pipes aligned by major axis.

Each group of experiments was simulated with 1000 iterations. As shown in Table 2.1, the pipes with well-fitting adjoining surfaces, fulfilling an overlap of 80 % or better, was challenging to attain with random orientation of pipes, mainly when the manufacturing tolerances were broader. Also, only 17% of pipes with a wide tolerance range, under random orientation of alignment, achieved the required overlap. Aligning the pipes along their major axis, improved it to 47%. Excellent results were achieved in pipes with narrow manufacturing tolerances (100%) irrespective of the nature of alignment (randomly or along the major axis). The research showed how significant the effect of ovality on pipe end overlap and a sound weld (Paterson et al., 2014).

Table 2.1 Result of iteration of 53mm pipes (Looser – M1; tighter – M2) (Paterson et al., 2014)

Configuration Of pipe orientation	**Random**	**Seam aligned**	**Random**	**Seam aligned**
Material and wall thickness	**316 L Current wall thickness**	**316 L Current wall thickness**	**2304 Half wall thickness**	**2304 Half wall thickness**
Pipe to pipe	%	%	%	%
Low tolerance N1 to N1	17	47	1	12
High tolerance N2 to N2	100	100	79	82
N1 to N2	33	39	4	6

The main objective of the research was to determine how to eliminate areas that serve as spots for product residues which will inadvertently cause the control, reduction and eventual elimination of biofilms. Generally, biofilms in process plants are removed by using mostly mechanical cleaning and antimicrobial agents. However, there is a shutdown of production during mechanical cleaning, thus it affects profitability. Also, its effectiveness is limited as it has no access to occluded areas (Mamvura et al., 2011; Xavier et al., 2005).

Process plants that require sanitary piping have to integrate the ASME Bioprocessing Equipment Standard (BPE-97) or DIN EN ISO 1127 to control the manufacturer's tolerance range. The reality is that pipe tolerances exist because no two pipes are ever manufactured identically. From a manufacturing point of view, this would be too costly. In addition, the effects of transport (combined with residual stresses) can impact on characteristics as delivered. This implies the need for some pre-welding work onsite. Onsite, fabricators cannot change pipe tolerances, they can however control the nature of alignment of pipe ends before welding, by altering pipe ends. An option to accommodating differences of pipes due to tolerance is by swaging. Cold working by swaging leads to greater yield strength. The most common use of swaging in manufacturing is to attach fittings to a pipe, with a mechanical or hydraulic tool expanding the pipe end (Godwin, 1993; Samuel et al., 1993; Urband and Garrison, 2003).

There is a research gap in determining the extent to which swaging pipe ends will influence the fit up of pipe joints and affect overall hygienic conditions, providing a less expensive means of dealing with imperfect tolerance.

3. EXPERIMENTAL PROCEDURES

This section contains experimental details, methods, and apparatus used during the course of the project. For validation of the hypothesis, it was important to obtain related data that served as a reasonable baseline and guide to tests conducted. To increase the quality of onsite prepared welds, site preparation of pipe ends was under investigation.

This chapter describes the process used. This involved subjecting randomly manufactured stainless steel pipes to a one of two stage swaging process, welding under the same programme, and cutting coupons from the joint area of pipes welded under different swage conditions. The different weld areas' surface topography and morphology were analysed to determine which was the least favourable for microbe attachment.

3.1. Stainless steel pipes preparation

For the implementation of this research, 40 representative, randomly selected, AISI 304 stainless steel thin wall pipes offcuts with nominal 50,65mm bore, (wall thickness in relation to the outer diameter is less than 3% - i.e. <1,5mm wall thickness) were obtained from different production batches. These were obtained with the assistance of FischerSA, Pretoria, South Africa.

3.1.1. Sample measurement

Only those pipes that ranged from OD 50,00mm to 52mm were selected for treatment. This served as a constraint allowance for tolerance. The selected offcuts were measured to determine the major and minor axis of the external diameter. The wall thickness was also measured three times at each end with 120^{o} offset spacing as shown in Figure 3.1. The position of the major axis and minor axis on each pipe end was marked on both ends.

The pipes were sorted using the tighter tolerance end. They were then classified based on closeness to tolerance values in relation to DIN EN ISO 1127 manufacturing standards for OD 50,65mm nominal bore AISI 304 stainless steel thin-walled pipes. A total of 40 complying pipes resulted. Therefore, the pipes were arranged according to minimum axis proximity to tolerance range. The ovality was calculated and the pipe end with the best properties was selected.

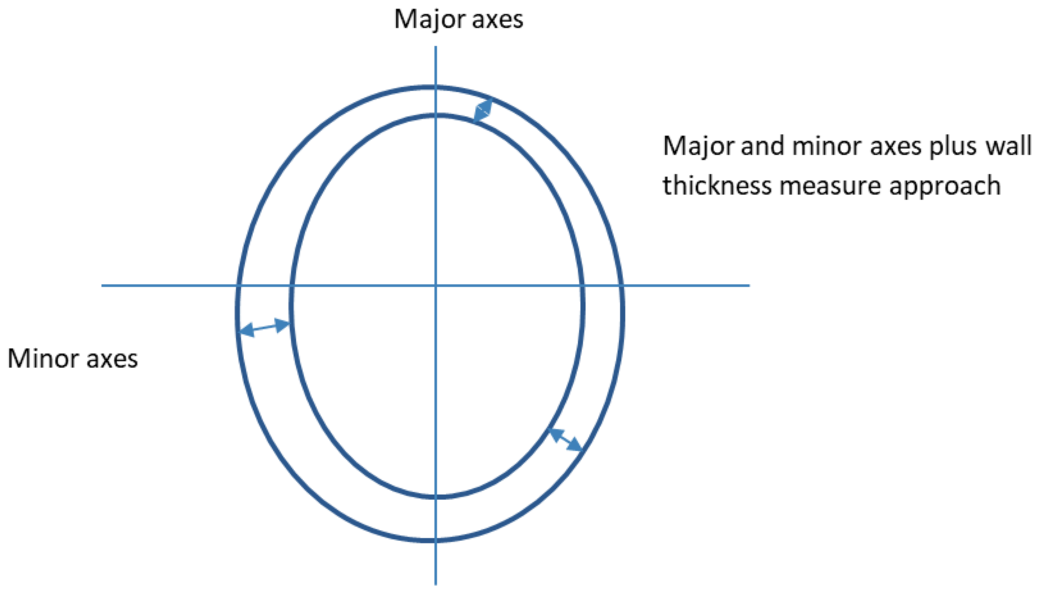

Figure 3.1 Diagram of pipe end geometry.

3.1.2. Sample redistribution

The pipes were randomly distributed into three groups.

- Group 1: No changes were made to these pipes, they serve as control.
- Group 2: End modified by simply swaging, to achieve a standard inner diameter and therefore overcome out of roundness effects through plastic deformation.
- Group 3: the application of a transverse impact load before end modification commenced.

Group 3 was introduced because, during a visit to FischerSA, it was observed that pipes ends were first impacted across the diameter with a hammer or nutcracker before swaging. The purpose was to completely eliminate residual stresses and to prevent springback. Each group contained samples that fall within the accepted tolerance range and those which did not.

3.2. Swaging

304 stainless steel pipes have proof stress of 215 MPa with an elastic modulus of 200GPa. This implies an elongation percentage of 0,09% at the onset of plasticity. Using Hooke's law ($\sigma=E\varepsilon$), its minimum yield point is 0,09%. Swaging the pipes beyond 0,09% circumferential elongation will result in plastic deformation. A benchmark of a minimum of 2% and a maximum of 4% (allowing for different pipe diameters) swage expansion was chosen to ensure complete eradication of residual stress, thereby limiting springback and to accommodate initially oversized pipes, without causing significant change to flow characteristics. It is noted that as flow velocity is a function of pipe area, a change of about 3% in circumference corresponds to a 1,03%/3,14159 increase in diameter and about a 1% change in its area. This was not expected to change flow characteristics (Stewart, 2008).

The swaging punch used was machined from a solid cylinder of mild steel, machine tapered at the start to ensure a smooth transition to the original pipe. The tool tapered to a diameter of 52,5mm at its widest point (>50,00 +4% mm diameter) and included a 100mm long parallel section at the wide end to assist clamping if used for welding. This is shown in Figure 3.2A below. For swaging, the pipes were secured in a custom-made expansion device as seen in Figure 3.2B. A hydraulic press was used to push the swage tool into the pipes forcing expansion. See Appendix B for design.

For Group 3, the impact load was applied transversely using a hammer.

For Group 2 and Group 3 swaged pipes, each individual pipe end was re-measured as the swaging resulted in a new diameter. In some instances, there was a change in major and minor axis orientations as well as the relative offset of the seam to the minor axis. The swaging resulted in permanent plastic deformation.

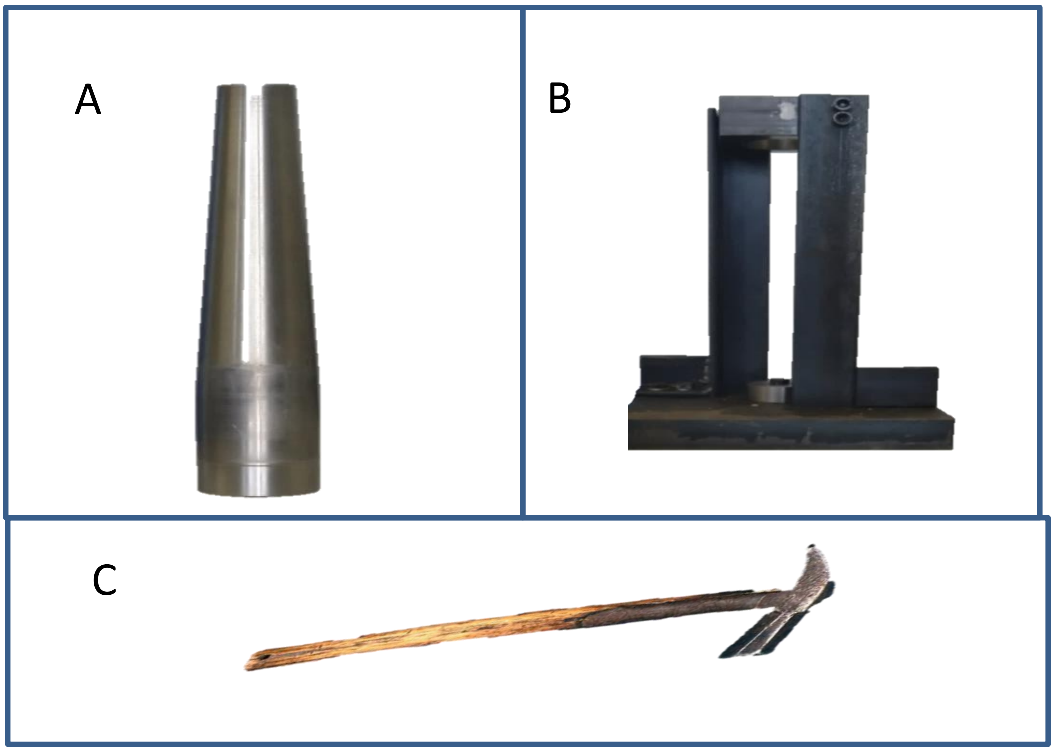

Figure 3.2 Diagram of the swaging device:

(A) swage tool head used to expand pipe end (B) Expansion chamber (C) hammer used for transverse impact

3.3. Welding parameters

The three pipe groups were joined by welding using pre-programmed TIG orbital welding. This was executed by Orbital welding Solutions Projects (PTY) Limited (OWS) using a Power Pack, a synergic pulse Fronius FPA 2003 and a Welding Head: Polysoude MU 1V 64, as seen in Figure 3.3. Argon Gas 99,99% Purity used as both the external shielding gas and purging shielding Gas. A 2% thoriated 2,4mm thick, tungsten electrode was used, with no wire feeder.

The three pipe groups were aligned under these conditions:

I. Group 1 pipes randomly aligned

II. Group 1 pipes aligned along major axis

III. Group 2 pipes randomly aligned

IV. Group 2 pipes aligned along major axis

V. Group 3 pipes randomly aligned

VI. Group 3 pipes aligned along major axis

For the arc length, the gap between the tungsten electrode and the work-piece was 2mm. This gap was based on weld current, arc stability, and pipe concentricity/ovality. The nominal orbital welding speed was 63mm/min. Weld current was 50 Amps Peak current and 28 Amps background current on average. OWS used robust clamps to ensure alignment and compression of the oval pipes to assure near perfect roundness during tacking. This was important for the Group 1 pipes, whilst effect of out of roundness was reduced by the clamping, residual stresses related to clamping remained.

i:

ii

iii:

iv

Figure 3.3 Orbital welding process (I) U IV 64 Orbital Head, (II) Swaged tube ends (Tack Welded) (III) Tube Fit-up Clamp (IV) Completed Orbital Weld

3.4. Impact of welding parameters

The second part of the experiment investigates the impact of the weld set-up procedures. The purpose was to determine the pipe end modification that least favours microbial growth. 75mm x 40mm coupons were cut longitudinally along the pipe sections from the; unswaged, swaged and impact with swaged sections and included 40mm of the joining weld. The geometric profile of the coupons was then examined. The welded joint geometry profiles were determined by longitudinal cutting, polishing and then examination to determine surface finish profiles around the full circumference of un-welded, unswagged and swaged pipe specimen.

3.4.1. Optical Microscope

An optical microscope was used to view the surfaces produced after welding and compared to the normal surface available initially. The OLYMPUS BX 63 optical microscope was used. The samples were mounted, ground, polished and etched (to reveal grain boundaries) before viewing. The samples were electrolytically etched using oxalic acid and 4A of current.

3.4.2 Geometric profile analysis

Coupons were cleaned with ethanol, to eradicate any deposits prior to roughness measurements (Boulangé-Petermann et al., 1997). Measurements were quantified using the Dimension 3100 Atomic Force Microscope to determine the following parameters:

a. Average roughness (R_a)

b. Root-mean-square profile height (R_q)

c. Maximum peak-to-valley height (R_{max})

d. Surface skewness (R_{skw})

e. Surface kurtosis (R_{kur}).

R_a, R_q and R_{max} are utilised to assess the coupon's surface topography, while R_{skw} and R_{kur} are used to describe the surface morphology (Ivanova et al., 2011). See Appendix A for definitions of the acronyms used for surface topography. Each pipe specimen was then compared to determine the relative smoothness of coupons as discussed in result and discussion.

4. RESULTS AND DISCUSSION

This chapter gives detailed results of the experiments conducted according to Chapter 3. The chapter is divided into four main sections. Section 4.1 will report on the pipe measurement results, section 4.2 presents the macrostructure and weld appearance results, section 4.3 provides the surface topography and morphology results, section 4.4 provides a summary and discussion of the results obtained.

4.1 Measurement Results

40 random samples of AISI 304 stainless steel seam welded pipes of 50,65mm nominal bore and 1,43mm nominal wall thickness was obtained. These were offcuts related to different manufacturers and batches.

Accepted Tolerance: DIN EN ISO 1127 (Standards, 1996) (Last reviewed EN: 2014)

The accepted manufacturing tolerance dimensions for the 50,65mm pipe are shown in Table 4.1 below:

Table 4.1 Tolerance dimensions for 50,65mm

Tolerance class		
Outside diameter	Minimum of -0,75% (-0,30) mm	Maximum of +0,75% (+ 0,30) mm
	Lowest acceptable value 50,35 mm	Highest acceptable value 50,95 mm.
Pipe thickness	Minimum of -10% (-0,20) mm	Maximum of +10% (+ 0,20 mm)
	Lowest acceptable value 1,29 mm	Highest acceptable value 1,57 mm.

The wall thickness of all pipe ends (top-end A and bottom-end B) were measured at equal spacing (0^O, 120^O, 240^O spacing indicated in Figure 3.1). The minimum and maximum axis diameters were measured at each end and the major axis marked, the results shown in Table 4.2 below.

In relation to DIN EN ISO 1127 standards, 100 % of the pipes were within the tolerance limit based on wall thickness as shown in Figure 4.2 while 51,25% of the pipes conformed with both maximum and minimum nominal bore criteria as indicated in Figure 4.1.The ovality of both ends A and B was calculated as shown in Table 4.3 to determine which pipe end was of tighter tolerance. The pipe ends showed varied levels of ovality and tolerance compliance. This emphasized the diversity of the samples. The pipes were then sorted from high tolerance to low tolerance, based on the end with the least ovality, proximity to the tolerance range for the minimum OD axis and conformity with DIN EN ISO1127 manufacturing tolerance for 304 stainless steel thin walled seam welded pipes (Standards, 1996).

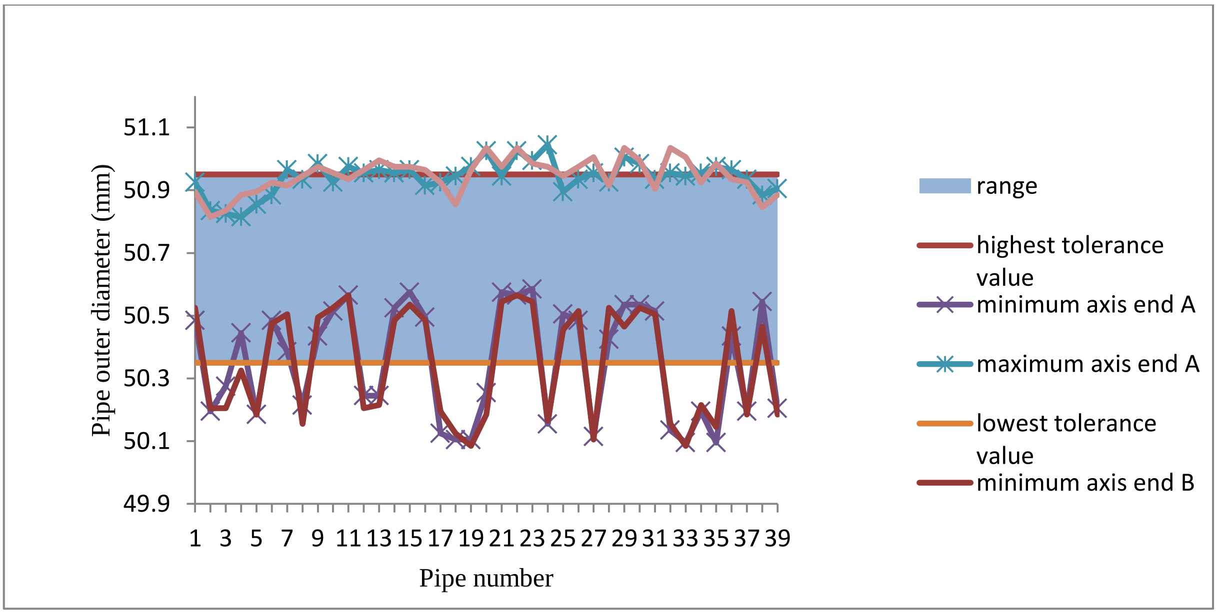

Figure 4.1 Graph showing number of pipes within the accepted tolerance range for diameter

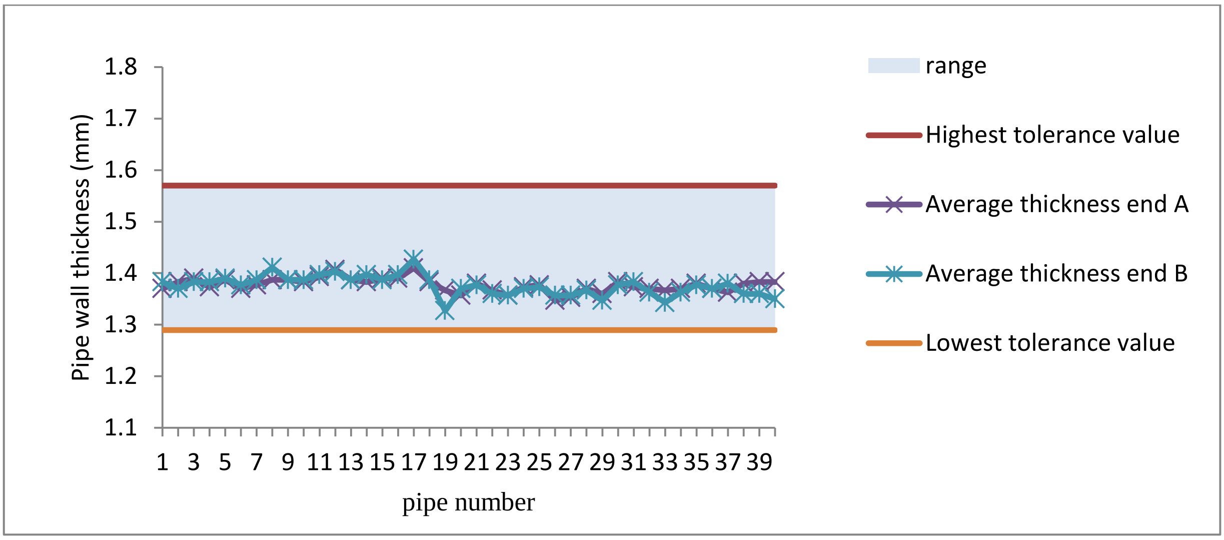

Figure 4.2 Graph showing number of pipes within the accepted tolerance range for thickness

4.1.1 Pipe Distribution into experimental groups

Pipes were randomly further separated into the three groups as previously discussed in chapter 3.

A. No pipe end treatment (Group 1)

B. Swage only group (Group 2)

C. Impact and Swage group (Group 3)

Group 2 and Group 3 pipes were expanded with the swage and ironing device. Prior to swaging, the Group 3 pipe ends were distorted transversely by impact with a hammer before swaging, as shown in Figure 4.3 below. The purpose was to reduce residual stresses resulting from welding and subsequent straightening.

Table 4.2 Measurement of pipe ends diameter (minor and major axis) wall thickness

Pipe End A(top)							**Pipe End B(bottom)**					
Pipe No	Diameter (mm)		Wall Thickness (mm)				Diameter (mm)		Thickness (mm)			
	Minor axis (d)	Major axis (D)	0^{O}	120^{O}	240^{O}	mean	Minor axis (d)	Major axis (D)	0^{O}	120^{O}	240^{O}	mean
1	50,485	50,925	1,360	1,380	1,370	**1,370**	50,525	50,895	1,400	1,380	1,370	**1,383**
2	50,195	50,835	1,390	1,390	1,370	**1,383**	50,205	50,815	1,350	1,380	1,380	**1,370**
3	50,175	50,855	1,380	1,400	1,390	**1,390**	50,145	50,865	1,380	1,390	1,380	**1,383**
4	50,275	50,825	1,390	1,360	1,370	**1,373**	50,205	50,835	1,370	1,390	1,390	**1,383**
5	50,445	50,815	1,390	1,390	1,380	**1,387**	50,325	50,885	1,390	1,400	1,380	**1,390**
6	50,185	50,855	1,370	1,360	1,380	**1,370**	50,185	50,895	1,390	1,380	1,360	**1,377**
7	50,485	50,885	1,370	1,400	1,360	**1,377**	50,475	50,925	1,380	1,390	1,390	**1,387**
8	50,385	50,965	1,410	1,390	1,360	**1,387**	50,505	50,915	1,420	1,400	1,414	**1,411**
9	50,215	50,935	1,390	1,370	1,400	**1,387**	50,155	50,945	1,380	1,380	1,400	**1,387**
10	50,435	50,985	1,380	1,380	1,390	**1,383**	50,495	50,975	1,380	1,380	1,400	**1,387**
11	50,515	50,925	1,390	1,380	1,410	**1,393**	50,525	50,955	1,390	1,400	1,400	**1,397**
12	50,565	50,975	1,400	1,400	1,420	**1,407**	50,565	50,935	1,420	1,380	1,410	**1,403**
13	50,245	50,955	1,380	1,380	1,400	**1,387**	50,205	50,965	1,380	1,400	1,380	**1,387**
14	50,245	50,965	1,380	1,390	1,380	**1,383**	50,215	50,995	1,390	1,400	1,400	**1,397**
15	50,525	50,955	1,380	1,390	1,400	**1,390**	50,485	50,975	1,380	1,380	1,400	**1,387**
16	50,575	50,965	1,400	1,380	1,390	**1,390**	50,535	50,975	1,400	1,400	1,390	**1,397**
17	50,495	50,915	1,400	1,410	1,420	**1,410**	50,485	50,965	1,430	1,430	1,420	**1,427**
18	50,125	50,925	1,380	1,380	1,390	**1,383**	50,195	50,925	1,380	1,380	1,400	**1,387**
19	50,105	50,945	1,370	1,360	1,370	**1,367**	50,125	50,855	1,320	1,350	1,310	**1,327**
20	50,105	50,975	1,370	1,350	1,350	**1,357**	50,085	50,965	1,370	1,360	1,380	**1,370**
21	50,255	51,025	1,380	1,370	1,390	**1,380**	50,185	51,035	1,390	1,360	1,380	**1,377**
22	50,575	50,945	1,380	1,370	1,350	**1,367**	50,545	50,975	1,360	1,350	1,370	**1,360**
23	50,565	51,025	1,350	1,370	1,350	**1,357**	50,565	51,035	1,370	1,350	1,350	**1,357**
24	50,585	50,995	1,370	1,370	1,380	**1,373**	50,545	50,985	1,360	1,380	1,370	**1,370**
25	50,155	51,045	1,380	1,380	1,370	**1,377**	50,165	50,975	1,370	1,380	1,370	**1,373**
26	50,505	50,895	1,320	1,360	1,360	**1,347**	50,455	50,945	1,360	1,360	1,350	**1,357**
27	50,485	50,935	1,330	1,370	1,360	**1,353**	50,515	50,975	1,370	1,350	1,350	**1,357**
28	50,115	50,955	1,370	1,360	1,380	**1,370**	50,105	51,005	1,380	1,370	1,350	**1,367**
29	50,425	50,925	1,330	1,370	1,380	**1,360**	50,525	50,915	1,340	1,340	1,360	**1,347**
30	50,535	51,005	1,380	1,380	1,390	**1,383**	50,465	51,035	1,380	1,380	1,370	**1,377**
31	50,535	50,985	1,370	1,370	1,380	**1,373**	50,525	50,995	1,380	1,380	1,390	**1,383**
32	50,515	50,935	1,370	1,360	1,380	**1,370**	50,505	50,905	1,350	1,360	1,380	**1,363**
33	50,135	50,955	1,360	1,380	1,360	**1,367**	50,155	51,035	1,360	1,330	1,340	**1,343**
34	50,095	50,945	1,370	1,380	1,360	**1,370**	50,085	51,005	1,370	1,350	1,370	**1,363**
35	50,195	50,955	1,390	1,370	1,380	**1,380**	50,215	50,925	1,370	1,370	1,390	**1,377**
36	50,095	50,975	1,380	1,370	1,360	**1,370**	50,145	50,985	1,350	1,390	1,370	**1,370**
37	50,435	50,965	1,350	1,360	1,380	**1,363**	50,515	50,935	1,380	1,370	1,390	**1,380**
38	50,195	50,935	1,370	1,370	1,400	**1,380**	50,185	50,925	1,360	1,350	1,370	**1,360**
39	50,545	50,885	1,380	1,380	1,390	**1,383**	50,465	50,845	1,360	1,350	1,370	**1,360**
40	50,205	50,905	1,370	1,370	1,410	**1,383**	50,185	50,885	1,350	1,360	1,340	**1,350**

Table 4.3 Calculation of pipe ends ovality with selected end highlighted

Pipe no	**Diameter end A (mm)**			**Diameter end B (mm)**			**Ovality %** $\left(\frac{D-d}{nominal\ D(\ \ )}100\right)$	
	Minor axis (d)	Major axis (D)	(D-d)	Minor axis (d)	Major axis (D)	(D-d)	**End A**	**End B**
1	50,485	50,925	0,44	50,525	50,895	0,37	0,866	0,728
2	50,195	50,835	0,64	50,205	50,815	0,61	1,260	1,201
3	50,175	50,855	0,68	50,145	50,865	0,72	1,339	1,417
4	50,275	50,825	0,55	50,205	50,835	0,63	1,083	1,240
5	50,445	50,815	0,37	50,325	50,885	0,56	0,728	1,102
6	50,185	50,855	0,67	50,185	50,895	0,71	1,319	1,398
7	50,485	50,885	0,40	50,475	50,925	0,45	0,787	0,886
8	50,385	50,965	0,58	50,505	50,915	0,41	1,142	0,807
9	50,215	50,935	0,72	50,155	50,945	0,79	1,417	1,555
10	50,435	50,985	0,55	50,495	50,975	0,48	1,083	0,945
11	50,515	50,925	0,41	50,525	50,955	0,43	0,807	0,846
12	50,565	50,975	0,41	50,565	50,935	0,37	0,807	0,728
13	50,245	50,955	0,71	50,205	50,965	0,76	1,398	1,496
14	50,245	50,965	0,72	50,215	50,995	0,78	1,417	1,535
15	50,525	50,955	0,43	50,485	50,975	0,49	0,846	0,965
16	50,575	50,965	0,39	50,535	50,975	0,44	0,768	0,866
17	50,495	50,915	0,42	50,485	50,965	0,48	0,827	0,945
18	50,125	50,925	0,8	50,195	50,925	0,73	1,575	1,437
19	50,105	50,945	0,84	50,125	50,855	0,73	1,654	1,437
20	50,105	50,975	0,87	50,085	50,965	0,88	1,713	1,732
21	50,255	51,025	0,77	50,185	51,035	0,85	1,516	1,673
22	50,575	50,945	0,37	50,545	50,975	0,43	0,728	0,846
23	50,565	51,025	0,46	50,565	51,035	0,47	0,906	0,925
24	50,585	50,995	0,41	50,545	50,985	0,44	0,807	0,866
25	50,155	51,045	0,89	50,165	50,975	0,81	1,752	1,594
26	50,505	50,895	0,39	50,455	50,945	0,49	0,768	0,965
27	50,485	50,935	0,45	50,515	50,975	0,46	0,886	0,906
28	50,115	50,955	0,84	50,105	51,005	0,9	1,654	1,772
29	50,425	50,925	0,5	50,525	50,915	0,39	0,984	0,768
30	50,535	51,005	0,47	50,465	51,035	0,57	0,925	1,122
31	50,535	50,985	0,45	50,525	50,995	0,47	0,886	0,925
32	50,515	50,935	0,42	50,505	50,905	0,40	0,827	0,787
33	50,135	50,955	0,82	50,155	51,035	0,88	1,614	1,732
34	50,095	50,945	0,85	50,085	51,005	0,92	1,673	1,811
35	50,195	50,955	0,76	50,215	50,925	0,71	1,496	1,398
36	50,095	50,975	0,88	50,145	50,985	0,84	1,732	1,654
37	50,435	50,965	0,53	50,515	50,935	0,42	1,043	0,827
38	50,195	50,935	0,74	50,185	50,925	0,74	1,457	1,457
39	50,545	50,885	0,34	50,465	50,845	0,38	0,669	0,748
40	50,205	50,905	0,7	50,185	50,885	0,70	1,378	1,378

After the expansion of both Groups 2 and Group 3, an expansion of 3,6 ±0,4% mm was achieved. The results are listed in Table 4.4 below:

Table 4.4 New pipe diameter for Group 2&3 with % percentage increase and new ovality (D= diameter)

No treatment (Group 1)		**Swage only (Group 2)**						**Impact + Swage (Group 3)**			
Pipe	Original D	Pipe	New D	% increase	Ovality new %	Ovality old %	Pipe	New D	% increase	Ovality new %	Ovality old %
24A	50,99	19B	52,77	3,766	1,319	1,437	1B	52,68	3,507	0,433	0,728
12A	50,97	33B	52,8	3,458	1,201	1,732	18B	52,8	3,682	0,787	1,437
30A	51,00	15A	52,71	3,444	0,551	0,846	35B	52,82	3,721	0,846	1,398
11B	50,95	21A	52,82	3,518	0,748	1,516	36B	52,95	3,854	1,417	1,654
27B	50,97	23A	52,87	3,616	1,102	0,906	37B	52,89	3,838	0,807	0,827
10B	50,97	28A	52,9	3,817	0,827	1,654	8B	52,89	3,879	0,728	0,807
17A	50,91	31A	52,81	3,579	1,063	0,886	13A	52,93	3,876	1,26	1,398
29B	50,82	32A	52,84	3,74	0,669	0,827	20A	52,87	3,718	1,28	1,713
29B	52,8	4A	52,73	3,748	0,807	1,083	22A	52,89	3,818	0,709	0,728
2B	50,81	40A	52,79	3,703	0,768	1,378	26A	52,79	3,723	0,709	0,768
38A	50,93	16A	52,81	3,62	0,748	0,768	3A	52,71	3,648	0,748	1,339
25B	50,97	6A	52,82	3,864	0,965	1,319	34A	53	4,034	1,555	1,673
		7A	52,72	3,606	0,689	0,787	39A	52,86	3,881	0,65	0,669
		9A	52,86	3,779	1,102	1,417	5A	52,8	3,906	0,709	0,728

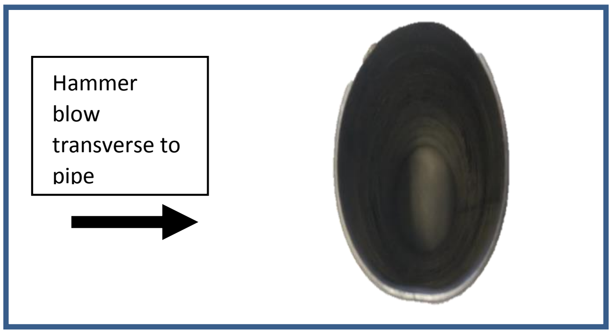

Figure 4.3 Direction of hammer blow for impact force to facilitate plastic

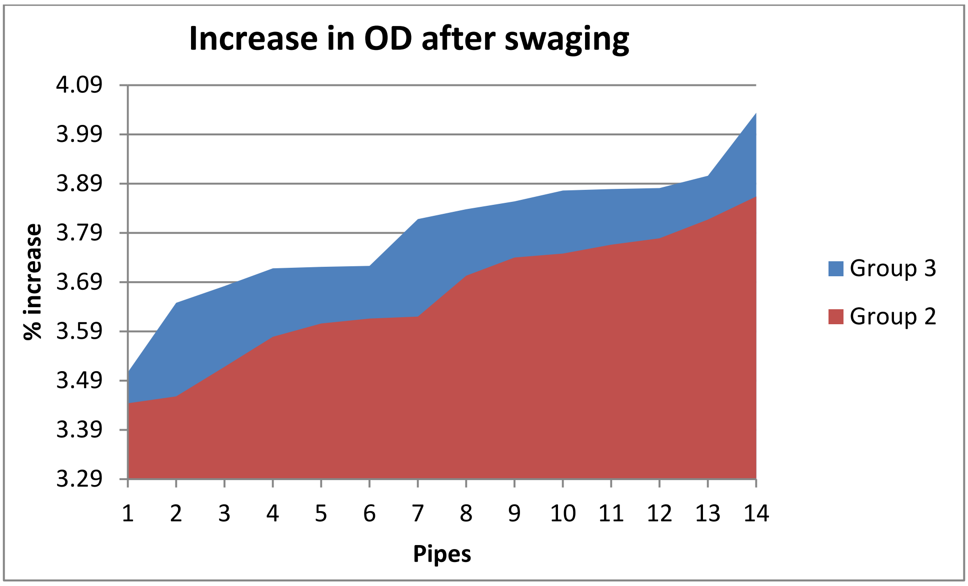

Figure 4.4 Graph indicating increase in pipe OD after swaging for groups 2 and 3

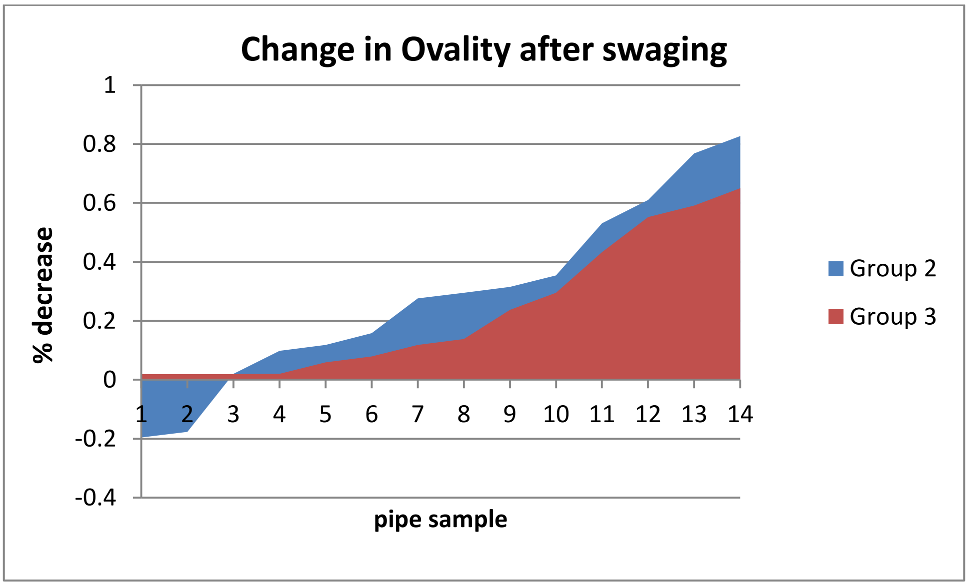

Figure 4.5 Graph indicating change in pipe ovality after swaging for groups 2 and 3

As shown in Figure 4.4 after swaging, 71% of pipes in Group 2 and 93% of pipes in Group 3 achieved at least 3,6% mm increase in end diameter with group 3 pipes expanding noticeably better than group 2. Ovality reduced in all of the group 3 samples while it only decreased for 84% in Group 2, as shown in Figure 4.5, with 34% of Group

2 and 53% of Group 3 achieved equal to or less than 0.8% out of roundness after treatment.

Table 4.4 shows that the application of distortion through impact before swaging, helped reduce residual stresses, including springback introduced during pipe production. This resulted in a more stable and uniform deformation.

For welding Group 1 pipes were paired, 50% with random orientation and 50% with the maximum axis aligned.

Group 2 and Group 3 pipes were paired with random orientation within their own group. All pipes were then orbital TIG (Tungsten Inert Gas) welded under a circumferential clamping diameter constraint. The inert gas used was 99,99% argon.

4.2. Result of different welding procedures on samples

The macrostructure, surface profile, surface topography, and surface morphology of the weld samples were done, and the results are presented below.

4.2.1. Macrostructure and Weld Appearance

The cross-sections and surface of a typical weld are shown in Figure 4.6. All weld samples were clamped to ensure tight fit-up and alignment for welding. The surface appearance of the welded joint was good, smooth, of uniform weld width, and without apparent defects such as cracking, undercutting, or porosity.

4.2.2. Surface profile of stainless steel pipe joints

An OLYMPUS BX 63 optical microscope was used to investigate the microstructure of the weld interface. The analysed results of the three groups are shown in Figure 4.7 i, ii and iii.

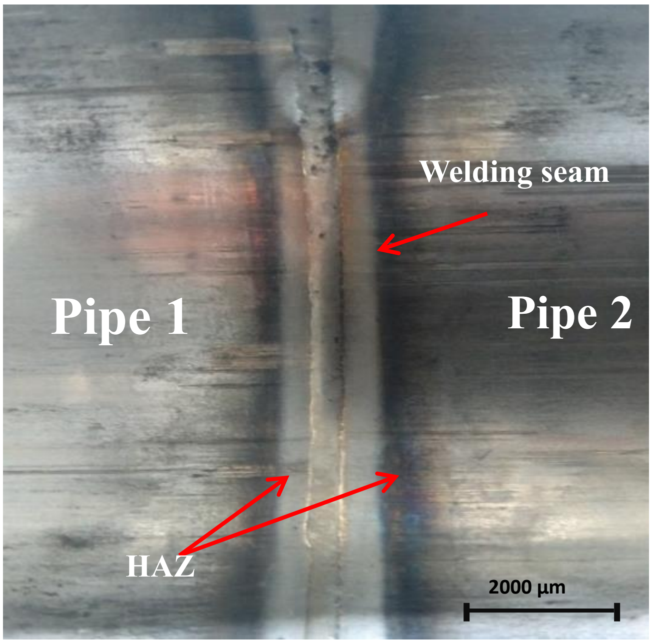

Figure 4.6 Cross-section of the weld area of welded pipes

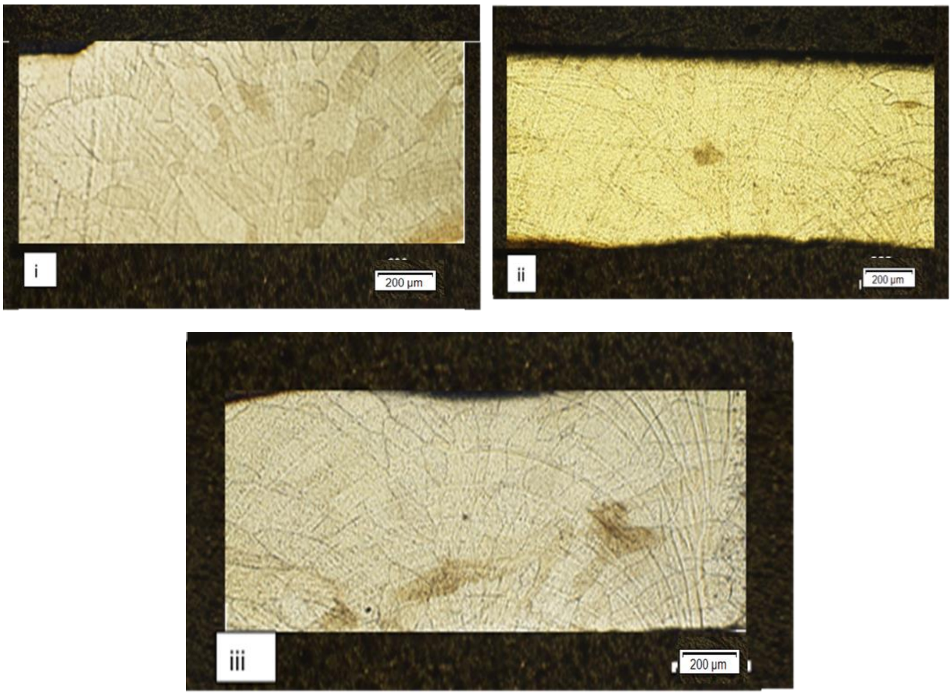

Figure 4.7 Polished and etched weld surface under optical microscope at 10x (i) Group 1 (ii) Group 2 (iii) Group 3

4.2.3. Result of different welding procedures on surface topography and surface morphology parameters

This section presents the results for surface topography and surface morphology for Group 1, Group 2, and Group 3. The Dimension 3100 Atomic Force Microscope was used to determine the surface these parameters, with the surface profile covering the weld zone and the HAZ area of typical Group 1, Group 2 and Group 3 shown in Figure 4.8. The detailed surface topography and surface morphology parameters are seen in Table 4.5 (see Appendix A for the definition of acronyms).

Table 4.5 Surface topography and surface morphology parameters

		Surface topography			Surface morphology	
		R_a	R_q	R_{max}	R_{skw}	R_{kur}
Group 1 No pipe end treatment (Ns)	**1**	50,223	68,457	502,271	-0,732	5,357
	2	38,000	49,935	299,812	1,092	4,381
	3	41,343	54,224	327,994	-0,388	3,412
	4	53,824	70,075	421,651	0,746	3,574
	5	49,312	58,326	358,922	-0,201	3,214
	6	47,851	62,903	402,320	-0,104	3,313
Group 2 Swage only(SW)	**1**	20,187	25,677	167,071	0,501	3,357
	2	48,105	59,177	383,541	0,727	3,416
	3	49,491	64,207	435,843	0,951	4,793
	4	67,613	80,293	362,753	0,26	2,144
	5	28,442	35,687	244,091	-0,533	3,149
	6	37,002	45,155	291,891	0,251	2,917
	7	76,087	100,22	538,410	1,225	4,554
Group 3 Impact plus Swage (SI)	**1**	11,072	13,770	82,773	-0,072	2,717
	2	36,045	45,907	362,280	0,818	3,812
	3	17,081	21,232	163,500	0,519	3,878
	4	40,991	52,987	338,20	-0,314	3,52
	5	49,481	58,849	301,050	0,061	2,252
	6	31,682	38,037	180,730	0,596	2,391
	7	72,705	88,394	548,000	0,379	2,673

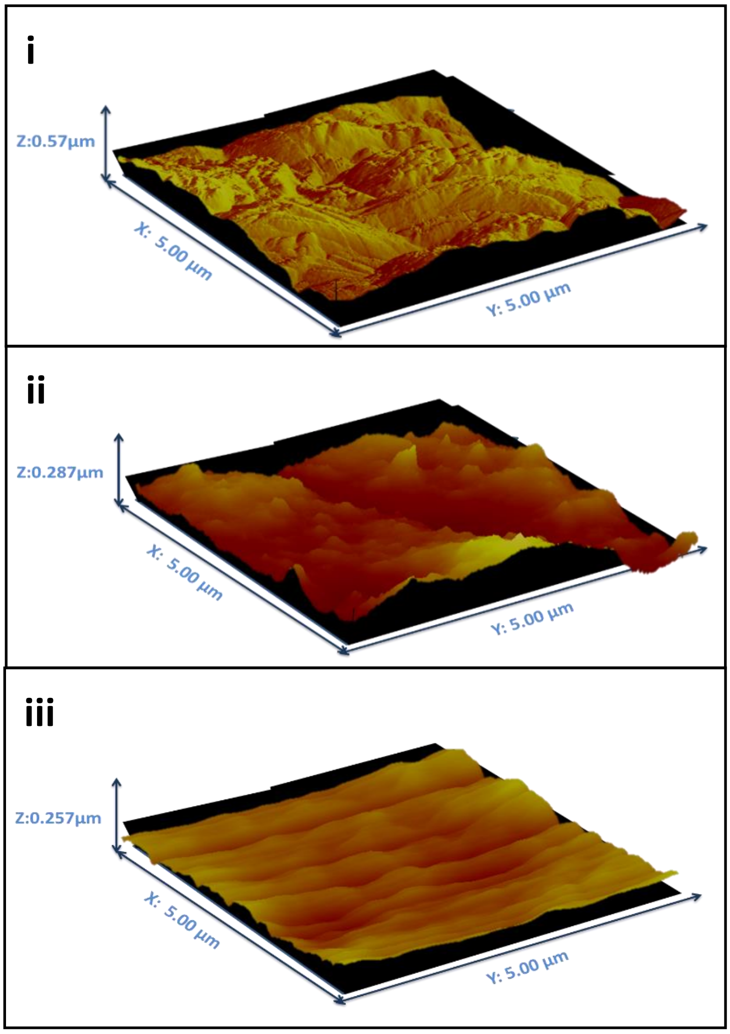

Figure 4.8 Surface analysis AFM with 5x5µm^2 surface area for (i) Group 1 (ii) Group 2 (iii) Group 3

4.2.3.1. Surface topography analysis of weld surface

For the hygienic industry, surfaces generally require an average roughness of (Ra) < 800 nm (Frantsen and Mathiesen, 2009). The surface finish of all the pipe welds in this experiment showed a 2B finish. 'A 2B finish is a smooth, moderately reflective cold-rolled annealed and pickled or descaled finish'. It is the most widely used stainless steel surface finish and is especially common in industrial, chemical and food processing applications, and is specified because it is highly corrosion resistant. The pipes were categorised as smooth since R_a < 500 nm (Detry et al., 2010; Lelièvre et al., 2002).

From Table 4.5 above, and the ranking of the R_a, R_q, and R_{max} shown in Figure 4.9, Figure 4.10 and Figure 4.11 below, it was deduced that for R_a, Group 3 pipes had the lowest roughness values with the lowest minimum, maximum and average values, followed by Group 2 pipe weld surfaces and then Group 1 welded pipes. Only Sw7 (Group 2) and Si7 (Group 3) had relatively high roughness values as they were randomly aligned but they were still lower than most of the group 1 pipes.

The results were also similar for the R_q and R_{max} of the weld surfaces.

These results show that swaging, especially after applying an impact force parallel to the axis of the pipe sufficient to distort its end before swaging, led to a lower roughness surface topography. However, it is important to note that clamping of the pipe ends assisted all the samples to achieve similar values.

- R_a (average roughness)

Group 1 > Group 2 > Group 3

- R_q (Root-mean-square profile height)

Group 1 > Group 2 > Group 3

- R_{max} (Maximum peak-to-valley height)

Group 1 > Group 2 > Group 3

These results serve as evidence to show swaging, especially when applying an impact force before swaging with the major axis aligned generally led to less rough surface topography.

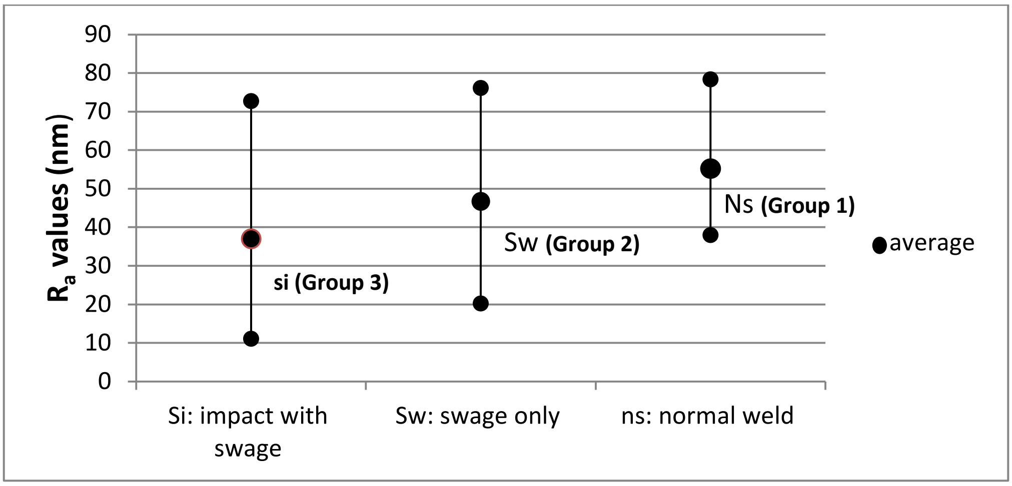

Figure 4.9 Average surface roughness (Ra) of pipe groups indicating minimum, average and maximum values.

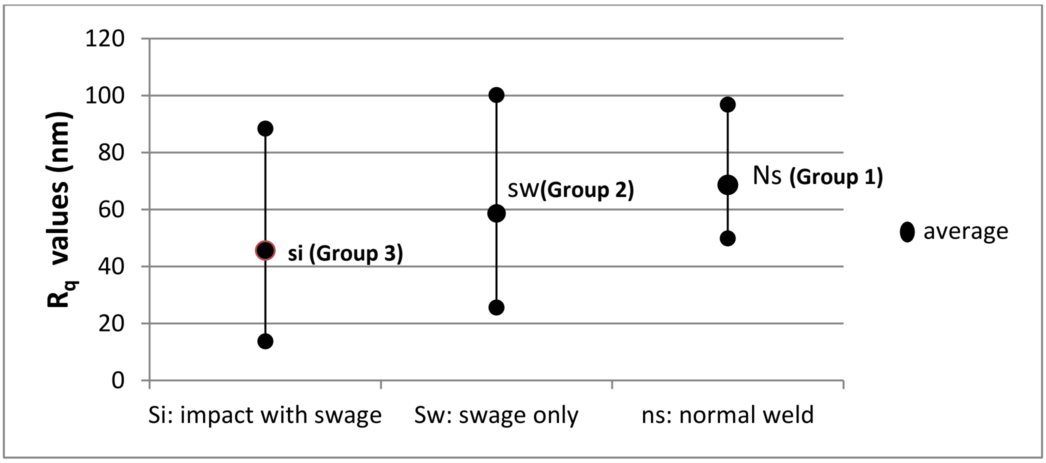

Figure 4.10 Profile height (R_q) of pipe groups indicating minimum, average and maximum values

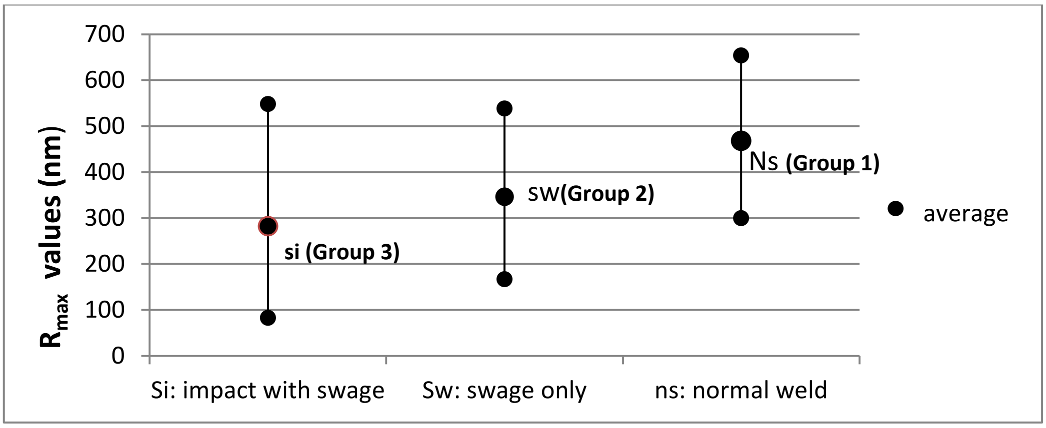

Figure 4.11 Maximum peak-to-valley height (R_{max}) of pipe groups indicating minimum, average and maximum values

4.2.3.2. Surface morphology analysis of weld surface

Surface morphology was applied to the coupons. The results were presented in Table 4.5. The investigation was to determine the smoother surface leading to limit bacterial accumulation. Appendix A lists definitions of the acronyms used for surface morphology.

Coupons with R_{skw} values close to zero indicate that there is a balance between valleys/pits and peaks (meaning coupons have almost symmetrical surfaces). The presence of peaks still serves as areas for microbes to accumulate. The diagrams below are all symmetrical the desirable one is smoother. We are seeking smoother surfaces as shown in Figure 4.12 on the right hand side (C).

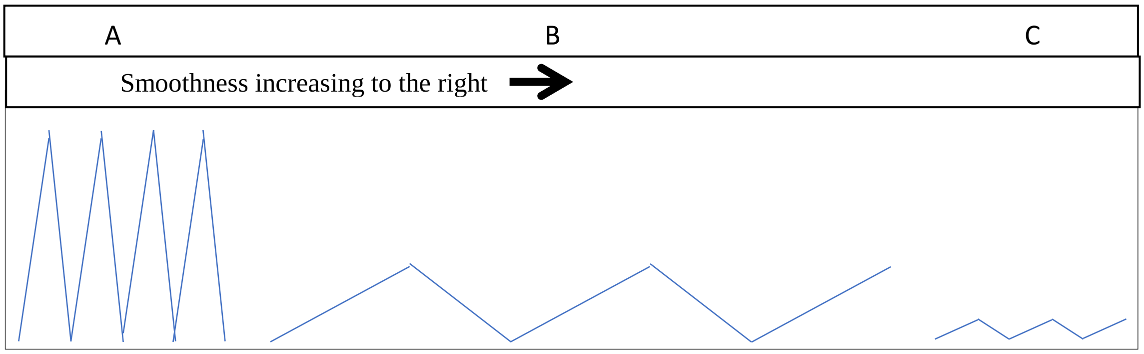

Figure 4.12 Samples of symmetrical surfaces

The coupons from the control group all had $R_{kur} > 3$, with 42% of Group 2 and 70% of the Group 3 had a R_{kur} value of ≈ 3. A R_{kur} value ≈ 3 shows that the surface was almost even, indicating that Group 3 had a smoother surface in comparison to the other groups.

4.3. Discussion

The effect of pipe end preparation before welding plays an important role on the formation and propagation of biofilms in hygienic process plants. Biofilms contain inorganic, organic and biological (microorganisms) materials. In a study (Detry et al., 2010) the connection between microbe cell size, surface topography, and morphology was emphasized, i.e. surface roughness and defects aid retention of microbial cells. Microbes such as E. coli cells that measure 2–3,4 µm in length and diameters of 0,5–0,9 µm on average get trapped in grooves or grain boundaries of weld surfaces (Trueba and Woldringh, 1980). Bacteria will attach themselves to small scratches, rather than larger indentations which appear more like a flat surface; therefore, it is more difficult for the microbes to attach (Detry et al., 2010).

Surface topography and morphology data can be used to predict bacterial attachment as rough surfaces are more predisposed to microbe loading than smooth surfaces. Commercially sourced thin-walled pipes have varying tolerances which greatly affects fit up and thus orbital welding outcomes, resulting in a rougher surface which favours biofilm formation. Swaging pipe ends, most especially impacting it with a force to prevent springback (thereby reducing internal stresses), ensures greater uniformity and better fit up during pipe welding, also the clamping of pipes before orbital welding enhances fit up thus limiting distortion after welding as observed in Group 3.

In summary:

The coupons in this study were analysed using an Atomic Force Microscope, a non-destructive, practical technique for assessing surface topography and surface morphology in a measurable manner.

Perfect surfaces have the following characteristics:

(i) low R_a,

(ii) low R_{max},

(iii) $R_{skw} = 0$, and

(iv) $R_{kur} = 3$

The different surfaces results were ranked from best to worst:

R_{max}	Impact and Swage weld⇒swage surface⇒normal weld
R_a and R_q	Impact and impact weld⇒swage surface⇒normal weld
R_{skw}	Impact and Swage weld⇒swage surface⇒normal weld
R_{kur}	Impact and Swage weld⇒swage surface⇒normal weld

The following conclusions were reached:

As stainless-steel surfaces were welded:

- They developed a rougher texture with the HAZ covering 15±2mm on either side of the weld.
- Almost all the coupons surfaces contain largely peaks with a few pits/valleys.
- These surfaces encourage soil film formation.
- Group 1 coupons, (No pipe end treatment) the surface topography generally indicates the roughest weld group. The morphology showed that the samples had high variations of valleys and peaks.
- Group 2 coupons (Swage only), the surface topography showed these to be generally smoother than Group 1 but not as smooth as Group 3 coupons. The

surface morphology further emphasises this, with samples having mostly peaks apart from Pipe Sw7 which was randomly aligned before welding.

- Group 3 coupons (Impact and swage), were the smoothest with respect to the surface topography. The morphology showed that the samples had minimal variations of peaks apart from Si7 which was randomly aligned before welding.
- Clamping of pipes before welding helped achieve a good fit-up irrespective of pipe parameters.

5. CONCLUSION AND RECOMMENDATIONS

The research indicates that pipe alignment can be improved by modifying pipe ends. Swaging, particularly when applying an extra transverse impact before swaging, results in better feying surface fit up. As a result, better welds with less area for microbe attachment were achieved. This can be a more effective means of improved site welded pipes. In addition, pipe ends should be clamped to ensure better alignment and fit-up before welding. With better weld conditions achieved, better hygienic performance is anticipated.

It is paramount for all the active parties in the production process liaise together. The prospective advantages derived from the appropriate management of interfaces are listed in Table 5.1.

Table 5.1 Attainable advantages of effective management of gaps and challenges facing hygienic welded fabrication (Mamvura et al., 2017).

Factors	End users	Designers	Fabricators	Piping suppliers
Improved hygiene standards	+	+	+	
Improved welding procedures	+	+	+	
Improved welding quality	+	+	+	
Piping standards	+	+	+	+
Training & development of welders	+	+	+	
Improved supply chain communication	+	+	+	+

Whilst it is desirable that sheet and pipe manufacturers both tighten tolerances and reduce internal stresses, especially for pipes utilised in process plants for human consumables, it is realized that there are cost implications. Transport can also play a role. Consequently, systematic modification of pipe ends onsite is recommended, separating between pipe end modification before onsite welding, such that the welder concentrates only on fit-up and alignment. More effort should be put into improving the skills of fabricators generally. Clamping is also recommended as it improves alignment and fit-up. The whole process should be overseen by knowledgeable supervisors.

There is a disparity between practical realities and plant design. Increasingly stringent hygiene requirements may lead to amplified CIP, this leads to an increase in the demand for water and more production stops. Although good design plans exist for hygienic plants, there is a deficiency in practical steps, skill improvement, and appropriate observation in South Africa. There is a need to prioritise, creating easy replicable techniques for welders to increase the certainty of creating a good weld joint, because hygiene requirements, may well prove significantly demanding to achieve. In industry, biofilms can form quickly and are difficult to remove. However, as shown, swaging pipe ends can play a part in controlling biofilms.

Impact coupled with swaging prior to welding can be effective in improving fit up leading to a reduced bacterial load. Clean in place (CIP) procedures will be required less often. This translates to less strain on municipal water sources and chemical wear and tear on pipes. Consequently, the pipe end modification proposed should prove commercially economical and ease operational costs. However, they may well both increase initial capital costs and time of production. In principle, the more hygienic the fabrication process, the lesser the need for CIP, thus leading to a more productive plant as production is not stopped as much for CIP.

Future work and recommendations

The study carried out led to further questions that could be explored in the future. More research has to be conducted to answer these questions which are:

- A comparative study of swaging with other methods of disinfection of pipe welds to discover which method is most efficient under the same conditions.
- Research on the probability of successfully achieving a perfect weld with a deep analysis of all pipe defects, welding process defects, and other factors
- The effect swaging has on the welding of pipes to pipe bends.
- Test of swaged pipes in industry in comparison to unswagged ends to quantify cost effect.

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APPENDIX A: SURFACE TOPOGRAPHY AND SURFACE MORPHOLOGY PARAMETERS

The five parameters used are defined as:

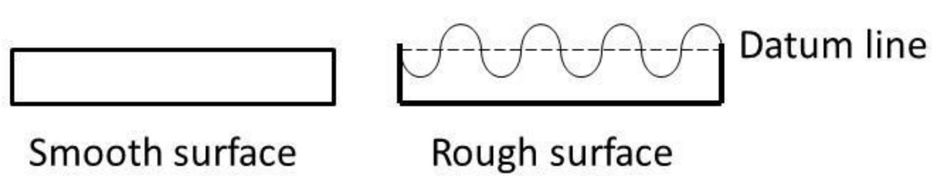
6.1.1. Average roughness (R_a)

It is the average distance from the profile to the mean line over the length of assessment, measured in µinch or µm and it is determined by the following formula:

$$R_a = \frac{1}{l_m}\int_0^{l_m} |y(x)|\, dx$$ (Scardino *et al.*, 2008).

where l_m is the number of sampling points and y(x) is the residual surface.

R_a does not differentiate between peaks and valleys (Mummery, 1992). The mean line is a form of reference datum and all the descriptors used to characterise the surface topographies are measured with respect to this line. The mean line is the plane that represents the geometrical plane of the surface where the volumes above and below the plane are equal. The larger the value of R_a, the greater the roughness profile of the surface roughness (Scardino *et al.*, 2008). The following image gives a qualitative vision of this parameter:



(Scardino et al., 2008).

6.1.2. Root-mean-square (RMS) profile height (R_q)

This is the square root of the average of the square of the deviation of the profile from the mean line and it is determined by the following formula:

$$R_q = \sqrt{\frac{1}{l_m}\int_0^{l_m} y^2(x)dx}$$

(Scardino *et al.*, 2008).

R_a and R_q are frequently used to express surface roughness but cannot differentiate between the peaks and valleys of a surface and therefore are considered somewhat deceptive (Scardino *et al.*, 2008).

6.1.3. Maximum peak-to-valley height (R_{max})

It is the maximum peak-to-valley height within one cut-off (Scardino *et al.*, 2008).

6.1.4. Surface skewness (R_{skw})

It is a measure of the direction of the asymmetry of the distribution of heights in the sample or a measure of the average of the first derivative of the surface i.e. the departure of the surface from symmetry. This statistical parameter is given by the following expression:

$$R_{skw} = \frac{\sum_{i=1}^{N}(Z_i - Z_{ave})^3}{N\sigma^3}$$

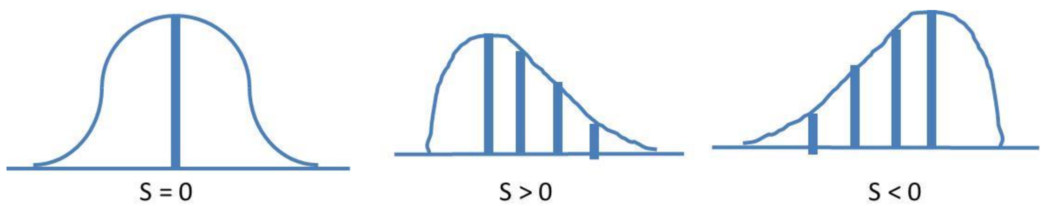
Where: $$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(Z_i - Z_{ave})^2}{N}}$$

(Scardino *et al.*, 2008).

The numerical value of R_{skw} gives information about the direction of the asymmetry of the distribution of heights:

- If R_{skw} >0: positive asymmetry i.e. indicates that the surface is made up of mainly peaks and asperities
- If R_{skw} =0: symmetric distribution
- If R_{skw} <0: negative asymmetry i.e. indicates that the surface is made up of mainly pits or valleys

Therefore a negatively skewed surface is good for lubrication purposes. The following image gives a qualitative vision of this parameter:



(Scardino *et al.*, 2008).

6.1.5. Surface kurtosis (R_{kur})

It is a measure of the peakedness of the distribution of heights in the sample by comparing it to the normal distribution. This statistical parameter is given by the following expression:

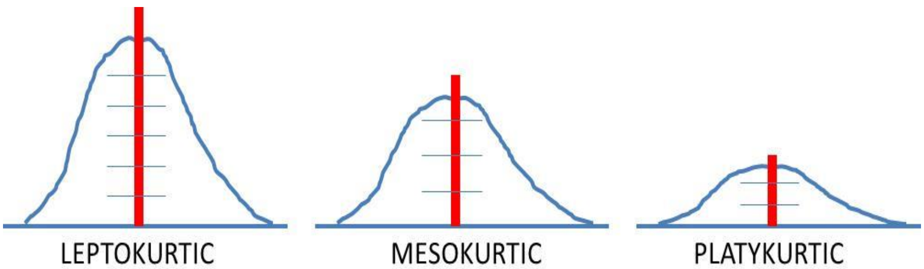
$$R_{kur} = \frac{\sum_{i=1}^{N}(Z_i - Z_{ave})^4}{N\sigma^4}$$

Where: $$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(Z_i - Z_{ave})^2}{N}}$$

The numerical value of R_{kur} gives us information about the distribution of heights:

- If $R_{kur} > 3$: leptokurtic distribution (high peaks or deep valleys)
- If $R_{kur} = 3$: mesokurtic distribution (normally distributed surface)
- If $R_{kur} < 3$: platykurtic distribution (lack of high peaks or deep valleys)

If the surface heights are normally distributed (i.e. bell curve) then R_{skw} is 0 and R_{kur} is 3. The following image gives a qualitative vision of this parameter:

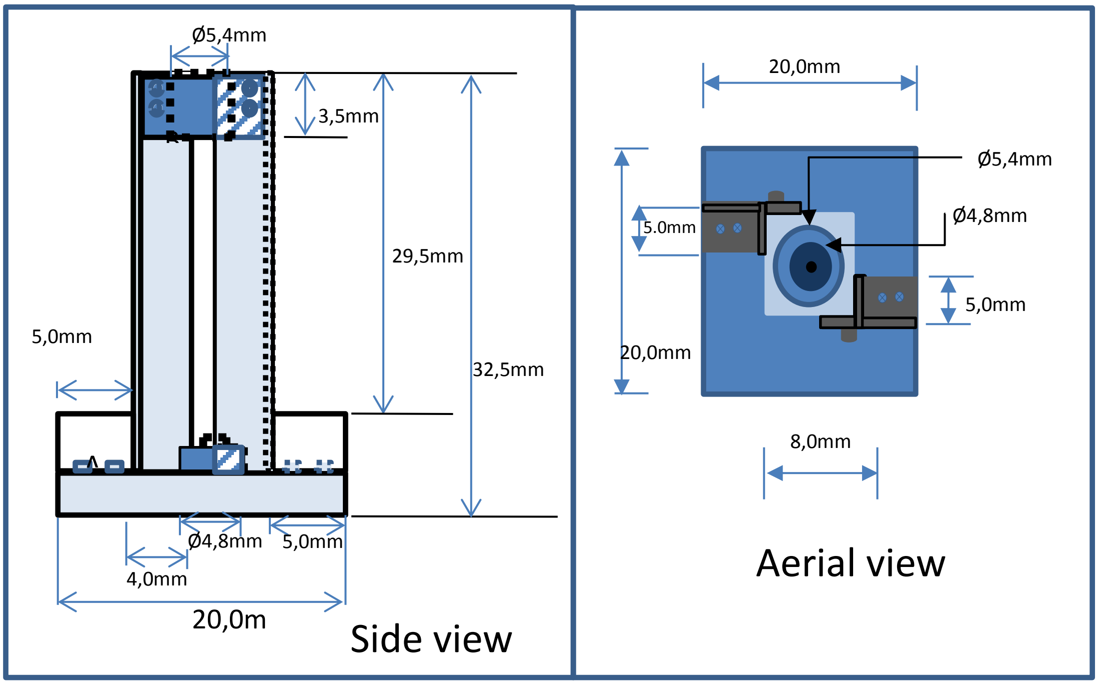


(Scardino *et al.*, 2008).

APPENDIX B: SWAGE FRAME AND PUNCH DESIGN

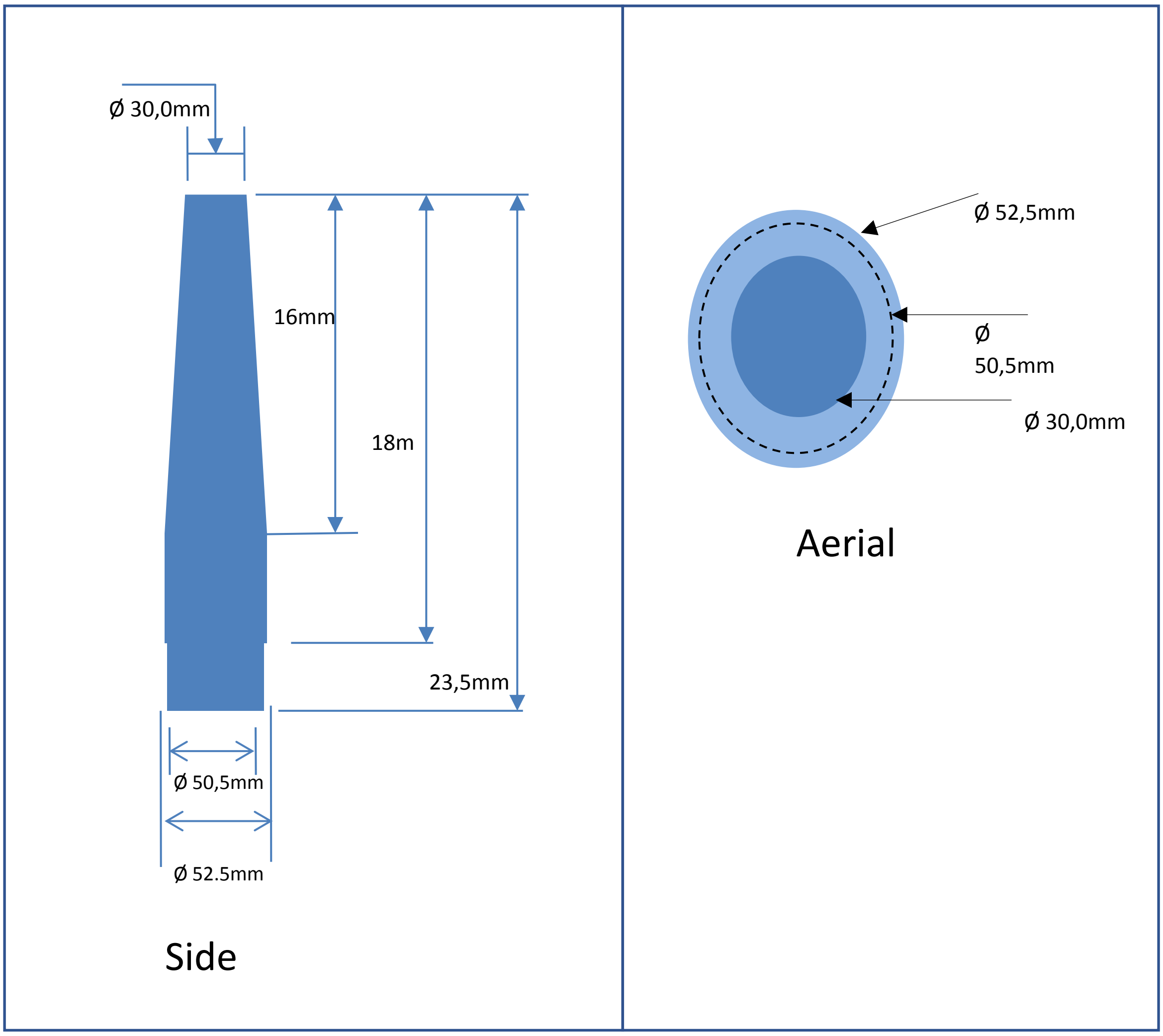
Swage frame design:

Component: mild steel



SWAGE PUNCH:

All contact surfaces to be polished to avoid scratching stainless steel. Corners need to be radiuses as required to facilitate flow, with a 2 degree draft.



APPENDIX C: OWS'S ORBITAL SYSTEM USED FOR WELDING

Orbital welding parameters:

Power Pack: Fronius FPA 2003.

Welding Head: Polysoude MU 1V 64.

Wire Feeder: N/A Fusion Welds Only.

External Shielding Gas Used: Argon Gas 99% Purity.

Purging Shielding Gas Used: Argon Gas 99% Purity.

Tungsten Used: 2,4mm Thk, 2% Thoriated.

The trial orbital welding speed was 63mm p/min.

Weld current utilized was 50Amps Peak current and 28 Amps Back ground current on average

Arc Length: The gap between the tungsten and work-piece was 2mm,