EFFECT OF ELECTRODE TYPES ON THE SOLIDIFICATION CRACKING SUSCEPTIBILITY OF AUSTENITIC STAINLESS STEEL WELDMENT

BY

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CERTIFICATION

This is to certify that this research work “Effect of electrode types on the solidification cracking susceptibility of austenitic stainless steel weldment” was carried out by JUSTUS UCHENNA ANAELE (20114771028), in partial fulfilment for the award of an M.Eng. Degree, in the Department of Materials and Metallurgical Engineering, Federal University of Technology, Owerri.

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This work is dedicated to Mr. and Mrs. Aloysius Anaele.
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ABSTRACT

The effect of electrode types on the solidification cracking susceptibility of austenitic stainless steel weld metal was studied. The work also investigated the effect of electrode types on the strain hardening exponent of austenitic stainless steel welded joints. Manual metal arc welding method was used to produce the joints with the tungsten inert gas (TIG) welding serving as the control. Tensile tests and metallography of the joints were carried out using standard techniques. Chemical analyses of the fusion zones of the joints were conducted. The results indicate that weldments produced from E 308 –16 (gauges 10 and 12, rutile coated electrodes), E 308 – 16 (gauge 12, lime-titania coated electrode) and TIG welded joints fall within the range of $1.5 \leq \frac{Cr_{eq}}{Ni_{eq}} \leq 1.9$ (where $Ni_{eq}$ and $Cr_{eq}$ are nickel and chromium equivalents respectively. The E 308 – 16 (gauge 12, lime-titania coated electrode) weld had the greatest resistance to solidification cracking. The welded joints produced from E 310 – 16 (gauge 10) electrode had $\frac{Cr_{eq}}{Ni_{eq}}$ ratio $< 1.5$ and solidified with austenite mode and were susceptible to solidification cracking. The E 312 – 16 (gauge 10 electrode) produced welded joints having $\frac{Cr_{eq}}{Ni_{eq}}$ ratio $> 1.9$ and solidified with a ferrite mode. This weld had a low resistance to solidification cracking. The values of the strain hardening exponent and tensile strength of the welded joints were 0.379 and 475N/mm$^2$ for E 308-16 (gauge 10, rutile coated) electrode; 0.406 and 425N/mm$^2$ for E 308-16 (gauge 12, rutile coated) electrode; 0.382 and 425N/mm$^2$ for TIG welding; 0.353 and 517N/mm$^2$ for E 308–16 (gauge 12, lime-titania coated) electrode; 0.435 and 508N/mm$^2$ for E 310-16 (gauge 10, rutile coated) electrode and 0.396 and 525 N/mm$^2$ for E 312-16 (gauge 10, rutile coated) electrode. E 310 – 16 (gauge 10 electrode) had the greatest strength and strain hardening coefficients of 1180N/mm$^2$ and 0.435 respectively, and was recommended for welded joints when high formability is desirable. Also, the E 312 – 16 (gauge 10 electrode) was recommended for welded joints when tensile strength is very desirable.

Keywords: Austenitic stainless steel, solidification cracking, electrode type, welding, strain hardening coefficient.
CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

Stainless steel is a common name for steel alloys that consist of 10.5 weight percent or more of chromium (Cr) and more than 50 weight percent of iron (Fe). Stainless steels may be classified by their crystalline structure into three main types: Austenitic, Ferritic and Martensitic stainless steel. Austenitic stainless steel (ASS) contains a maximum of 0.15 percent carbon, a minimum of 16 percent chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic temperature to the melting point of the alloy.

Austenitic stainless steels have become the most widely used stainless steels and correspond to about 70 percent of all the stainless steel produced worldwide, as a result of their mechanical and metallurgical properties and their good weldability (Cui et al., 2006). The excellent properties of ASS which range from high tensile strength, good impact resistance, excellent ductility, corrosion and wear resistances have found various applications in domestic as well as in many engineering industries, some of which are cooking utensils, food processing equipment, equipment for chemical industry, truck trailers, kitchen sinks, exterior architecture, pressure boilers and vessels, fossil-fired power plant, fuel gas desulphurization
equipment, evaporator tubing, super heater and reheating tubing, steam headers and pipes among others (Galal et al., 2005; www.Steel.org/learning/glossary).

In recent times, advancement has been made in such joining process as adhesives, mechanical fasteners, brazing and soldering. However, welding remains the most important metal joining process, even as arc welding is the most widely used fusion-welding process. In the fabrication of austenitic stainless steel components, welding is one of the most employed methods (Afolabi, 2008; Ovat et al., 2012). However, many research findings have proved that improper technique employed in welding austenitic stainless steel may lead to serious consequences of the structure (Woollin, 1994; Korinko et al., 2001; Parijslann, 2002).

Despite the good weldability property exhibited by ASS, hot cracking has been the major metallurgical problem encountered during welding of Austenitic stainless steel components. It is caused by the formation of low melting eutectics at the grain boundaries during welding, which cause failure under the action of shrinkage stresses associated with solidification. Solidification cracking is a type of hot cracking which depends on mechanical restraint and metallurgical susceptibility (Baldev et al., 2006). It consists of fractures at the interdendritic and/or intergranular weld metal boundaries in the solidification process, during which the liquid phase of the mushy melt becomes rich in impurities, mainly sulphur (S) and phosphorus (P). This phenomenon reduces the mechanical strength at the grain and
dendritic boundaries, rendering them susceptible to cracking and failure eventually (Arantes et al., 2007). One of such failures is the corrosion cracking of a grade 304 stainless steel pipe improperly seam welded and meant for the conveyance of glucose solution in Illinois USA (James, 2000).

In view of the problem of solidification cracking in ASS weldment, many works have been carried out in order to explain the phenomenon of solidification cracking and ways of preventing it. As early as 1941, Scherer et al., found that crack resistance in ASS weld metal may be improved by adjusting the composition to 5 – 35 percent ferrite in the completed weld. Hull (1967) confirmed this by stating that when ferrite content in the completed weld increase beyond 35 weight percent, the weld metal would become susceptible to solidification cracking, but the mechanism by which crack resistance is achieved by the effect of retained ferrite in the weld metal is still not completely understood.

Good attempts, however, have been made to explain the effect. Borland and Younger (1960) suggested that the higher solubility for impurity elements in delta – ferrite leads to less interdendritic segregation and reduces cracking tendency. Their et al. (1987) found that the volume contraction associated with ferrite – austenite transformation reduces tensile stresses close to the crack tip, which decreases cracking tendency. Apart from the effect of retained delta–ferrite in the control of solidification cracking in ASS weldment, Baldev et al. (2006) and
Borland (1960) suggested that solidification cracking in ASS weld metal could be minimized by the various practices which reduce mechanical restraint in the completed weld metal. These research works all yielded positive results.

1.2 PROBLEM STATEMENT

As can be seen in some of the research works cited above, solidification cracking in austenitic stainless steel weldment is a function of the weld metal composition. The composition of ASS weldment can be affected by the composition of the electrode used in carrying out the welding process. The choice of electrode type is critical and has continued to pose a serious challenge in the weldability of ASS materials. A well designed product, for example, can fail by cracking if the weld rod selected results in the weld zone having lower alloy content than that of the parent metal. Therefore, there is need to determine how the electrode type affects the solidification cracking susceptibility of ASS weldments. This research work is supposed to address the issues raised above while investigating the possible mechanism responsible for crack sensitivity in the weld microstructure.
1.3 OBJECTIVE

The main aim of this research is therefore, to investigate the effect of electrode types on the microstructural susceptibility of the austenitic stainless steel weldment to solidification cracking. The specific objectives are:

i. To determine the electrode type that would impact crack resistant properties in the ASS weldment.

ii. To determine the solidification mode of ASS weldments produced from different stainless steel electrodes.

iii. To evaluate the metallurgical susceptibility of such solidification microstructures to solidification cracking.

iv. To determine the effect of the different electrodes on the strain hardening exponent of an austenitic stainless steel weldment.

1.4 JUSTIFICATION OF STUDY

Irrespective of the problems encountered during fabrication of austenitic stainless steel (ASS) via welding of which solidification cracking is the most deleterious, welding remains the principal joining method. It is therefore, important to control the metallurgy of the weld metal in the quest to realize a quality weld with crack resistant property necessary to overcome premature failures arising from solidification cracking in ASS fabricated components. A study on the microstructural effect of electrode types on the solidification cracking
susceptibility of ASS weld joints, therefore, is supposed to provide an insight into the assessment of cracking propensity by a simple analysis and evaluation of the weld metal composition and microstructure respectively.

1.5 SCOPE OF STUDY

With respect to the title of this thesis, this research was limited to the metallurgical susceptibility of an austenitic stainless steel weld metal to solidification cracking. The effect of different stainless steel electrodes on the microstructure, solidification mode and composition of the weld metal was studied in an attempt to find out how the weld metal composition affects the propensity for solidification cracking in austenitic stainless steel weldment. Weld metal chemical analysis was conducted to enable the computation of chromium and nickel equivalents which in turn determined the weld metal propensity to solidification cracking. The parameters studied were:

i. Ferrite number

ii. Sulphur and phosphorus content (by weight percent)

iii. Solidification mode

iv. \( \frac{\text{Cr}}{\text{Ni}} \) ratio

The effect of the different welding electrodes on the strain hardening exponent was also investigated and established.
Beyond the scope of this study were liqutation and ductility dip cracking. Furthermore, this study assumed cracking in austenitic stainless steel weld metal as a function of the composition. The contribution of strain (constraint) to solidification cracking was beyond the scope of this research.
CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 STAINLESS STEELS

A small amount of carbon alloyed with iron makes steel. When the properties of the steel result from alloying additives (such as chromium, nickel, molybdenum, niobium, titanium, etc.) other than carbon, it may be regarded as stainless steel.

Iron is allotropic in that it exists in at least two distinct crystalline forms, primarily dependent upon temperature. At high temperatures the face centered cubic (FCC) crystal structure of iron is stable and the term used to describe this phase is austenite. At very high and low temperatures the body centered cubic (BCC) crystal structure is the more stable phase and is given the name of delta (\(\delta\)) and alpha (\(\alpha\)) ferrite respectively. Rapid cooling with the attendant high solidification rates from the molten steel can ‘quench in’ the normal high temperature phase. Alloying additions can also alter the temperature ranges where these phases are most stable. Nickel atoms are normally the same size as iron atoms and arrange themselves in FCC structure over a large temperature range. Therefore, substitution of nickel atoms for iron atoms has the effect of stabilizing the austenite phase down to low temperatures. Chromium atoms are BCC and therefore a large substitutional addition of chromium to the steel has the effect of stabilizing the ferrite phase. Carbon and nitrogen atoms are smaller and occupy interstitial sites.
between the primary atoms in a given crystal. The unit cell structure of the austenite phase accommodates these interstitial atoms more readily than the unit cell structure of the ferrite phase. Carbon and nitrogen are therefore, very strong stabilizers at relatively small volume fractions. Sulphur and phosphorus are considered trace impurities, remnant from primary and secondary processing (Korinko et al., 2001).

Woollin (1994) reported that steels which contain a minimum of around 12% chromium are usually referred to as ‘stainless steels’ as a result of their resistance to corrosion due to the formation of a tenacious surface film which protects the underlying steel. Baldev et al. (2006) maintained that stainless steels contain typically 16-25% Cr, 7-20% Ni, and less than 0.08% C. For improved corrosion resistance, 2-6% Mo, 0.1-0.2%N and niobium or titanium in the stabilized varieties are added. Stainless steels are extensively used in a variety of applications where corrosion resistance is required in combination with good strength and toughness.

There are several categories of stainless steels based on crystal structure and strengthening mechanisms. They include:

i. Ferritic stainless steels

ii. Martensitic stainless steels

iii. Austenitic stainless steels

iv. Precipitation hardening stainless steels
v. Duplex stainless steels.

Each of these families has characteristic properties, designed to meet specified needs.

2.1.1 PROPERTIES OF AUSTENITIC STAINLESS STEELS

The austenitic stainless steels (ASS) are the largest and most important group in the stainless steel range and were developed by the addition, to the Fe – Cr system of alloying elements such as nickel (Ni) and manganese (Mn), which expand the austenite phase field to room temperature. Numerous austenitic stainless steel grades are available, with compositions in the range 16-26% Cr, 8-30% Ni, and various other alloying additions. Austenitic stainless steels containing chromium and nickel as the principal alloying elements (in addition to iron) are identified as American Iron and Steel Institute (AISI) 300 series types. Those containing chromium, nickel, and manganese (in addition to iron) are identified as AISI 200 series types (Afrox product manual; AISI handbook 1988; Woollin, 1994).

Austenitic stainless steels can be hardened by cold working, but not by heat treatment. In the annealed condition, they are non-magnetic. While resistance to corrosion is their principal attribute, they are also selected for their good ductility, toughness and excellent strength properties at high or extremely low temperatures. They are considered to be the most weldable of the high alloy steels and can be welded by all fusion and resistance welding processes.
2.1.2 APPLICATIONS OF AUSTENITIC STAINLESS STEELS

Austenitic stainless steels constitute the largest stainless steel family in terms of alloy type and usage. Because of its excellent mechanical properties and corrosion performance, it is largely used in various corrosive conditions between cryogenic to elevated temperature range. Austenitic stainless steel is probably the most common choice in material selection for chemical and food processing equipment, cryogenic vessels, welding construction, low and high pressure boilers, vessels, fossil-fired power plant, flue gas desulphurization equipment, evaporator tubing, super heater, reheating tubing, steam headers and pipes to mention but a few (Cui et al., 2006; Afolabi, 2008; Callister et al., 2012). Austenitic stainless steels are preferred over many other materials because of their performance in even the most aggressive environments, and they are fabricated by methods common to most manufacturers.

2.1.3 FABRICATION OF AUSTENITIC STAINLESS STEEL COMPONENTS

Using austenitic stainless steels for the various applications highlighted in section 2.1.2, will certainly involve different shapes and sizes ranging from simple to intricate. The manufacturer must employ ingenuity in the fabrication of austenitic stainless steel to suit the environmental and design considerations. Where design requires very intricate shape, the manufacturer would probably resort to foundry in
order to fabricate the component. Considering the fact that austenitic stainless steels have relatively high coefficient of expansion, distortion, warping and hot cracking can be a problem. In view of this, particular precautions should be taken in fabricating austenitic stainless steel components by foundry. Besides casting, austenitic stainless steel products, components, or equipment are mostly fabricated by employing the metal forming processes which include forging, rolling, stretching, bending, drawing etc. austenitic stainless steels are easily cold formed into desired shapes due to the fact that they have excellent ductility and good formability. In the fabrication of austenitic stainless steel components, Afolabi (2008) noted that welding is the principal joining method. Ideally, austenitic stainless steel fabrication should be done in an area where no other types of steel or material are processed, in order to prevent contamination.

The product manual from Afrox limited suggested the following guidelines for fabricating austenitic stainless steel components:

i. Thermal cutting should be done with appropriate process, that is, plasma arc, laser or arc air, not oxy-fuel cutting.

ii. If machining is performed, it should be done without overheating the base metal, which would cause oxidation.

iii. Grinding should be done with the correct grade of disc and with discs segregated for use only on austenitic stainless steel.
iv. All hand tools (files, deburring, knives etc.) should be segregated and used only on austenitic stainless steel.

v. All wire brushes should be made of stainless steel and used only on austenitic stainless steel.

2.1.4 WELD JOINT DESIGN

Welding is one of the most important and versatile means of fabrication available to industry. In a welded fabrication welds are used to join different parts. Such junctions of parts are called weld joints and are defined as the locations where two or more members are to be joined. Joint design is a general term used for a group of variables, which include the geometry of the parts as prepared for welding, thickness of the parts, arrangement of the parts, weld joint and restraint of the weld joint. The weld joint is designed to meet a certain combination of properties required for satisfactory performance in service. The objectives of weld joint design are to provide an assembly that:

i. Will perform its intended functions

ii. Will have required reliability and safety

iii. Is capable of being fabricated, inspected, transported and installed in service at minimum total cost.

The optimum choice of a weld design is one that meets all design and service requirement at a minimum cost. The selection of the weld type is particularly
assigned to the product design engineer, who considers the strength of the required joint, joint type and geometry, nature of materials to be joined, joining method to be employed, weldability of the material to be joined, and other service conditions where the weldment is to be applied. In addition, the joint design should be selected primarily on the bases of load requirements while the type of joint is determined by the relative positions of the two members being joined. The type of joint required often determines the weld type (fillet weld, groove weld, backing weld, flange weld, plug or slot weld, spot or projection weld, seam weld, and surfacing weld) to be adopted. The five basic types of weld joints as illustrated in Figure 2.1 include:

i. Lap joint produced by overlapping the members to be joined and then welding the edges.

ii. Butt joint obtained by placing the members to be joined edge – to – edge.

iii. Corner joint obtained by joining the edges of the two parts to be joined whose surfaces are at right angle to each other.

iv. Edge joint produced by joining two parallel members.

v. T – Joint obtained by joining two parts whose surfaces are approximately at right angles to each other.

(Baldev et al., 2006; Parmar, 2010; http://www.spartanmechanics.net/images/types of welding joints.JPG)
2.2 WELDING PROCESSES FOR AUSTENITIC STAINLESS STEELS

One of the most employed methods of fabricating austenitic stainless steel components is welding. A weld is a union between pieces of metal at faces rendered plastic or liquid by heat or pressure or both. The prime function of the welding operation is therefore, to provide metallic bonds between atoms at the interfaces of the joint (Okorafor et al., 2011).

2.2.1 PREWELD PREPARATION

Austenitic stainless steel needs to be prepared without contamination as any sources of free iron, rust, carbon or hydrogen etc; can cause welding or corrosion problems. It is imperative that the base metal be properly cleaned before welding. In most cases this involves:

i. Wirebrush or grind to remove any oxidation.
ii. Chemically clean all surfaces that were machine-cut with cutting fluids.

iii. Remove all oil, grease, moisture etc.

iv. Wipe all surfaces to be welded with acetone or isopropyl alcohol.

v. Weld in an area segregated from the welding of other alloys and use hold-down fixtures, vices, tools, and clamps etc; made of stainless steel or covered with protective material to prevent contamination (Afrox product manual).

2.2.2 WELDING AUSTENITIC STAINLESS STEELS

An important part of successful welding of austenitic stainless steel requires proper selection of alloy (for both the base and the filler rod), and correct welding procedures. According to AISI handbook (1988) the two important objectives in making weld joints in austenitic stainless steels are:

   i. Preservation of corrosion resistance

   ii. Prevention of cracking

In pursuit of these objectives stated above, it is therefore necessary, to exercise a reasonable degree of care during welding to minimize or prevent any deleterious effect that may occur and to preserve the same degree of corrosion resistance and strength in the weld zone that is an inherent part of the base metal.

   The two basic methods for welding stainless steels are:

   i. Fusion welding
ii. Resistance welding

In electric arc fusion welding, heat is provided by an electric arc struck between a carbon or metal electrode (connected to one terminal of a power supply) and the metal to be welded (which is connected to the other terminal).

In resistance welding, bonding is the result of heat and pressure. Heat is produced by the resistance to flow of electric current through the parts to be welded, and pressure is applied by the electrodes (Srinivasan, 2008; Okorafor et al., 2011).

In the study of the effect of electrode types on the solidification cracking susceptibility of austenitic stainless steel weldment, electric arc fusion welding procedure was adopted.

There are four principal processes for fusion welding of stainless steels. They are:

i. Shielded metal arc welding (SMAW)

ii. Gas tungsten arc welding (GTAW)

iii. Gas metal arc welding (GMAW)

iv. Submerged arc welding (SAW)

Other fusion welding methods for welding stainless steels include electron beam, laser and plasma arc welding. In all the cases, the weld zone is protected from the atmosphere by a gas, slag or vacuum, which is absolutely necessary to achieve and preserve optimum corrosion resistance and mechanical properties in the weld joint (AISI handbook 1988; Parmar, 2010).
2.2.2.1 SHIELDED METAL ARC WELDING (SMAW)

Shielded metal arc welding is a fast and versatile process that is very popular for welding austenitic stainless steels, especially for joining shapes that cannot be easily set up for automatic welding methods. It is characterized by the use of a solid electrode wire with an extruded baked-on coating material. Shielded metal arc welding is commonly called covered electrode welding due to the fact that the electrode is coated. The electrode coatings are generally lime-based or titania base materials, depending on the type of welding to be done and the type of power supply used (alternating current, AC, or direct current, DC, reverse polarity). The welding is performed manually with the operator holding the electrode at an angle, with the end just far enough away from the base metal to maintain an arc. As the metal melts off the end of the rod, the operator moves the electrode closer to the workpiece as well as moving it along the joint. The shielded metal arc welding operation and setup of the equipment are shown in Figures 2.2 and 2.3 respectively. The electrode coating is beneficial to the weld joint in several ways as stated below:

i. The primary function of the electrode coating is to initiate and maintain the arc column between the electrode and the workpiece.

ii. Impurities are removed from the molten metal by the flux.
iii. A gaseous envelope is formed by the decomposition of the ingredients in the electrode coating. This excludes the oxygen and nitrogen in the air from contact with the molten weld pool.

iv. The slag formed on top of the weld metal acts as a protective covering against contamination by the atmosphere as the weld cools, and serves to control the shape of the weld pool.

v. It provides alloy additions to the weld metal.

The handling and storage of coated stainless steel shielded metal arc welding electrodes is very important because coatings tend to absorb moisture, and the moisture in the weld zone during welding can lead to porosity which weakens the weld and becomes focal points for corrosion. For this reason, austenitic stainless steel electrodes must be stored in a warm, dry environment and preferably in the original sealed container (AISI handbook 1988; Baldev et al., 2006; Srinivasan, 2008; Parmar, 2010).

2.2.2.2 GAS TUNGSTEN ARC WELDING (GTAW)

Gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding as it is sometimes called is a fusion arc welding process that uses an inert gas usually argon, to protect the weld zone from the atmosphere. The fact that gas tungsten arc welding lends itself to autogenous welding makes it very significant in this study.
The electrode holder holds the tungsten electrode and controls the flow of shielding gas to the weld zone. The shield gas replaces the air in the arc area. An arc is established between the end of the tungsten electrode and the parent metal at the joint line. The electrode does not melt during the welding process (hence regarded as non-consumable electrode). The current is controlled by the power
supply unit. Where necessary, filler metal may be fed manually to supply metal to the joint. The filler metal must match the base metal composition. The welding operation and equipment setup are shown in Figures 2.4 and 2.5 respectively.

Fig. 2.4: Gas metal arc welding operation (Kalpakjian, 2008)

Fig. 2.5: Gas metal arc welding equipment setup (Kalpakjian, 2008)
When deep penetration is not important, alternating current, AC, is preferred to direct current, DC. This is because alternating current combines the work of cleaning action of electrode positive (reverse polarity) with deep penetration characteristic of electrode negative (straight polarity) of direct current (AISI handbook 1988; Baldev et al., 2006; Srinivasan, 2008).

2.2.2.3 WELDING PROCEDURE

The two welding techniques employed in this study as discussed in preceding sections, are:

i. Shielded metal arc welding

ii. Gas tungsten arc welding

In order to investigate the effect of electrode types on the solidification cracking susceptibility of austenitic stainless steel weldment, the base metal was welded in two different welding procedures namely:

i. Welding with no filler addition or with filler metal of matching composition with the base metal. This welding technique is regarded as autogenous welding and is applied in this study during the gas tungsten arc welding.

ii. Welding with non-matching filler rod or with a consumable electrode. This welding technique is applied in this study during the shielded metal arc welding operation. The resulting weld metal composition would depend
upon the filler material type, and the level of dilution which is controlled by
the welding process and the variables employed.

2.2.3 WELDING ELECTRODES

Arc welding is a fusion welding process in which coalescence of the metals is
achieved by the heat from an electric arc between an electrode and the workpiece.
The electrodes used in arc welding process are classified as:

i. Consumable Electrode

ii. Non – consumable Electrode

Consumable electrodes provide the source of the filler metal in arc welding. These
electrodes are available in two principal forms:

i. Electrode rods (also called sticks)
ii. Electrode wire

Welding rods are typically 255 – 450mm long and 9.5mm or less in diameter. The
problem with consumable welding rods, at least in production welding operations,
is that they must be changed periodically, reducing arc time of the operator.
Consumable electrode weld wire has the advantage that it can be continuously fed
into the weld pool from spools containing long lengths of wire, thus avoiding the
frequent interruptions that occur when using welding sticks. In both rod and wire
forms, the electrode is consumed by the arc during the welding process and added
to the weld joint as filler metal.
Non-consumable welding electrodes are made of tungsten (or carbon) which resists melting by the arc. Despite its name, a non-consumable electrode is gradually depleted during welding process, analogous to the gradual wearing of a cutting tool in a machining operation by vaporization mechanism. For arc welding processes that utilize non-consumable electrodes, any filler metal used in the operation must be supplied by means of a separate wire that is fed into the weld pool (Parmar, 2010; www.wikipedia.org).

2.2.3.1 AUSTENITIC STAINLESS STEEL ELECTRODE CLASSIFICATION

The American Welding Society (AWS) classifies flux core arc welding electrodes as tubular wire, with a filler metal classification number of AS. 22 AWS for stainless steels. The AWS classification for stainless steels for flux core arc welding electrodes starts with the letter E as its prefix. Following the E prefix, the American Iron and Steel Institute’s (AISI) three digit stainless steel number is used. This number indicates the type of stainless steel in the filler metal. To the right of the AISI number, the AWS adds a dash followed by a suffix number. The
number 1 is used to indicate an all – position filler metal, and the number 3 is used to indicate an electrode to be used in the flat and horizontal positions only. The electrode classification code represented as E X X T- X is defined in Fig. 2.6.

![Identification system for steel flux cored arc welding electrodes](image)

Figure 2.6: Identification system for steel flux cored arc welding electrodes (Courtesy of AWS, 1980)

Some of the common stainless steel electrodes according to the AWS specifications include: E 308-16, E 308H-16, E 308-15, E 308L-15, E 308-17, E 308L-17 among others (AIPD Welding operations 1, sub-course (OD1651); [http://www.cascom.army.mil/ordinance/](http://www.cascom.army.mil/ordinance/), Davies, 2008).

2.2.4 WELDING METALLURGY OF AUSTENITIC STAINLESS STEELS

When joining any material to be used under demanding conditions, it is important to ensure that the joint has adequate properties to perform successfully in service. When a fusion welding process is employed, the original microstructure of the
fusion zone is destroyed and a new structure develops, in a similar manner to that of a casting. The resulting room temperature structure depends upon the phases developed during solidification, and the extent of subsequent solid state transformations (Woollin, 1994). The physical properties and serviceability of the resulting weld metal is determined by the microstructure and thermal history (Korinko et al., 2001). According to Srinivasan (2008) the structural changes that occur during welding depend majorly on:

i. The welding process used

ii. The type and composition of filler rod or electrode used

iii. Condition under which the weld is made and

iv. The composition of the parent metal

During the welding of austenitic stainless steel, the temperatures of the base metal adjacent to the weld reach levels at which microstructural transformations occur. The degree to which these changes occur and their effect on the finished weld in terms of resistance to corrosion and mechanical properties depend upon the following:

i. Alloy content

ii. Section thickness

iii. Filler material type

iv. Joint design
v. Welding procedure and method

vi. Welder’s skill

A weld joint consists of several zones which include:

i. Weld metal zone also regarded as the mixed zone which is essentially a solidified structure of the base metal and filler metal. The degree of dilution is controlled by the welding process and the variables employed.

ii. Unmixed zone in the base metal adjacent to the fusion line where the base metal has melted but is not mixed with the filler material.

iii. Partially melted zone which has experienced thermal cycles with peak temperatures lying between the solidus and liquidus temperatures.

iv. Heat affected zone (HAZ) which has experienced thermal cycles (peak temperatures) high enough to cause microstructural changes but insufficient (being less than the solidus temperature) to effect melting.

Each zone because of its characteristic microstructural features has different properties. Baldev et al. (2006) found that a ternary eutectic transformation occurs during solidification of austenitic stainless steel weld metal, with the simultaneous formation of austenite and delta-ferrite (δ) from the liquid (weld pool). As shown in Figure 2.7, the relative proportions of austenite and delta-ferrite (δ) in the solidified weld metal are a function of the composition expressed in \[ \text{ratio} \].
Where, \( \ldots = h \)

\[ \ldots = \]

Fig. 2.7: The 70% Fe section of the Fe-Cr-Ni phase diagram (Baldev et al., 2006)

Fig. 2.8: The 70% Fe section of the Fe-Cr-Ni phase diagram showing the solidification modes as a function of composition.
Culled from Baldev et al. (2006).

Where L, γ, and δ denotes liquid phase, austenite and delta-ferrite respectively.

A = Austenite solidification mode

AF = Austenite – ferrite solidification mode

FA = Ferrite – austenite solidification mode

F = Ferrite solidification mode

The various transformations that occur in the solid state were reported by Baldev et al. (2006) as follows: delta – ferrite to sigma phase, carbides and austenite. The sigma phase appears at temperature below 900 °C while transformation to sigma phase occurs in weld microstructures on ageing in the temperature range 600 – 950 °C. In the presence of carbon, the chromium carbide Cr23C6 precipitates rapidly on exposure in the temperature range of 550 – 850 °C. Austenitic stainless steels of the AISI 300 series of stainless steels were reported by Shankar et al. (2003) to solidify during welding as a mixture of austenite and ferrite. The ferrite
almost fully transforms to austenite on cooling, but there could be retention of a few percent δ-ferrite in the weld metal.

2.2.5 SOLIDIFICATION MODE AND WELD METAL MICROSTRUCTURE

The various solidification modes occurring in austenitic stainless steels as reported by Shankar et al. (2003) and Baldev et al. (2006) are:

i. Austenite (A)

ii. Austenite – Ferrite (AF)

iii. Ferrite – Austenite (FA)

iv. Ferrite (F)

In any of the solidification modes stated above, the fraction of ferrite remaining in austenite weld metal after solidification has been presented graphically as a function of composition on the WRC – 1992 constitution diagram for stainless steels weldment as shown in Figure 2.9.

The WRC – 1992 constitution diagram was developed from manual metal arc weld metal and is applicable to common arc welding processes. However, the microstructure developed may be sensitive to cooling rate, which controls the extent solid state transformation. Consequently, Laser and Electron Beam welds do not necessarily conform to the predictions of the diagram (David et al., 1987; David et al., 1989). Predictions can be made for a particular composition by
categorizing the alloying elements as ‘ferrite stabilizing’ (examples are chromium, molybdenum, silicon, niobium, etc.) or ‘austenite stabilizing’ (examples are nickel, manganese, carbon, nitrogen etc.) and calculating the ‘chromium and nickel equivalents’ which are then plotted on the diagram as displayed in Figure 2.9.

Fig. 2.9: The WRC – 1992 constitution diagram for estimating ferrite content and showing solidification mode in stainless steel weldments (Kotecki et al., 1992)

The concept of nickel equivalent (\[\text{Ni}_{\text{eq}}\]) is the term used for the cumulative effects of austenite stabilizing elements as a weighted summation of their respective concentration levels. On the other hand, chromium equivalent (\[\text{Cr}_{\text{eq}}\]) is the term used for the cumulative effects of ferrite stabilizing elements as a weighted summation of their respective concentrations.
Austenite crystals form from the melt under conditions when $\frac{\%}{\%} < 1.5$ and there is no further change in the structure after solidification. The austenite–ferrite solidification mode results under condition when $\frac{\%}{\%} \approx 1.5$, with austenite being the primary phase and a part of the remaining liquid solidifies as eutectic ferrite. When $\frac{\%}{\%} \approx 1.6$, the solidification mode would most likely be ferrite–austenite. Fully ferritic solidification mode results under condition when $\frac{\%}{\%} \approx 1.9$ (Woollin, 1994; Baldev et al., 2006).

Table 2.1 shows the list of chromium and nickel equivalent proposed by different researchers.

### 2.2.6 WELDABILITY PROBLEMS IN AUSTENITIC STAINLESS STEELS

Austenitic stainless steels are considered to be the most weldable of all the high alloy steels. Austenitic stainless steels however, have a lower coefficient of thermal conductivity, which causes a tendency for heat to concentrate in a small zone adjacent to the weld. Also, they have coefficient of thermal expansion approximately 50 percent greater than that of mild steel. Consequently, this makes austenitic stainless steel weld metal susceptible to warpage, distortion and hot cracking. Many research findings have shown that the major metallurgical problem
encountered during welding of austenitic stainless steels is hot cracking (AISI handbook 1988; Shankar et al., 2003; Baldev et al., 2006;).

Table 2.1: List of possible and that may be used (Korinko et al., 2001)

| Author        | Year        | . . (wt.%) | . . (wt.%) |
|---------------|-------------|------------|------------|
| Schaeffler    | 1949        | + + 1.5 + 0.5 | + 0.5 + 30 |
| DeLong et al. | 1956        | + + 1.5 + 0.5 | + 0.5 + 30 + 30 |
| Hull          | 1973        | + 1.21 + 0.48 + | + (0.11 − ) + 0.0086 ) + 24.5 + |
|               |             | 0.14 + 2.27 + 0.72 + | 14.2 + 0.41 + 0.44 |
|               |             | 2.20 + 0.21 + 2.48 | |
| Hammar and    | 1979        | + 1.37 + 1.5 + | + 0.31 + 22 + |
| Svenson       |             | 2 + 3       | 14.2 + |
| Siewert and   | 1992        | + + 0.7    | + 35 + 20 + |
| Kotecki       |             |             | 0.25 |
| (WRC, 1992)   |             |             | |

Austenitic stainless steels show no other major change during cooling to room temperature, and therefore, no pre-heat is normally required when welding them. However, some precipitation may occur during cooling, such as the formation of chromium carbides on the heat affected zone grain boundaries, leading to depletion of chromium and leaving the material in a sensitized state and vulnerable to
intergranular attack also known as weld decay. The risk of weld decay has reduced significantly in recent years through the development of low carbon grades which contains less than or equal to 0.03 percent carbon, and stabilized grades containing titanium or niobium which form carbides preferentially to chromium (Woollin, 1994). Besides hot cracking, Parmar (2010) listed stress corrosion cracking, knife edge attack, carbide precipitation, and ferrite and sigma phase transformations as the specific problems associated with the welding of austenitic stainless steels.

Welding austenitic stainless steels therefore, requires special attention considering the weldability problems discussed above which are associated with the weld metal.

2.2.7 WELD DEFECTS AND QUALITY

When performing welding on metals, the base materials are typically subjected to rapid heating and cooling in localized areas. Such thermal stress conditions coupled with entrapment of gases or foreign materials within the weld can produce distortion and lead to weld metal cracking which result in detrimental mechanical properties and poor performance of the welded assembly if not controlled. Weld defects are inevitable as no weld is completely perfect in real situations. Weld defects are generally stress raisers and initiation sites for crack initiation and propagation leading to premature failure of the weld in service.
Fracture mechanics utilizes the knowledge of these defects (their sizes, shape and location) and stress level (including residual stresses and externally imposed stress) in the control of weld metal failure. According to Baldev et al. (2006) defects in welded joints are classified into three namely:

i. Physical discontinuity (unacceptable contour, surface irregularities, undercut, underfill, lack of fusion, insufficient or excessive penetration etc.)

ii. Microstructural defects (cracks, porosity, blow holes, grain coarsening, solid inclusions, slag inclusions etc.)

iii. Defects related to residual stresses and distortion

Cracks are fracture – type interruptions either in the weld itself or in the base metal adjacent to the weld. This type of defect is perhaps the most serious welding defect because it constitutes a discontinuity in the metal that causes significant reduction in the strength of the weld metal. For this reason, cracks in weldments are never acceptable whereas there are acceptable limits for slag inclusions and porosity in welds. Welding cracks are caused by embrittlement or low ductility of the weld metal and/or base metal combined with high restraint during contraction. For instance, if the contraction occurring during solidification of the weld is restricted, the strains developed will induce residual stresses that cause cracking. Hot (cracks that occur at elevated temperature during weld metal solidification) or cold (cracks that occur after the weld metal has cooled to room temperature) cracks
may manifest as centerline cracking (segregation induced cracking, bead shape induced cracking, or surface profile induced cracking), heat affected zone cracking or as transverse cracking which were explained in the James F. Lincoln Arc Welding Foundation manual on weld cracking.

Porosity consists of small voids in the weld metal formed by gases entrapped during solidification. The shapes of the voids vary between spherical (blow holes) to elongated (worm holes). Shrinkage voids are cavities formed by shrinkage during solidification.

Lack of fusion also known as incomplete fusion consists of a weld bead in which fusion has not occurred throughout the entire cross section of the joint. A lack of penetration means that fusion has not penetrated deeply enough into the root of the joint, relative to specific standards.

Solid inclusions are any non-metallic solid material entrapped in the weld metal. The most common type is slag inclusion generated during the various arc-welding processes that use flux. Instead of floating to the top of the weld pool, globules of slag become encased during solidification of the metal.

Unacceptable contour which refers to defects in form of undercut, underfill or overlap appearing on the weld profile. The weld should have a certain desired profile for maximum strength.
Baldev et al. (2006) opined that the testing, measurement and control of welds should be optimized based on fitness – for – purpose. In this way the reliability of weld performance is evaluated by measurement and control of weld properties. Effective testing programme is to detect defects and measure weld properties as specified by the design based on fitness – for – purpose philosophy. Weld metal test may be classified as:

i. Destructive test for measurement of weld properties often performed to determine if a weldment is of adequate quality in terms of strength and soundness. The common destructive testing methods used are:
   i. Tension test
   ii. Hardness test
   iii. Bend test
   iv. Charpy V – Notched Impact test
   v. Drop Weight test
   vi. Plain Strain Fracture Toughness test
   vii. Fatigue test and
   viii. Creep test

ii. Non-destructive testing (NDT) methods for detecting defects such as cracks, porosity, lack of fusion, solid inclusions, unacceptable contour
and other miscellaneous defects. Some common non-destructive testing technique used in weld metal quality control include the following:

i. Radiographic test

ii. Liquid /dye penetrant test

iii. Eddy – current testing

iv. Magnetic – particle inspection

v. Ultrasonic inspection and

vi. Leak and pressure testing methods

The NDT techniques are used during manufacture as a quality control tool to determine the quality of the work.

The quality of a weld may be defined as the ability of a weld metal to perform satisfactorily in the given design environment. A simple quality control measure is the number of weld defects per unit length of actual weld. Criteria used to determine weld quality include:

i. Weld appearance

ii. Mechanical properties

iii. Soundness of weld and

iv. Weld chemical composition.

If any of these criteria are not monitored, the integrity of the weld could be compromised. To maintain quality, stage inspection is an effective tool. In general,
pursuance of quality assurance in fabrication of welded structures requires the following operations:

i. Approval of detailed drawing by the client

ii. Approval of raw materials and consumables by client

iii. Preparation of quality assurance plan, manufacturing and NDT procedures

iv. Calibration of testing equipment

v. Qualification of welding consumables, welding procedure and welders

vi. Qualification of NDT Personnel

vii. Quality control during welding production

viii. Non – destructive testing of welds

ix. Quality control during post weld heat treatment (PWHT) and NDT after PWHT

x. Load and leak pressure testing of welds

xi. Documentation

(Baldev et al., 2006; Srinivasan, 2008).

2.3 SOLIDIFICATION CRACKING IN AUSTENITIC STAINLESS STEELS

Hot cracking refers to cracking that occurs during welding, casting or hot working at temperatures close to the melting point of the material. The cracking is known to
occur both above the liquation temperature known as the supersolidus cracking, and in the solid state called subsolidus cracking. The various types of hot cracks encountered in austenitic stainless steel weldment as classified by Baldev et al. (2006) include:

i. Solidification cracking

ii. Heat affected zone liquation cracking

iii. Ductility dip cracking

Shankar et al. (2003) noted that supersolidus cracking may manifest as solidification cracking occurring in the presence of a liquid phase in the fusion zone, or as liquation cracking in the heat affected zone (HAZ) where it is accompanied by grain boundary melting. Solidification cracking in the austenitic stainless steel weld metal is considered the most deleterious and more widely observed than the other types of cracking.

Solidification cracking consists of fractures at the interdendritic and/or intergranular weld metal boundaries in the solidification process, during which the liquid phase of the mushy melt becomes rich in impurities mainly sulphur and phosphorus. This phenomenon reduces the mechanical strength at the grain and dendritic boundaries, thereby rendering the weld metal susceptible to solidification cracking (Brooks et al., 1991; Arantes et al., 2007). Gooch (1990) reported that during weld metal solidification, some segregation inevitably occurs. In materials
which solidify as austenite for instance, silicon, niobium, and impurity elements such as sulphur and phosphorus segregate into the interdendritic regions, which therefore solidify at lower temperatures than the bulk of the steel structure. This may lead to the formation of interdendritic solidification cracks as a consequence of contraction during cooling. Shankar et al. (2003) opined that solidification cracking occurs predominantly by the segregation of solutes to form low-melting phases, which under the action of shrinkage stresses accompanying solidification cause cracking in the weld metal.

2.3.1 CONTROL OF SOLIDIFICATION CRACKING

Solidification cracking can be controlled by adopting the correct welding procedure to obtain a favorable solidification mode and structure. The most common means of avoiding solidification and liquation cracking is to choose a filler material type which gives some residual ferrite in the weld metal. The association of delta-ferrite with cracking resistance in austenitic stainless steel weld metal is quite old. As early as 1938, Scherer et al. (1941) filed a patent, which claimed that crack resistant austenitic stainless steel weld deposits could be produced if the composition is adjusted to result in 5 – 35 percent ferrite in the completed weld. This has proved extremely effective, although the mechanism by which the effect is achieved is still the subject of debate. Hull (1967) however, found that when ferrite content in the completed weld increase beyond 35 weight
percent, the weld metal would again become susceptible or sensitive to solidification cracking.

A number of factors have been proposed to explain the beneficial effects of delta-ferrite on the cracking behavior of austenitic stainless steel weldment as compiled by Shankar et al. (2003):

i. The higher solubility for impurity elements in delta-ferrite leads to less interdendritic segregation and reduces cracking tendency (Borland and Younger, 1960).

ii. Cracks are arrested by the irregular path offered by a duplex austenite – ferrite structure. The peritectic / eutectic reaction interface arrests remaining pockets of liquid and thus crack propagation (Matsuda, 1979).

iii. The lower surface energy of the austenite – δ-ferrite boundary and its reduced wettability by eutectic films compared to austenite – austenite or δ-ferrite – δ-ferrite interfaces is an important factor (Hull, 1967).

iv. The presence of δ-ferrite results in a large interface area due to the solid state transformation to austenite that begins soon after solidification. The increased area disperses the concentration of impurity elements at the grain boundaries.

v. The ductility of ferrite at high temperatures is greater than that of austenite, allowing relaxation of thermal stresses.
vi. The lower the thermal expansion coefficient of ferrite as compared to
austenite results in less contraction stresses and fissuring tendency.

vii. The solidification temperature range of primary ferrite welds is less than
that of primary austenite solidified welds, providing a smaller critical
temperature range for crack formation (Pellini, 1952).

viii. The presence of ferrite refines the grain size of the solidified weld metal,
which results in better mechanical properties and cracking resistance.

ix. The higher coefficients for impurity diffusion in ferrite as compared with
austenite allow faster homogenization in ferrite and less tendency for
cracking.

x. Coarse grain formation in the heat affected zone (HAZ) occurring by
recrystallisation and grain growth in fully austenitic weld metals increases
susceptibility to liquation cracking (Kujanpaa et al., 1985), while ferrite
forming compositions are not susceptible to such cracking.

xi. The volume contraction associated with the ferrite – austenite transformation
reduces tensile stresses close to the crack tip, which decreases cracking
tendency (Their et al., 1987).

Nevertheless, solidification cracking continues to cause concern in fully austenitic
stainless steels, when ferrite is restricted and when composition adjustments during
welding are difficult. Several theories have been postulated by Pellini (1952),
Medovar (1954) Borland (1960), and Holt (1992) in attempt to explain the phenomenon of solidification cracking.

2.3.2 FORMS OF SOLIDIFICATION CRACKING

Solidification cracking in austenitic stainless steel weld metal exists in different forms. Shankar et al. (2003) classified solidification cracking in austenitic stainless steel weldment as stated below:

i. Gross cracking, occurring at the junctions of dendrites with differing orientations. This type of solidification cracking is detected by visual inspection and liquid penetrant test.

ii. Microfissuring in the interdendritic regions which are revealed only by application of strain to the cracked region or at high magnifications.

2.3.3 EFFECT OF COMPOSITION ON CRACKING TENDENCY OF AUSTENITIC STAINLESS STEEL WELDMENT

Composition affects the tendency of austenitic stainless steel weld metal towards cracking in the following ways:

i. Solidification mode is dependent on weld metal composition. Shankar et al. (2003) and Baldev et al. (2006) found that ferrite – austenite / ferrite
solidification modes reduce the tendency for solidification cracking in austenitic stainless steel weld metal.

ii. Segregation pattern in the weld metal is also a function of the composition. Segregation determines the wetting characteristics and constitutional supercooling in the interdentritic regions.

2.3.3.1 EFFECT OF SULPHUR AND PHOSPHORUS ON THE CRACKING PROPENSITY OF AUSTENITIC STAINLESS STEEL WELD METAL

Sulphur is known to be an undesirable impurity in welding of austenitic stainless steels due to the formation of low-melting sulphide films (Fe – FeS eutectics) along the interdendritic and grain boundary regions. Sulphur is almost insoluble in iron, chromium and nickel which are the three major constituents of stainless steels. The phase diagrams for sulphur binaries with all the three elements (iron, chromium, and nickel) as reported by Shankar et al. (2003) showed that a wide and deep solid – liquid regions with low partition coefficients for sulphur in austenite. Consequently, sulphur is strongly rejected into the liquid during solidification of austenite, forming low-melting eutectics and lowering the melting point of the interdendritic liquid. This phenomenon of forming low-melting point eutectics along the interdendritic and grain boundary regions causes cracking in austenitic stainless steel weld metal during solidification. On the other hand, delta – ferrite
shows higher solubility for sulphur, phosphorus, silicon, and niobium; and thus beneficial in reducing solidification cracking. This is true as sulphur, phosphorus, silicon and niobium have the ability of forming low-melting eutectic phases which promote cracking in the weld metal. Solidification in the ferrite – austenite mode is known to increase tolerance for sulphur content to as high as 0.05 weight percent. Arantes et al. (2007) found that austenitic stainless steel weldments with sulphur and phosphorus contents summing up to 0.042 weight percent showed good weldability. Lundin et al. (1988) investigated weldability of free – machining stainless steels, and found that, provided a ferritic solidification mode is maintained, austenitic stainless steel weldments with sulphur contents up to 0.35 weight percent could show satisfactory weldability.

Phosphorus ranks next to sulphur in the list of elements which are detrimental to good weldability in austenitic stainless steels. Like sulphur, phosphorus forms low-melting eutectics with iron, chromium, and nickel. Phosphide eutectics at the interdendritic regions have been found to extend the brittleness temperature range in the varestraint test, to as much as 250K lower than the solidus solidus in fully austenitic type 310 steel (Matsuda et al., 1981). Accordingly, sulphur, phosphorus, boron, niobium, titanium and silicon were identified as most harmful, as they possess low solubility in the solidified weld metal and form low-melting eutectics with iron, chromium, and nickel which promote solidification cracking. Among the
elements whose effects on solidification cracking were investigated, Hull (1960) found molybdenum, manganese, and nitrogen to be somewhat beneficial.

2.3.4 THEORY OF HOT CRACKING

The initial theory of hot cracking as proposed by Medovar (1954) states that the wider the liquid – solid range of the alloy, the greater the susceptibility to hot cracking. This theory provided a good foundation for the explanation of hot cracking phenomenon but had a serious short coming in that the theory neglected other factors that could be responsible for hot cracking, stressing that segregation resulting from the wide freezing range appeared to be the sole cause of hot cracking. A more complete theory was developed by Borland (1960). Borland stated that for high cracking susceptibility, in addition to a wide freezing range, the liquid must be distributed in a way that allows high stresses to be built up between the grains.

It was further expounded that under the action of shrinkage stresses in a restrained weld, the already solidified part can crack when wetted by the low-melting eutectic liquids. The ratio of interfacial energies of the solid and liquid phases is an important determinant of hot cracking during welding. The effect of this ratio on wetting angle is given by:
Where \( \gamma_{sl} \) and \( \gamma_{ss} \) are the interfacial energies of the solid–liquid and solid–solid boundaries respectively. And \( \theta \) is the wetting angle. When \( \theta \) is nearly zero, the wetting of solid–solid boundary is enhanced and cracking tendency of the weld metal would be promoted under this condition (Shankar et al., 2003; Baldev et al., 2006). Borland’s theory revealed the importance of wetting in relation to solidification cracking tendency of the weld metal but the effect of wetting angle of the liquid and solid phases on cracking propensity is very difficult to quantify. In attempt to modify Borland’s theory, Matsuda (1990) suggested that hot cracking is constituted by crack initiation and crack propagation acting distinctly at the critical solidification and is a function of the weld metal composition. The overall idea according to Shankar et al. (2003) is that, irrespective of the stress field experienced during welding, the temperature range of cracking susceptibility (or sensitivity) known as the brittleness temperature range (BTR) can be considered as a function of the weld metal composition. Matsuda et al. (1989 a, b) have shown that the brittleness temperature range can be obtained by calculation of liquid composition applying the Schiel’s equation and using suitable numerical techniques for computation. Hot cracking test methods that enable the measurement of the brittleness temperature range (BTR) are therefore very useful in predicting weld metal cracking in actual situations.
2.4 EVALUATION OF SOLIDIFICATION CRACKING IN AUSTENITIC STAINLESS STEEL WELDMENT

Hot cracking is believed to occur due to the inability of the solidifying weld metal to support strain in the critical temperature range during solidification (Borland, 1960). The literature reviewed so far showed that solidification cracking in weld metal is a function of two important parameters namely:

i. Weld metal composition

ii. Stain developed in the weldment

2.4.1 COMPOSITION EVALUATION CRITERIA

The assessment of the propensity for cracking susceptibility of austenitic stainless steels can be evaluated from the composition of the weld metal. This is based on the following parameters:

i. Summation of the concentration level of sulphur (S) and phosphorus (P) expressed in weight percent (S+P) wt. %

ii. Ferrite number (FN)

iii. Weld metal microstructure and

iv. The ratio of chromium equivalent to nickel equivalent

Brooks et al. (1991) stated that stainless steels with a value of \( \frac{\text{Cr}_{\text{eq}}}{\text{Ni}_{\text{eq}}} \leq 1.5 \), are susceptible to solidification cracking, whereas stainless steels with a value of
1.5, are immune to solidification cracking or nearly so. Stainless steels with 
(S+P) ≤ 0.02% and with only an austenitic structure in the solid phase are not 
susceptible to solidification cracking. Moreso, stainless steels with (S+P) ≤ 0.03% 
and ferrite number (FN) ≥ 4, (S+P) ≤ 0.04% and ferrite number (FN) ≥ 8, and 
(S+P) ≤ 0.05% and ferrite number (FN) ≥ 12, are not susceptible to solidification 
cracking (Arantes et al., 2007). Based on the above knowledge, the tolerance of 
sulphur and phosphorus contents in solidification cracking susceptibility is 
seemingly influenced by the arbitrary unit values called the ferrite number (FN). 
The amount of ferrite is indicated either as the percentage of ferrite present in the 
microstructure or as a ferrite number. The volume percentage of ferrite can be 
estimated as about 70% of the ferrite number (FN) but the relationship depends 
upon the type and origin of the stainless steel used and the measurement technique. 
A minimum ferrite number is necessary to avoid hot cracking in austenitic stainless 
steel welds (Vasudevan et al., 2004; Vasudevan, et al., 2005; http://www.diverse-
technologies.net).

2.4.2 STRAIN EVALUATION CRITERIA
The amount of strain developed in the weld metal may be used to evaluate the 
solidification cracking susceptibility of an austenitic stainless steel weldment. In 
actual welds, the amount of strain experienced by the weld metal is difficult to 
estimate in view of complex geometric and thermal conditions. Hence controlled
strain applied on a geometrically simple specimen is preferred for evaluation of cracking tendency. Several tests that satisfy the above condition exist for the determination of austenitic stainless steel weld metal propensity to solidification cracking (Shankar et al., 2003).

The programmierter Verformungsriß Test (PVT) employs the tensile strain rate developed during welding and the critical strain rate for the onset of cracking is measured and used for the assessment of weld metal cracking propensity. In the Sigmajig Test, the critical tensile stress for crack initiation is determined and used for evaluation of solidification cracking tendency of the weld metal. The Varestraint test uses a controlled, rapidly applied bending strain to produce cracking, and the crack lengths are used for evaluation of weldment cracking tendency. In the longitudinal varestraint test (LVT) strain is applied in the direction of welding and the resultant total crack length (TCL) and cracking threshold strain (CTS) are considered the most important assessment criteria. In the transvarestraint test (TVT), strain is applied transverse to the welding direction, and the maximum crack length (MCL) is used for the assessment of the weld metal cracking tendency. The temperature associated with a distance corresponding to maximum crack length gives the lower temperature of the brittleness temperature range (BTR). The maximum crack length can thus be used to determine the
temperature range of cracking during solidification called the brittleness

temperature range (BTR).

Recent work on solidification cracking in austenitic stainless steel welds by
Shankar et al. (2003) has shown that opinion is divided on the choice of strain
criteria for cracking assessment of materials due to difficulties in applying the
results of variable restraint tests to actual welding situations.

2.5 PHYSICAL METALLURGICAL ASPECT OF A WELD JOINT

During welding, a small volume of metal is molten by a heat source which is
moved along the line in which a joint is sought. In comparison with casting,
welding processes involve cooling rates of several orders of magnitude higher than
that in conventional casting and the growth rates are correspondingly higher. Since
the base metal must necessarily melt back for good fusion to occur, there is
considerable dilution into the weld puddle. As the heat source moves away, the
heat loss mainly by conduction starts the solidification process and the weld metal
starts solidifying epitaxially at the fusion line, and nucleation is not required to
initiate the growth of the solid. In pure metals, the melting and solidification is heat
flow controlled. Alloys such as austenitic stainless steel, solidify over a range of
temperature. The temperature above which the alloy is completely molten is called
the liquidus while the temperature below which the alloy is completely solid is
called solidus. The difference between the liquidus temperature and solidus
temperature is the equilibrium solidification (or melting) temperature range. The composition of the solid phase in equilibrium with the liquid phase is a function of temperature. Therefore, alloy solidification involves heat flow and solute redistribution. An understanding of weld metal solidification requires a consideration of both heat and mass transfer phenomenon. The solidification and fluid flow phenomena are affected by the weld metal composition and welding parameters, which governs weldability aspects such as hot cracking (solidification cracking, HAZ liquation cracking, and ductility dip cracking), grain structure and weld puddle shape (Kurz et al., 1989; Baldev et al., 2006; Parmar, 2010)

2.5.1 WELD METAL MICROSTRUCTURE

Weld metal microstructure is composed of the weld metal composition, size and shape of grains, volume fraction, and distribution of the constituents. Hot cracking is known to be sensitive to the composition which is a part of the weld metal microstructure.

The knowledge of the solute redistribution, solidification modes, constitutional supercooling, microsegregation and banding are required in order to explain the development of weld metal microstructure. The solute atoms in a liquid are redistributed during solidification. The redistribution of the solute depends on the phase diagram, diffusion, fluid flow, undercooling, etc. such that at any temperature, $T$, the equilibrium segregation coefficient, $K$, is given by:
Where \( \textit{c}_s \) and \( \textit{c}_l \) are the compositions of the solid and liquid respectively at the solid – liquid interface.

During solidification of a pure metal, the solid – liquid interface is usually planar, unless severe thermal undercooling is imposed. During the solidification of an alloy, however, the solid – liquid interface and hence the solidification mode can be planer, cellular, or dendritic (which consist of columnar dendrites and equiaxed dendrites) depending on the solidification conditions (actual temperature gradient, growth rate, degree of undercooling, and diffusivity in the liquid) and the material system involved. Microsegregation across cells or dendritic arms is a consequence of solute redistribution during solidification. In addition to microsegregation, solute segregation can also occur as a result of growth rate fluctuations caused by thermal fluctuations. This phenomenon is called banding. These concepts (microsegregation, constitutional undercooling, banding, solute redistribution and solidification mode) discussed above determine the weld metal microstructure which has serious implication on the strength and corrosion behavior of the weld metal (Kurz et al., 1989; Baldev et al., 2006; Parmar, 2010).
2.6 SUMMARY OF LITERATURE REVIEW

The literature review presented in this chapter reported extensively on the weldability of austenitic stainless steel. Many researchers believed that the major problem of austenitic stainless steel weld metal is hot cracking or solidification cracking (AISI handbook 1988; Woollin, 1994; Shankar et al., 2003; Baldev et al., 2006; Arantes et al., 2007). While maintaining that the standard welding practices for austenitic stainless steels focus on the selection of appropriate filler metal to control the weld metal microstructure. Building on the foundation of many researchers whose findings were cited in this work, the author investigated the effect of electrode types on the solidification cracking susceptibility of austenitic stainless steel weld metal. The composition evaluation criteria was employed in the assessment of the weld metal propensity for cracking as there are difficulties in applying the results of variable restraint tests (obtained through the strain evaluation criteria) to actual welding situation (Shankar et al., 2003). Literature on the physical metallurgy of weld joint, theories of hot cracking and development of weld metal microstructure were reviewed in attempt to establish the sensitivity of solidification cracking on weld metal composition.
CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 MATERIALS

The base metal of the test specimens used for this study is type 304H austenitic stainless steel (18.55%Cr, 8.72%Ni, and 0.057% C). The bulk material was procured from Sabatex Stainless Steel Products, Onitsha. The nominal chemical composition of the material is shown in Table 3.1.

Table 3.1: Chemical composition (wt. %) of the austenitic stainless steel material

| Element | C  | Cr  | Ni  | Si  | Mn  | S   | P   | Mo  | Al  | Cu  | Co  | Nb  | V   | B   | Sn  | As  | Ga  | Fe  |
|---------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Wt. %   | 0.0570 | 18.5500 | 8.7200 | 0.4400 | 1.7200 | 0.0075 | 0.0230 | 1.7200 | 0.0057 | 0.2010 | 0.1110 | 0.0270 | 0.0750 | 0.0022 | 0.0086 | 0.0870 | 0.0004 | 69.8000 |

3.1.1 ELECTRODE MATERIAL

Different stainless steel electrodes were used for the welding operation. The electrode classification according to American Welding Society (AWS) standard as well as their composition is shown Table 3.2.

3.2 WELDING AND TESTING EQUIPMENT

The following welding and testing equipment were used in the course of this study:

i. SPECTROMETER: This equipment was used for chemical analysis of the parent and weld metal. The test was carried out at the laboratory of
Table 3.2: Chemical composition of the electrodes

| Elements (wt. %) | E 308 – 16 (Rutile coated) Electrode(10&12) | E 308 – 16 (Lime-titania) Electrode | E 310 – 16 Electrode | E 312 – 16 Electrode |
|-----------------|-----------------------------------------------|-------------------------------------|-----------------------|-----------------------|
| C               | 0.08                                          | 0.08                                | 0.08 – 0.12           | 0.15                  |
| Mn              | 0.7 – 2.0                                     | 0.5 – 2.5                           | 1.0 – 2.5             | 0.7 – 2.0             |
| Si              | 0.3 – 0.85                                    | 0.9                                 | 0.3 – 0.7             | 0.3 – 0.9             |
| Cr              | 18 – 21                                       | 18 – 21                             | 25 – 28               | 28 – 32               |
| Ni              | 9 – 11                                        | 9 – 11                              | 20 – 22               | 8 – 10.5              |
| S               | 0.03                                          | -                                   | 0.03                  | 0.03                  |
| P               | 0.03                                          | -                                   | 0.03                  | 0.03                  |
| Mo              | 0.5                                           | -                                   | 0.5                   | 0.75                  |
| Cu              | 0.75                                          | -                                   | 0.75                  | 0.75                  |

ii. WELDING MACHINE: Shielded Metal Arc Welding (SMAW) and Tungsten Inert Gas (TIG) welding machines were used for fabricating the weld joints. The SMAW welding was carried out in at FUTO welding workshop while the TIG welding operation was carried out at National Metallurgical Training Institute (NMTI), Onitsha.

iii. MICROSTRUCTURAL EXAMINATION: Metallographic analysis of the fusion zone of the weldments were carried out at Testing, Certification and Research Engineering Services (TCR), India.
3.3 EXPERIMENTAL PROCEDURE

3.3.1 MATERIAL PREPARATION

Sixty (60) identical pieces were cut out from the bulk material to dimension of 55mm (length) x 35mm (width) x 3mm (thickness). The edges of each piece were prepared according to AWS standard for square butt welded joints, joint gap being one – third of the thickness of the material to be joined, as shown in the diagram below:

![Diagram of the metal pieces to be joined with dimensions](image)

Figure 3.1: Diagram of the metal pieces to be joined with dimensions

Necessary preweld preparations were made by wire brushing and grinding the surfaces to be joined in order to remove oxide films, scales, and dust particles. The smooth finished surfaces were cleaned with acetone to remove moisture, grease or oil. These cleaning operations were carried out in order to achieve metallurgical cleanliness of the surfaces to be joined as well as atomic closeness of the intended weld.
3.3.2 WELDING PROCEDURE

Two methods of welding were adopted namely, Shielded Metal Arc Welding (SMAW) and Tungsten Inert Gas (TIG) Welding. The welding operations were conducted under constant condition as displayed in Table 3.3 below.

Table 3.3: Welding parameters held constant in the welding operation.

| WELDING PARAMETERS | TUNGSTEN INERT GAS WELDING | MANUAL METAL ARC WELDING |
|--------------------|----------------------------|--------------------------|
| Welding current    | 110A                       | 110A                     |
| Welding speed*     | 60mm /min.                | 60mm /min.               |
| Voltage            | 40V                        | 40V                      |
| Polarity           | DC electrode negative     | DC electrode negative    |
| Heat source        | Arc                        | Arc                      |
| Weld pool shield   | Argon gas                  | Electrode flux           |
| Filler rod         | 304H stainless steel wire  | Welding electrode        |
| Argon gas pressure | 10bars                     | -                        |

*since the welding process was carried out manually, the welding speed is approximate and represents the average values.

The variable parameter in this study was the welding electrodes while the weld joints produced from TIG autogeneous welding served as the control or standard of comparism. The specimens used in this research were the welded joints produced in six distinct categories, viz:

i. CATEGORY A: Six specimens were produced by using E 308 – 16, gauge 10 (rutile) welding electrode in a shielded metal arc welding process.
ii. CATEGORY B: Six specimens were produced by using E 308 – 16, gauge 12 (rutile) welding electrode in a shielded metal arc welding process.

iii. CATEGORY C: Six specimens were produced by using E 308 – 16, gauge 12 (lime-titania) welding electrode in a shielded metal arc welding process.

iv. CATEGORY D: Six specimens were produced by using E 310 – 16, gauge 10 welding electrode in a shielded metal arc welding process.

v. CATEGORY E: Six specimens were produced by using E 312 – 16, gauge 10 welding electrode in a shielded metal arc welding process.

vi. CATEGORY F: Six specimens were produced from Tungsten Inert Gas (TIG) autogeneous welding process using the base metal as the filler rod.

3.3.2 WELD CLEANING AND INSPECTION

After the welding operation, the welded joints were visually examined or inspected. Faulty and poor welded joints were excluded. Satisfactory joints were cleaned by machining and grinding to a fine surface finish.

3.4 TEST SPECIMENS

Each specimen (welded joint) has a dimension of 110mm x 35mm x 3mm. Two test specimens from each category A – F, were prepared for tensile test, chemical analysis and micrographic test respectively.
3.4.1 PREPARATION OF SPECIMEN FOR TENSILE TEST

The test specimen for tensile test was machined to fit into the grip of the tensile testing machine, to a gauge length of 25mm. The tensile test specimen was 3mm thick and 4mm wide as shown in Fig. 3.2a.

Figure 3.2a: Tensile test specimen

3.4.2 PREPARATION OF SPECIMEN FOR CHEMICAL ANALYSIS

The weld joints produced in this work were subjected to chemical analysis, with the aid of a spectrometer, to determine their respective fusion zone chemistry. Although the weld metal had three zones (unaffected parent metal, heat affected zone and the fusion zone), the zone of interest for chemical analysis was the fusion zone since it consist of a solidified structure of the welding electrode (or filler rod) and the base metal – that is, the region of dilution. The sample for chemical analysis was prepared by cutting out the fusion zone from the weld metal and grinding the surface to the requirement of the spectrometer.
3.4.3 PREPARATION OF SPECIMEN FOR METALLOGRAPHIC TEST

Metallographic test of the weld joints were conducted using standard test techniques. The test was conducted distinctly on the parent metal, heat affected zone as well as the fusion zone for each test specimen. The samples for metallographic test were prepared in the following manner:

i. Wet grinding with water was carried out for all the specimens by using silicon carbide (SiC) emery papers of grades 220, 400, 800, and 1100.

ii. Polishing process was carried out by using special polishing cloth with aluminum oxide (Al₂O₃) solution 5µm grain size.

iii. Etching process was done by immersing each specimen in etching solution (Nital solution) which consists of 98% methyl alcohol and 2% Nitric acid, for 30sec. After which the specimens were washed with water and alcohol and then dried.

iv. Microstructures of the parent metal, heat affected zone and fusion zone were examined for each test specimen, with optical microscope provided with computer and digital camera.

Results obtained from the tensile test, chemical analysis and metallographic tests were tabulated and discussed in the next chapter.
CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 EXPERIMENTAL RESULTS

The experimental results in this work were obtained from tensile test, weldment analysis and metallographic test.

4.1.1 EXPERIMENTAL RESULTS FROM TENSILE TEST

The tensile flat specimen of gauge length 25mm, width 4mm and thickness 3mm was subjected to tensile load applied at a uniform rate until the specimen fractured. The corresponding increase in length for each test load was measured and recorded. The experiment was repeated for each test specimen (welded joints produced from different electrodes, TIG autogeneous welded joint and the unwelded parent material). The following results were obtained.

From the results in Table 4.1, the following properties of the material were determined and tabulated in Table 4.2 – 4.8.

i. Engineering stress \( \sigma \) = \( \frac{-F}{A} \) \( \text{N/mm}^2 \) \( \text{---------------------- 4.1} \)

Where \( F \) and \( A \) are the applied load (N) and original cross sectional area of the test specimen (mm\(^2\)).

\[
= \times \text{----------------------------- 4.} \]
| Unwelded parent material | Load (N) | 0 | 1000 | 2000 | 2800 | 3700 | 3600 | 5000 | 5400 | 5600 | 5800 | 6000 | 6200 | 6300 |
|--------------------------|----------|---|------|------|------|------|------|------|------|------|------|------|------|------|
| E308-16/10 (Rutile) Specimen | Elongation | 0.000 | 0.750 | 0.875 | 1.125 | 1.500 | 1.556 | 3.813 | 5.625 | 7.250 | 10.000 | 19.310 |
| ∆L (mm)                  |          | 0.000 | 0.375 | 0.813 | 1.250 | 1.688 | 2.063 | 2.500 | 3.125 | 4.375 | 5.625 | 6.500 |
| E308-16/12 (Rutile) Specimen | Load (N) | 0 | 1000 | 2000 | 2600 | 3200 | 4200 | 4000 | 4600 | 5000 | 5100 | 4200 |
| Elongation               | 0.000 | 0.750 | 0.781 | 1.000 | 1.250 | 1.625 | 1.938 | 2.500 | 3.125 | 3.750 | 4.500 |
| ∆L (mm)                  |          | 0.000 | 0.375 | 0.719 | 0.969 | 1.250 | 1.563 | 1.719 | 3.125 | 4.375 | 5.625 | 8.938 |
| E308-16/12 (Lime-titania) Specimen | Load (N) | 0 | 1000 | 2000 | 2800 | 3400 | 4300 | 4200 | 5300 | 5600 | 5800 | 6200 |
| Elongation               | 0.000 | 0.313 | 0.750 | 1.031 | 1.250 | 1.469 | 1.750 | 3.125 | 4.375 | 5.625 | 7.188 |
| ∆L (mm)                  |          | 0.000 | 0.313 | 0.750 | 1.250 | 1.668 | 1.875 | 3.125 | 4.375 | 5.625 | 6.875 | 8.125 |
| E312-16/10 Specimen      | Load (N) | 0 | 1000 | 2000 | 3300 | 4500 | 4400 | 5200 | 5600 | 5800 | 6200 | 6300 |
| Elongation               | 0.000 | 0.313 | 0.750 | 1.250 | 1.500 | 1.750 | 2.750 | 3.125 | 4.375 | 5.625 | 6.938 |
| ∆L (mm)                  |          | 0.000 | 0.406 | 0.844 | 1.250 | 1.500 | 1.750 | 2.750 | 3.125 | 4.375 | 5.625 | 6.938 |
| TIG Specimen             | Load (N) | 0 | 1000 | 2000 | 3050 | 3700 | 3580 | 4300 | 4500 | 4850 | 5200 | 4600 |
| Elongation               | 0.000 | 0.406 | 0.844 | 1.250 | 1.500 | 1.750 | 2.750 | 3.125 | 4.375 | 5.625 | 6.938 |
| ∆L (mm)                  |          | 0.000 | 0.406 | 0.844 | 1.250 | 1.500 | 1.750 | 2.750 | 3.125 | 4.375 | 5.625 | 6.938 |

Table 4.1: Tensile test results for the respective test specimens
where \( W \) = Cross sectional width of the test specimen = 4mm,

and \( T \) = Thickness of the specimen = 3mm.

Tensile strength of the material, \( \sigma = \frac{\text{Maximum Load (N/mm}^2\text{)}}{A_0} \)  \( \text{-------- 4.3} \)

ii. Engineering strain \( (\epsilon) = \frac{\Delta l}{l_0} \)  \( \text{--------------------------- 4.4} \)

Where

\( \Delta l \) = extension or elongation (mm),

and \( l_0 \) = orginal or gauge length  = 25mm

iii. Ductility:
(a) In terms of percentage elongation, ductility = \( \frac{\Delta \times 100}{100} \text{-------- 4.5} \)

Where \( \Delta l \) = elongation = \( l_f - l_0 \), \( l_f \) = final length at fracture

and \( l_0 \) = orginal length

(b) In terms of percentage reduction in area,

Ductility = \( \frac{A_o - A_f}{A_o} \times 100 \) \( \text{--------------------------- 4.6} \)

Where

\( A_f \) = final cross sectional area of the test specimen at fracture \( \text{(mm}^2\text{)} \)

and \( A_o \) = orginal cross sectional area of the test specimen = 12 \( \text{mm}^2 \)
iv. Modulus of elasticity (E) = \frac{\text{Engineering stress (}\sigma\text{)}}{\text{Engineering stress (}\epsilon\text{)}} (\text{N/mm}^2) \quad \text{------- 4.7}

That is, the slope of straight portion of the stress – strain curve.

v. True stress \( \sigma_t = \frac{\text{load}}{A_i} = \sigma (1 + \epsilon) \text{ (N/mm}^2\text{)} \quad \text{--------------------------- 4.8}

Where \( A_i \) = instataneous cross sectional area over which deformation is occurring (mm\(^2\)), \( \sigma \) is the engineering stress (N/mm\(^2\)) and \( \epsilon \) is the engineering strain.

vi. True strain (\( \epsilon \)) = \ln \frac{h(\epsilon)}{h(\epsilon)} = \ln (1 + \epsilon) \quad \text{--------------------------- 4.9}

Where \( h(\epsilon) \) = and \( \epsilon \) = engineering strain.

vii. Strain hardening coefficient (n) which is the slope of the plastic portion of the true stress (\( \sigma \)) – true strain (\( \epsilon \)) curve, given by:

\[ \sigma = K \epsilon \quad \text{--------------------------- 4.10} \]

where \( K \) is a constant known as the strength coefficient.

By taking the natural logarithm of both sides, the equation becomes:

\[ \ln \sigma = \ln K + \ln \epsilon \quad \text{--------------------------- 4.11} \]

viii. Joint efficiency = \( \frac{\text{Joint efficiency}}{\text{Joint efficiency}} \times 100 \quad \text{-------- 4.12} \)
TENSILE PROPERTIES FOR THE UNWELDED SPECIMEN

Table 4.2: Tensile properties for the unwelded specimen

| F (N) | ∆L (mm) | Li (mm) | $\sigma = F/A_0$ (Nmm$^{-2}$) | $\varepsilon = \Delta L/\Delta L_0$ | $\sigma = \sigma (1+\varepsilon)$ (Nmm$^{-2}$) | $\ln \sigma$ (Nmm$^{-2}$) |
|-------|---------|---------|-------------------------------|---------------------------------|-----------------------------------------------|--------------------------|
| 0     | 0.000   | 25.000  | 0.000                         | 0.000                           | 0.000                                         | 0.000                    |
| 1000  | 0.750   | 25.750  | 83.333                        | 0.030                           | 0.030                                         | 85.833                   | -3.521                   | 4.452                   |
| 2000  | 0.875   | 25.875  | 166.667                       | 0.035                           | 0.034                                         | 172.500                  | -3.370                   | 5.150                   |
| 2800  | 1.125   | 26.125  | 233.333                       | 0.045                           | 0.044                                         | 243.833                  | -3.123                   | 5.496                   |
| 3700  | 1.500   | 26.500  | 308.333                       | 0.060                           | 0.058                                         | 326.833                  | -2.843                   | 5.789                   |
| 3600  | 1.556   | 26.556  | 300.000                       | 0.062                           | 0.060                                         | 318.672                  | -2.807                   | 5.764                   |
| 5000  | 3.813   | 28.813  | 416.667                       | 0.153                           | 0.142                                         | 480.217                  | -1.952                   | 6.174                   |
| 5200  | 4.625   | 29.625  | 433.333                       | 0.185                           | 0.170                                         | 513.500                  | -1.773                   | 6.241                   |
| 5400  | 5.625   | 30.625  | 450.000                       | 0.225                           | 0.203                                         | 551.250                  | -1.595                   | 6.312                   |
| 5600  | 7.250   | 32.250  | 466.667                       | 0.290                           | 0.255                                         | 602.000                  | -1.368                   | 6.400                   |
| 5800  | 10.000  | 35.000  | 483.333                       | 0.400                           | 0.336                                         | 676.667                  | -1.089                   | 6.517                   |
| 6000  | 14.500  | 39.500  | 500.000                       | 0.580                           | 0.457                                         | 790.000                  | -0.782                   | 6.672                   |
| 5000  | 19.310  | 44.310  | 416.667                       | 0.772                           | 0.572                                         | 738.500                  | -0.558                   | 6.605                   |

The corresponding graphs (for the unwelded parent material) of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.1, 4.2 and 4.3 respectively.

Tensile strength (T.S) = $\frac{\sigma}{\Delta L_0} = 525$Nmm ; Lo = 25m; Lf = 44.31mm

Fracture mode is ductile and the location is slightly away from the centre line.
### TENSILE PROPERTIES FOR THE TIG TEST SPECIMEN

#### Table 4.3: Tensile properties for the TIG test specimen

| F (N) | $\Delta L$ (mm) | Li (mm) | $\sigma = F/A_0$ (Nmm$^{-2}$) | $e = \ln (1 + e)$ | $\varepsilon = \sigma (1 + e)$ | $\sigma = \sigma (1 + e)$ | In $\varepsilon$ | In $\sigma$ |
|-------|-----------------|---------|-----------------------------|-----------------|-----------------------------|-----------------------------|----------------|-------------|
| 0     | 0.000           | 25.000  | 0.000                       | 0.000           | 0.000                       | 0.000                       | -              | -           |
| 1000  | 0.406           | 25.406  | 83.333                      | 0.016           | 0.016                       | 84.687                      | -4.128         | 4.439       |
| 2000  | 0.844           | 25.844  | 166.667                     | 0.034           | 0.033                       | 172.293                     | -3.405         | 5.149       |
| 3050  | 1.250           | 26.250  | 254.167                     | 0.050           | 0.049                       | 266.875                     | -3.020         | 5.587       |
| 3700  | 1.500           | 26.500  | 308.333                     | 0.060           | 0.058                       | 326.833                     | -2.843         | 5.789       |
| 3580  | 1.750           | 26.750  | 298.333                     | 0.070           | 0.068                       | 319.217                     | -2.693         | 5.766       |
| 4000  | 2.188           | 27.188  | 333.333                     | 0.088           | 0.084                       | 362.507                     | -2.478         | 5.893       |
| 4300  | 2.750           | 27.750  | 358.333                     | 0.110           | 0.104                       | 397.750                     | -2.260         | 5.986       |
| 4500  | 3.125           | 28.125  | 375.000                     | 0.125           | 0.118                       | 421.875                     | -2.139         | 6.045       |
| 4850  | 4.375           | 29.375  | 404.167                     | 0.175           | 0.161                       | 474.896                     | -1.825         | 6.163       |
| 5000  | 5.625           | 30.625  | 416.667                     | 0.225           | 0.203                       | 510.417                     | -1.595         | 6.235       |
| 5100  | 6.438           | 31.438  | 425.000                     | 0.258           | 0.229                       | 534.446                     | -1.473         | 6.281       |
| 4600  | 6.938           | 31.938  | 383.333                     | 0.278           | 0.245                       | 489.716                     | -1.407         | 6.194       |

The corresponding graphs (for the TIG test specimen) of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.4, 4.5 and 4.6 respectively.

Tensile strength (T.S) \( \frac{425}{Nmm} \) = 425 Nmm

Fracture mode is ductile and the location is at the heat affected zone.
TENSILE PROPERTIES FOR THE E 312 -16/10 JOINT TEST SPECIMEN

Table 4.4: Tensile properties for E 312 – 16/10 test specimen

| F (N) | ∆L (mm) | Li (mm) | $\sigma$ = F/Ao (Nmm $^{-1}$) | $\varepsilon$ = $\Delta$L/Lo | $\varepsilon$ = ln (1 + $\varepsilon$) | $\sigma$ = $\sigma$ (1 + $\varepsilon$) (Nmm $^{-2}$) | In $\sigma$ | In $\varepsilon$ |
|-------|---------|---------|-----------------|----------------|----------------|-----------------|---------|----------|
| 0     | 0.000   | 25.000  | 0.000           | 0.000         | 0.000         | 0.000           | -       | -        |
| 1000  | 0.313   | 25.313  | 83.333          | 0.013         | 0.012         | 84.377          | -4.387  | 4.435    |
| 2000  | 0.750   | 25.750  | 166.667         | 0.030         | 0.030         | 171.667         | -3.521  | 5.146    |
| 3300  | 1.250   | 26.250  | 275.000         | 0.050         | 0.049         | 288.750         | -3.020  | 5.666    |
| 4500  | 1.688   | 26.688  | 375.000         | 0.068         | 0.065         | 400.320         | -2.728  | 5.992    |
| 4400  | 1.875   | 26.875  | 366.667         | 0.075         | 0.072         | 394.167         | -2.627  | 5.977    |
| 5000  | 2.688   | 27.688  | 416.667         | 0.108         | 0.102         | 461.467         | -2.282  | 6.134    |
| 5200  | 3.125   | 28.125  | 433.333         | 0.125         | 0.118         | 487.500         | -2.139  | 6.189    |
| 5400  | 3.750   | 28.750  | 450.000         | 0.150         | 0.140         | 517.500         | -1.968  | 6.249    |
| 5600  | 4.375   | 29.375  | 466.667         | 0.175         | 0.161         | 548.333         | -1.825  | 6.307    |
| 5800  | 5.625   | 30.625  | 483.333         | 0.225         | 0.203         | 592.083         | -1.595  | 6.384    |
| 6000  | 6.250   | 31.250  | 500.000         | 0.250         | 0.223         | 625.000         | -1.500  | 6.438    |
| 6200  | 6.875   | 31.875  | 516.667         | 0.275         | 0.243         | 658.750         | -1.415  | 6.490    |
| 6300  | 8.125   | 33.125  | 525.000         | 0.325         | 0.281         | 695.625         | -1.268  | 6.545    |

The corresponding graphs (E 312 – 16/10 test specimen) of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.7, 4.8 and 4.9 respectively.

Tensile strength (T.S) = $\sigma$ = 525Nmm

Fracture mode is ductile and the location is at the fusion zone.
TENSILE TEST RESULTS FOR THE E 310-16/10 JOINT TEST SPECIMEN

Table 4.5: Tensile properties for E 310 – 16/10 test specimen

| F (N) | \( \Delta L \) (mm) | Li (mm) | \( \sigma = F/Ao \) (Nmm \(^{-\frac{1}{2}}\)) | \( \varepsilon = \Delta L/Lo \) | \( \varepsilon = \ln (1+ \varepsilon) \) (Nmm \(^{-\frac{1}{2}}\)) | \( \sigma = \sigma (1+ \varepsilon) \) (Nmm \(^{-\frac{1}{2}}\)) | \( \ln \sigma \) (Nmm \(^{-2}\)) |
|-------|-----------------|---------|----------------------|----------------|----------------------|----------------------|----------------|
| 0     | 0.000           | 25.000  | 0.000                 | 0.000          | 0.012                | 84.377                | -               |
| 1000  | 0.313           | 25.313  | 83.333                | 0.013          | 0.012                | 84.377                | -4.387         |
| 2000  | 0.750           | 25.750  | 166.667               | 0.030          | 0.030                | 171.667               | -3.521         |
| 3000  | 1.031           | 26.031  | 250.000               | 0.041          | 0.040                | 260.310               | -3.209         |
| 3300  | 1.250           | 26.250  | 275.000               | 0.050          | 0.049                | 288.750               | -3.020         |
| 4200  | 1.469           | 26.469  | 350.000               | 0.059          | 0.057                | 370.566               | -2.863         |
| 4000  | 1.750           | 26.750  | 333.333               | 0.070          | 0.068                | 356.667               | -2.693         |
| 4600  | 2.500           | 27.500  | 383.333               | 0.100          | 0.095                | 421.667               | -2.351         |
| 5000  | 3.125           | 28.125  | 416.667               | 0.125          | 0.118                | 468.750               | -2.139         |
| 5200  | 3.625           | 28.625  | 433.333               | 0.145          | 0.135                | 496.167               | -1.999         |
| 5400  | 4.375           | 29.375  | 450.000               | 0.175          | 0.161                | 528.750               | -1.825         |
| 5600  | 5.000           | 30.000  | 466.667               | 0.200          | 0.182                | 560.000               | -1.702         |
| 5800  | 5.625           | 30.625  | 483.333               | 0.225          | 0.203                | 592.083               | -1.595         |
| 5600  | 7.188           | 32.188  | 466.667               | 0.288          | 0.253                | 600.843               | -1.375         |

The corresponding graphs (for the E 310 – 16/10 test specimen) of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.10, 4.11 and 4.12 respectively.

Tensile strength (T.S) = \( \frac{508.3 \text{Nmm}}{0.75} \) = \( 508.3 \text{Nmm} \)

Fracture mode is ductile and the location is at the fusion zone.
TENSILE TEST RESULTS FOR THE E 308 -16/12 (Lime-Titania) JOINT TEST SPECIMEN

Table 4.6: Tensile properties for E 308 – 16/12 (lime-titania) test specimen

| F (N) | $\Delta L$ (mm) | Li (mm) | $\sigma = F/A_o$ (N/mm$^2$) | $\varepsilon = \sigma \Delta L/L_o$ | $\varepsilon = \ln (1+\varepsilon)$ | $\sigma = \sigma (1+\varepsilon)$ (N/mm$^2$) | ln $\sigma$ (N/mm$^2$) |
|-------|------------------|---------|-----------------------------|----------------------------------|---------------------------------|---------------------------------|-----------------|
| 0     | 0.000            | 25.000  | 0.000                       | 0.000                            | 0.000                           | 0.000                           | -               |
| 1000  | 0.313            | 25.313  | 83.333                      | 0.013                            | 0.012                           | 84.377                          | -4.387          |
| 2000  | 0.719            | 25.719  | 166.667                     | 0.029                            | 0.028                           | 171.460                         | -3.563          |
| 2800  | 0.969            | 25.969  | 233.333                     | 0.039                            | 0.038                           | 242.377                         | -3.269          |
| 3400  | 1.250            | 26.250  | 283.333                     | 0.050                            | 0.049                           | 297.500                         | -3.020          |
| 4300  | 1.563            | 26.563  | 358.333                     | 0.063                            | 0.061                           | 380.736                         | -2.803          |
| 4200  | 1.719            | 26.719  | 350.000                     | 0.069                            | 0.066                           | 374.066                         | -2.711          |
| 5000  | 2.500            | 27.500  | 416.667                     | 0.100                            | 0.095                           | 458.333                         | -2.351          |
| 5200  | 2.813            | 27.813  | 433.333                     | 0.113                            | 0.107                           | 482.092                         | -2.238          |
| 5300  | 3.125            | 28.125  | 441.667                     | 0.125                            | 0.118                           | 496.875                         | -2.139          |
| 5400  | 3.750            | 28.750  | 450.000                     | 0.150                            | 0.140                           | 517.500                         | -1.968          |
| 5600  | 4.375            | 29.375  | 466.667                     | 0.175                            | 0.161                           | 548.333                         | -1.825          |
| 5800  | 5.625            | 30.625  | 483.333                     | 0.225                            | 0.203                           | 592.083                         | -1.595          |
| 6100  | 6.875            | 31.875  | 508.333                     | 0.275                            | 0.243                           | 648.125                         | -1.415          |
| 6200  | 8.938            | 33.938  | 516.667                     | 0.358                            | 0.306                           | 701.385                         | -1.185          |

The corresponding graphs for the E 308 – 16/12 (lime-titania) of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.13, 4.14 and 4.15 respectively.

Tensile strength (T.S) = $\frac{F_r}{A_o} = 516.7$Nmm

Fracture mode is ductile and the location is at the heat affected zone.
TENSILE TEST RESULTS FOR THE E 308 -16/12 (Rutile) JOINT TEST SPECIMEN

Table 4.7: Tensile properties for E 308 – 16/12 (rutile) test specimen

| F (N) | ∆L (mm) | Li (mm) | σ = F/Ao (Nmm⁻²) | ε = ∆L/Lo | ln (1+ e) | ln σ | ln σ (Nmm⁻²) |
|-------|---------|---------|------------------|----------|-----------|------|-------------|
| 0 | 0.000 | 25.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | - |
| 1000 | 0.375 | 25.375 | 83.333 | 0.015 | 0.015 | 84.583 | -4.207 | 4.438 |
| 2000 | 0.781 | 25.781 | 166.667 | 0.031 | 0.031 | 171.873 | -3.481 | 5.147 |
| 2600 | 1.000 | 26.000 | 216.667 | 0.040 | 0.039 | 225.333 | -3.239 | 5.418 |
| 3200 | 1.250 | 26.250 | 266.667 | 0.050 | 0.049 | 280.000 | -3.020 | 5.635 |
| 4200 | 1.625 | 26.625 | 350.000 | 0.065 | 0.063 | 372.750 | -2.765 | 5.921 |
| 4000 | 1.938 | 26.938 | 333.333 | 0.078 | 0.075 | 359.173 | -2.595 | 5.884 |
| 4400 | 2.188 | 27.188 | 366.667 | 0.088 | 0.084 | 398.757 | -2.478 | 5.988 |
| 4600 | 2.500 | 27.500 | 383.333 | 0.100 | 0.095 | 421.667 | -2.351 | 6.044 |
| 4800 | 2.688 | 27.688 | 400.000 | 0.108 | 0.102 | 443.008 | -2.282 | 6.094 |
| 5000 | 3.125 | 28.125 | 416.667 | 0.125 | 0.118 | 468.750 | -2.139 | 6.150 |
| 5100 | 3.750 | 28.750 | 425.000 | 0.150 | 0.140 | 488.750 | -1.968 | 6.192 |
| 4200 | 4.500 | 29.500 | 350.000 | 0.180 | 0.166 | 413.000 | -1.799 | 6.023 |

The corresponding graphs for the E 308 – 16/12 (rutile) test specimen of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.16, 4.17 and 4.18 respectively.

Tensile strength (T.S) = \frac{425}{16/12} = \frac{425}{1.33} = 425Nmm

Fracture mode is ductile and the location is at the heat affected zone.
TENSILE TEST RESULTS FOR THE E 308 -16/10 (Rutile) JOINT TEST SPECIMEN

Table 4.8: Tensile properties for E308 – 16/10 (rutile) test specimen

| F (N) | ΔL (mm) | Li (mm) | $\sigma = \frac{F}{Ao}$ (Nmm $^2$) | $\varepsilon = \frac{\Delta L}{Lo}$ | $\varepsilon = \ln (1 + e)$ | $\sigma = \sigma (1 + e)$ (Nmm $^2$) | $\ln \sigma$ (Nmm $^2$) |
|-------|--------|--------|----------------------------------|----------------|-----------------|-------------------------------|----------------|
| 0     | 0.000  | 25.000 | 0.000                           | 0.000         | 0.000           | 0.000                         | 0.000         |
| 1000  | 0.375  | 25.375 | 83.333                          | 0.015         | 0.015           | 84.583                        | -4.207        |
| 2000  | 0.813  | 25.813 | 166.667                         | 0.033         | 0.032           | 172.087                       | -3.442        |
| 3200  | 1.250  | 26.250 | 266.667                         | 0.050         | 0.049           | 280.000                       | -3.020        |
| 4400  | 1.688  | 26.688 | 366.667                         | 0.068         | 0.065           | 391.424                       | -2.728        |
| 4200  | 2.063  | 27.063 | 350.000                         | 0.083         | 0.079           | 378.882                       | -2.535        |
| 4600  | 2.250  | 27.250 | 383.333                         | 0.090         | 0.086           | 417.833                       | -2.451        |
| 4900  | 2.500  | 27.500 | 408.333                         | 0.100         | 0.095           | 449.167                       | -2.351        |
| 5200  | 3.125  | 28.125 | 433.333                         | 0.125         | 0.118           | 487.500                       | -2.139        |
| 5400  | 3.750  | 28.750 | 450.000                         | 0.150         | 0.140           | 517.500                       | -1.968        |
| 5600  | 4.375  | 29.375 | 466.667                         | 0.175         | 0.161           | 548.333                       | -1.825        |
| 5700  | 5.625  | 30.625 | 475.000                         | 0.225         | 0.203           | 581.875                       | -1.595        |
| 5600  | 6.500  | 31.500 | 466.667                         | 0.260         | 0.231           | 588.000                       | -1.465        |

The corresponding graphs for the E 308 – 16/10 (rutile) test specimen of true stress versus true strain, stress versus strain and load versus extension are shown in Figures 4.19, 4.20 and 4.21 respectively.

Tensile strength (T.S) = $\frac{F}{A_o}$ = 475Nmm

Fracture mode is ductile and the location is at the heat affected zone.
Fig. 4.1: True stress – true strain graph for the unwelded specimen

Fig. 4.2: Engineering Stress – strain curve for the unwelded specimen
Fig. 4.3: Engineering Load – extension curve for the unwelded specimen

\[
y = 0.382x + 6.8498 \\
R^2 = 0.9964
\]

Fig. 4.4: True stress – true strain graph for TIG test specimen
Fig. 4.5: Engineering Stress – strain graph for TIG test specimen

Fig. 4.6: Engineering Load – extension graph for TIG test specimen
Fig. 4.7: True stress – true strain graph for E 312 – 16/10 test specimen

Fig. 4.8: Engineering Stress – strain graph for E 312 – 16/10 test specimen
Fig. 4.9: Engineering Load – extension graph for E 312 – 16/10 test specimen

\[ y = 0.4357x + 7.0736 \]

\[ R^2 = 0.9971 \]

Fig. 4.10: True stress – true strain graph for E 310 – 16/10 test specimen

\[ \ln(\sigma) = 0.4357 \ln(\varepsilon) + 7.0736 \]

\[ R^2 = 0.9971 \]
Fig. 4.11: Engineering Stress – strain graph for E 310 – 16/10 test specimen

Fig. 4.12: Engineering Load – extension graph for E 310 – 16/10 test specimen
Fig. 4.13: True stress – true strain graph for E 308 – 16/12 (lime-titania) test specimen

Fig. 4.14: Engineering Stress – strain graph for E 308 – 16/12 (lime-titania) test specimen
Fig. 4.15: Engineering Load – extension graph for E 308 – 16/12 (lime-titania) test specimen

Fig. 4.16: True stress – true strain graph for E 308 – 16/12 (rutile) test specimen
Fig. 4.17: Engineering Stress – strain graph for E 308 – 16/12 (rutile) test specimen

Fig. 4.18: Engineering Load – extension graph for E 308 – 16/12 (rutile) test specimen
\[ y = 0.3799x + 6.9895 \]
\[ R^2 = 0.9835 \]

Fig. 4.19: True stress – true strain graph for E 308 – 16/10 (rutile) test specimen

Fig. 4.20: Engineering Stress – strain graph for E 308 – 16/10 (rutile) test specimen
Fig. 4.21: Engineering Load – extension graph for E 308 – 16/10 (rutile) test specimen

Table 4.9: Section dimensions and area of each test specimen after fracture

| SAMPLES             | Width after Fracture (W) mm | Thickness after Fracture (T) mm | Area after Fracture $^2$ (A) mm $^2$ |
|---------------------|-----------------------------|----------------------------------|-------------------------------------|
| PARENT MATERIAL     | 2.20                        | 1.90                             | 4.18                                |
| TIG SPECIMEN        | 2.50                        | 2.10                             | 5.25                                |
| E 312 - 16/10       | 3.60                        | 2.80                             | 10.08                               |
| E 310 - 16/10       | 3.10                        | 2.80                             | 8.68                                |
| E308 - 16/12 (Lime-titania) | 3.00            | 2.30                             | 6.90                                |
| E 308 - 16/12 (Rutile) | 3.50                      | 2.90                             | 10.15                               |
| E 308 - 16/10 (Rutile) | 3.60                      | 2.90                             | 10.44                               |
Table 4.10: Strain hardening exponent (n) and some specific properties of each test specimen

| SAMPLES               | n       | Strength Coefficient (K) N/mm² | Joint Efficiency | %Elongation in Area | % Reduction in Area |
|-----------------------|---------|-------------------------------|-----------------|---------------------|---------------------|
| PARENT MATERIAL       | 0.421   | 1082.47                       | -               | 77.24               | 65.17               |
| TIG SPECIMEN          | 0.382   | 942.94                        | 80.95%          | 27.75               | 56.25               |
| E 312 - 16/10         | 0.396   | 1133.43                       | 100%            | 32.50               | 16.00               |
| E 310 - 16/10         | 0.435   | 1179.68                       | 96.82%          | 28.75               | 27.67               |
| E308-16/12 (Lime-titania) | 0.353 | 1050.48                       | 98.42%          | 35.75               | 42.50               |
| E 308 - 16/12 (Rutile) | 0.406  | 1102.13                       | 80.95%          | 18.00               | 15.42               |
| E 308 - 16/10 (Rutile) | 0.379  | 1084.64                       | 90.48%          | 26.00               | 13.00               |

4.1.2 EXPERIMENTAL RESULTS FROM THE WELD JOINT CHEMICAL ANALYSIS

The evaluation of the susceptibility of 304H stainless steel to solidification cracking when welded with different electrodes was based on the chemical composition and microstructural analysis of the weld metal. The chemical composition of the weldments produced from different stainless steel electrodes was determined by the spectrometer and the results are given in Table 4.11.
Table 4.11: Chemical composition of the weld joints

| Elements       | E 308-16/12 Wt. % | E 308-16/10 (Rutile) Weld | E 308-16/12 Lime-titania Weld | E 310-16/10 Weld | E 312-16/10 Weld | TIG Weld |
|----------------|------------------|---------------------------|--------------------------------|------------------|-----------------|----------|
| Carbon, C      | 0.0710           | 0.0730                    | 0.0740                          | 0.1350           | 0.0920          | 0.0600   |
| Silicon, S     | 0.6900           | 0.6300                    | 0.4900                          | 0.5100           | 0.9100          | 0.3760   |
| Manganese, Mn  | 1.2200           | 1.1800                    | 1.3900                          | 1.8700           | 1.3200          | 1.6200   |
| Phosphorus, P  | 0.0061           | 0.0010                    | 0.0010                          | 0.0010           | 0.0010          | 0.0022   |
| Sulphur, S     | 0.0110           | 0.0084                    | 0.0076                          | 0.0140           | 0.0130          | 0.0046   |
| Chromium, Cr   | 17.1500          | 17.0200                   | 19.5700                         | 23.8500          | 26.7100         | 18.4500  |
| Nickel, Ni     | 7.1900           | 7.2100                    | 8.7400                          | 17.9900          | 9.7300          | 8.7900   |
| Molybdenium, Mo| 0.1330           | 0.1660                    | 0.2320                          | 0.1570           | 0.0640          | 0.1740   |
| Aluminium, Al  | 0.0055           | 0.0049                    | 0.0056                          | 0.0170           | 0.0072          | 0.0055   |
| Copper, Cu     | 0.2920           | 0.4110                    | 0.2460                          | 0.1520           | 0.0790          | 0.1900   |
| Cobalt, Co     | 0.0830           | 0.0960                    | 0.1120                          | 0.0770           | 0.0640          | 0.1170   |
| Titanium, Ti   | 0.0240           | 0.0190                    | 0.0110                          | 0.4250           | 0.0160          | 0.0010   |
| Nobium, Nb     | 0.0270           | 0.0260                    | 0.0290                          | 0.0290           | 0.0470          | 0.0210   |
| Vanadum, V     | 0.0680           | 0.0700                    | 0.1050                          | 0.1080           | 0.1190          | 0.0770   |
| Tungsten, W    | 0.0100           | 0.0100                    | 0.0100                          | 0.0100           | 0.0100          | 0.0560   |
| Lead, Pb       | 0.0034           | 0.0030                    | 0.0030                          | 0.0030           | 0.0030          | 0.0038   |
| Boron, B       | 0.0021           | 0.0018                    | 0.0016                          | 0.0017           | 0.0012          | 0.0022   |
| Tin, Sn        | 0.0100           | 0.0098                    | 0.0090                          | 0.0075           | 0.0110          | 0.0110   |
| Arsenic, As    | 0.0860           | 0.0810                    | 0.0930                          | 0.0960           | 0.1160          | 0.0950   |
| Bismuth, Bi    | 0.0015           | 0.0015                    | 0.0015                          | 0.0015           | 0.0015          | 0.0015   |
| Calcium, ca    | 0.0002           | 0.0002                    | 0.0003                          | 0.0024           | 0.0003          | 0.0003   |
| Iron, Fe       | 72.9000          | 73.0000                   | 68.9000                         | 54.6000          | 60.7000         | 69.9000  |
From the results of the chemical analysis of the weld joints displayed in Table 4.11, the values of the chromium and nickel equivalence, Cr eq. / Ni eq. ratio, and (P+S) wt. % were computed and tabulated in Table 4.12. The Cr eq. and Ni eq. values were calculated for each weld joint using Welding Research Council (1992), Hammar and Svenson (1979) and Schaeffler (1949) equations – see details in appendix B.

Table 4.12: Values of Cr eq., Ni eq., Cr eq. / Ni eq. ratio, and (P+S) wt. % of the tested Weld joints.

| Weld Joints                  | Cr eq  | Ni eq  | Cr eq. / Ni eq. | (P+S) wt. % |
|------------------------------|--------|--------|----------------|-------------|
| E 308-16/12 (Rutile) Weld joint | 17.3019 | 9.7480 | 1.7750         | 0.0171      |
| E 308-16/10 (Rutile) Weld joint | 17.2042 | 9.8678 | 1.7435         | 0.0094      |
| E 308-16/12(Lime-titania) Joint | 19.8223 | 11.3915 | 1.7401         | 0.0086      |
| E 310-16/10 Weld joint        | 24.0273 | 22.7530 | 1.0560         | 0.0150      |
| E 312-16/10 Weld joint        | 26.8069 | 12.9698 | 2.0669         | 0.0140      |
| TIG Weld joint                | 18.6387 | 10.9375 | 1.7041         | 0.0068      |

The Cr eq. /Ni eq. ratio was calculated for each of the weldment using the Welding Research Council (WRC) 1992 model equation given as (Kotecki et al., 1992)

\[ \text{Cr eq.} / \text{Ni eq.} = + + 0.7 \]  

(4.13)

and

\[ \text{Cr eq.} / \text{Ni eq.} = 35 + 20 + 0.25 \]  

(4.14)
Where, \[ . . = h \]

\[ . . = \]

Cr = Chromium; Mo = Molybdenum; Nb = Nobium; C = Carbon; N = Nitrogen; and Cu = Copper.

Results obtained in Table 4.12 above was compared to 300 series stainless steel WRC 1992 constitution diagram shown in Figure 2.8, to determine the solidification mode and ferrite number of the respective welded joints, as shown in Table 4.13 below. The WRC constitution diagram in terms of chromium and nickel equivalence showing the solidification mode of the weld joints were displayed in Appendix C.

Table 4.13: Ferrite Number and Solidification mode of the respective weld joints.

| Weld Joints                      | Ferrite Number (FN) | Solidification Mode         |
|---------------------------------|---------------------|-----------------------------|
| E 308-16/12 (Rutile) Weld joint | 6                   | Ferrite - Austenite (FA)    |
| E 308-16/10 (Rutile) Weld joint | 5 – 6               | Ferrite - Austenite (FA)    |
| E 308-16/12 (Lime-titania) Joint| 10                  | Ferrite - Austenite (FA)    |
| E 310-16/10 Weld joint          | 0 – 1               | Austenite (A)               |
| E 312-16/10 Weld joint          | 50 – 55             | Ferrite (F)                 |
| TIG Weld joint                  | 8                   | Ferrite - Austenite (FA)    |

Figure 4.22 shows the effect of (P+S) wt. % and Cr eq. / Ni eq. on the cracking propensity of the respective weld joints.
Figure 4.22: plot of (P+S) wt. % versus Cr eq. / Ni eq. from readings obtained in Table 4.12

Figure 4.23: Cracking susceptibility of 300 series stainless steel based on Cr – Ni equivalence according to Hammar and Svenson (Korinko et al., 2001).
4.1.3 EXPERIMENTAL RESULTS FROM THE METALLOGRAPHIC TEST

The following results were obtained from the metallographic test conducted on the Heat Affected Zone (HAZ), Fusion Zone and the Unaffected Parent Metal of each test specimen.

4.1.3.1 THE MICROGRAPH AND ANALYSIS OF E 312 – 16/10 JOINT SPECIMEN

The transformation of ferrite to austenite in stainless steels has been shown by Leone et al. (1982) to originate in two ways: either in the solid after solidification or in the liquid after partial solidification. The section of the Fe-Cr-Ni phase diagram of Figure 2.8 shows that solidification modes are a function of composition, thus consolidating the fact that the E 312 – 16/10 weld metal solidified with a ferrite mode through the following sequence of transformations:

\[ L \rightarrow \text{ferrite} \rightarrow \text{austenite} \],

where \( L \), \( \text{ferrite} \), and \( \text{austenite} \) represent the liquid, ferrite and austenite phases respectively. Inoue et al., 2007; found that the growth of austenite from ferrite occurs by the rejection of Cr and admission of Ni, resulting in Cr enrichment and depletion of Ni in the advancing / interface. The micrograph of E 312 – 16/10 fusion zone test specimen shown in Plate 4.1a revealed a primary ferrite (dark) matrix containing secondary austenite (white) and carbide precipitation at the grain boundaries. The ferrite dendrites being the first to solidify
had a lathy morphology and partly transforms into austenite after solidification by diffusion controlled mechanism.

Plate 4.1a: Fusion zone micrograph of E 312 – 16/10 welded joint.

The micrograph of the HAZ of E 312 – 16/10 sample shown in Figure 4.1b showed that the region experienced peak temperatures too low to cause melting but high enough to induce microstructural changes including recrystallization, grain growth of austenite and solid state transformations such as carbide precipitation along grain boundaries which occurred by diffusion controlled mechanism.

Plate 4.1b: HAZ micrograph of E 312 – 16/10 welded joint
4.1.3.2 THE MICROGRAPH AND ANALYSIS OF E 310 – 16/10 JOINT SPECIMEN

Leone et al. (1982) found that vermicular ferrite results when austenite originates in the liquid, and then grows into the solid ferrite by a diffusion controlled mechanism. The Fe-Cr-Ni phase diagram shown in Figure 2.8 confirmed that the E 310 – 16/10 weld metal solidified with a primary austenite solidification mode through the following sequence of transformations: $\text{L} \rightarrow + \rightarrow$, where $\text{L}$ represents the liquid and austenite phases respectively. The micrograph of the E 310 – 16/10 fusion zone shown in Plate 4.2a revealed that primary austenite (white) formed directly from the liquid not only as a primary dendritic phase but also as a secondary phase around ferrite. The interdendritic ferrite (dark) had a vermicular morphology engulfed in the austenite matrix, with carbide precipitation along the grain boundaries.

Plate 4.2a: Fusion zone micrograph of E 310 – 16/10 welded joint.
The micrograph of the HAZ of E 310 – 16/10 welded joint shown in Plate 4.2b revealed growth of austenite grain accompanied with solute segregation and carbide precipitation along the grain boundaries.

Plate 4.2b: HAZ micrograph of E 310 – 16/10 welded joint

4.1.3.3 THE SOLIDIFICATION BEHAVIOR IN FERRITE – AUSTENITE DUPLEX MODE

It has become necessary to explain the micro-mechanism of Ferrite-Austenite (FA) solidification mode since TIG, E 308 – 16/12 (Rutile), E 308 – 16/10 (Rutile) and E 308 – 16/12 (Lime-titania) all solidified with the FA duplex mode. When the base metal is fully austenite, the growth of austenite is more favorable than the nucleation of ferrite because of no nucleation barrier of austenite at the fusion boundaries, and therefore austenite first grows epitaxially from the base austenite with planar front morphology. During this planar austenite solidification, because chromium is rejected into the liquid, the stability of ferrite increases in the liquid in
the front of the solid/liquid interface and causes the nucleation of ferrite on the growing planar austenite. Once the ferrite forms, it grows more rapidly as the primary phase with dendritic morphology to dominate over the planar austenite growth.

On the other hand, in the interdendritic region of primary ferrite at the final stage of solidification, because nickel is rejected into the liquid, the stability of austenite increases and causes the formation of austenite. Austenite, however, grows more easily from the austenite that has already solidified than the nucleation of austenite on the preceding ferrite or in the liquid, and therefore, the formation of the austenite at the dendrite boundaries is invariably epitaxially growth and fills the interdendritic region of the primary ferrite (Inoue et al., 2007).

4.1.3.4 THE MICROGRAPH AND ANALYSIS OF E 308 – 16/12 (Lime-Titania) JOINT SPECIMEN

Fu et al. (2009) noted that Ferrite – Austenite (FA) solidification duplex mode is characterized by the formation of primary ferrite, plus three phase (ferrite, austenite and liquid) reactions at the terminal solidification stage. The Fe-Cr-Ni phase diagram shown in Figure 2.8 confirmed that the E 308 – 16/12 (lime-titania) weld metal solidified with a duplex FA mode through the following sequence of transformations: "$L \rightarrow + \rightarrow + + \rightarrow +$", where $L$ represents
the liquid, ferrite and austenite phases respectively. The ferrite solidifies first from the liquid, having the appearance of eutectic – like network and grows by depletion of chromium. The remaining liquid being enriched in nickel suppresses further formation of ferrite and favors the nucleation and growth of austenite to consume the entire matrix. Meanwhile, only a part of the lathy ferrite formed in the solidification stage transforms to austenite upon cooling by diffusion controlled solid state reaction accompanied by carbide precipitation along the grain boundaries (Inoue et al., 2007; Fu et al., 2009). The fusion zone micrograph of E 308 – 16/12 (lime-titania) joint shown in Plate 4.3a revealed a plenty of fine colonies of lathy ferrite (dark) embedded in austenite (white) matrix. The result was a duplex microstructure consisting of thin lathy ferrite and austenite.

Plate 4.3a: Fusion zone micrograph of E 308 – 16/12 (lime-titania) welded joint.

The micrograph of the HAZ of E 308 – 16/12 (lime-titania) welded joint shown in Plate 4.3b revealed growth of austenite grain accompanied with much solute segregation and carbide precipitation along the grain boundaries.
4.1.3.5 THE MICROGRAPH AND ANALYSIS OF TIG JOINT SPECIMEN

The Fe-Cr-Ni phase diagram shown in Figure 2.8 confirmed that TIG weld metal solidified with a duplex FA mode, through the following sequence of transformations: $\text{L} \rightarrow + \rightarrow + + \rightarrow + , \text{ where L, }$ represents the liquid, ferrite and austenite phases respectively. Fu et al. (2009) suggested a similar result consisting of the coupled growth between ferrite and austenite, formed first from the melt and is surrounded by the liquid which eventually transforms to austenite. The fusion zone micrograph of TIG joint specimen shown in Plate 4.4a revealed primary equiaxed dendritic and lathy ferrite (dark) enclosed
in austenite (white) matrix, with the precipitation of carbides along grain boundaries.

Plate 4.4a: Fusion zone micrograph of TIG welded joint.

The micrograph of the HAZ of TIG welded joint shown in Plate 4.4b revealed growth of austenite grain accompanied with carbide precipitation along the grain boundaries.

Plate 4.4b: HAZ micrograph of TIG welded joint
4.1.3.6 THE MICROGRAPH AND ANALYSIS OF E 308 – 16/12 (Rutile) JOINT SPECIMEN

The Fe-Cr-Ni phase diagram shown in Figure 2.8 showed that the E 308 – 16/12 (rutile) weld metal solidified with a duplex FA mode through the following sequence of transformations: \[ \text{L,} \rightarrow + \rightarrow + + \rightarrow + , \]
where L, represents the liquid, ferrite and austenite phases respectively. It therefore follows that the ferrite and austenite form first from the liquid while the remaining liquid eventually transforms to austenite. The fusion zone micrograph of the E 308 – 16/12 (rutile) joint shown in Plate 4.5a revealed a duplex structure of ferrite and austenite. The primary ferrite (dark) dendrites having a combination of lathy and vermicular ferrite morphology contained in austenite (white) matrix, and a precipitation of carbide along grain boundaries. The amount of retained ferrite in E 308 – 16/12 (rutile) weld metal was found to be less than TIG and E 308 – 16/12 (lime-titania) weld metal respectively, but more than that observed in E 308 – 16/10 (rutile) weld metal.

Plate 4.5a: Fusion zone micrograph of E 308 – 16/12 (rutile) welded joint.
4.1.3.7 THE MICROGRAPH AND ANALYSIS OF E 308 – 16/10(Rutile) JOINT SPECIMEN

The Fe-Cr-Ni phase diagram shown in Figure 2.8 showed that the E 308 – 16/10 (rutile) weld metal solidified with a duplex FA mode through the following sequence of transformations: \[ \text{L} \rightarrow + \rightarrow + + \rightarrow + , \]
where \( \text{L} \) represents the liquid, ferrite and austenite phases respectively. Ferrite and austenite formed first from the liquid while the remaining liquid eventually transforms to austenite. The fusion zone micrograph of the E 308 – 16/10 (rutile) joint shown in Plate 4.6a revealed a duplex structure consisting of ferrite (dark) and austenite (white). The primary ferrite had a thin lathy morphology engulfed by austenite which grew epitaxially and fills the interdendritic region of the primary ferrite. Carbide precipitation was also observed along the grain boundaries.
Plate 4.6a: Fusion zone micrograph of E 308 – 16/10 (rutile) welded joint.

The micrograph of the HAZ of E 308 – 16/10 (rutile) welded joint shown in Plate 4.6b revealed growth of austenite grain accompanied with solute segregation and carbide precipitation along the grain boundaries.

Plate 4.6b: HAZ micrograph of E 308 – 16/10 (rutile) welded joint
4.1.3.8 THE MICROGRAPH AND ANALYSIS OF THE HEAT UNAFFECTED PARENT MATERIAL

The micrograph of the unwelded parent material shown in Plate 4.7 revealed the initial grain size of austenite with carbide precipitates along the grain boundaries.

![Micrograph of the unwelded parent material](Plate 4.7: Micrograph of the unwelded parent material)

4.2 DISCUSSION AND INTERPRETATION OF RESULTS

4.2.1 THE EFFECT OF WELDING ELECTRODE TYPES ON THE STRAIN HARDENING EXPONENT OF AUSTENITIC STAINLESS STEEL FABRICATED COMPONENTS.

The results displayed in Table 4.10 suggested that the type of welding electrode used in the fabrication of austenitic stainless steel components has effect on the strain hardening exponent of the material. In metal forming processes, the product shapes are produced by plastic deformation. In many products the mechanical properties depend on the control of strain hardening during processing, while in the
other instances, precise control of deformation, temperature, and strain rate during processing is required to develop the optimum structure and properties (Dieter et al., 1988).

In order to optimize the processes involved in metal forming, it is important to know how the types of welding electrode used during fabrication affects the plastic flow properties of the material. Strain hardening coefficient is one of the most important property considered during metal forming. Callister et al. (2010) opined that strain hardening coefficient (or exponent) is a measure of the ability of a metal to strain harden, which is a phenomenon whereby a ductile material becomes harder and stronger upon plastic deformation. A number of authors have reported that materials with a high value of strain hardening exponent allow more tensile deformation before a localized neck develops and hence enjoy the benefits of cold working (Dieter, et al.,1988 ; Callister, et al., 2010; and Campbell, 2008).

Consequently, materials with low strain hardening coefficient tends be less useful in cold forming.

In the present work carried out at a constant strain rate of 108rev/min., it was found that Autogeneous Tungsten Inert Gas welding as well as welding with E 312 – 16/10; E 308 – 16/12 (lime-titania); E 308 – 16/12 (rutile) and E 308 – 16/10 (rutile) stainless steel electrodes, reduce slightly the ductility and hence the formability (in cold state) of austenitic stainless material. However, welding with
E 310 – 16/10 stainless steel electrode (which produced the highest value of strain hardening exponent and strength coefficient of about 0.44 and 1180 respectively) is expected to allow for more tensile deformation prior to necking, even though it has a relatively low ductility of about 29% in terms of percentage elongation as compared with 77% ductility (percentage elongation) obtained from the unwelded parent material. Transformation induced plasticity in austenite is believed to be the reason for the higher value of strain hardening exponent obtained for E 310 – 16/10 weld metal. Moreso, the solidification mode of E 310 – 16/10 weld metal was found to be austenite. During plastic deformation, this structure transformed to martensite due to a diffusionless transformation caused by interface movement. Consequently, more dislocations were created which increased the strain hardening exponent of the material. This has been confirmed by many research works (Talyan et al., 1998; Neff et al., 1969; Bressanelli and Moskowitz 1966; Angel, 1954).

Welding with E 308 – 16/12 (lime-titania) electrode produced the least value of strain hardening exponent of about 0.35, and is supposed to exhibit a relatively lesser tensile deformation in the plastic region before necking, even though it has a relatively high ductility of about 36% in terms of percentage elongation.
The effect of electrode size on the strain hardening exponent was also investigated. E 308 – 16 (rutile) stainless steel electrode of gauges 10 and 12 were used on the same material and found that the one of E 308 – 16/12 (rutile) produced 0.41 value of strain hardening exponent with a corresponding low percentage elongation of 18%, while that of E 308 – 16/10 (rutile) had a strain hardening coefficient of 0.38.

4.2.2 EFFECT OF ELECTRODE TYPES ON THE SOLIDIFICATION MODE OF AUSTENITIC STAINLESS STEEL WELD METAL

The results displayed in Table 4.13 showed that the type of electrode selected in the welding of 304H stainless steel component affects the solidification microstructure of the weld metal. It was found that the TIG autogeneous weld had nearly the same solidification microstructure (FA) with the parent material – a result which was highly anticipated since there was no filler dilution in the completed weld as the tungsten electrode was non-consumable. Weldments produced from E 308 – 16/12 (rutile); E 308 – 16/10 (rutile) and E 308 – 16/12 (lime-titania) electrodes had a duplex structure of ferrite – austenite (FA) with more or less amount of retained ferrite. Filler rod or electrode dilution is believed to be responsible for the evolved microstructure and solidification mode as shown in the results of the fusion zones micrographs of the E 308 – 16/12 (lime-titania); E 308 – 16/12 (rutile); and E 308 – 16/10 (rutile) joints displayed in Plates 4.3a,
4.5a and 4.6a respectively. Joints produced from E 310 – 16/10 electrode had austenite solidification mode whereas the joints made from E 312 – 16/10 solidified with a primary ferrite solidification mode. The compromise reached between the parent material composition and filler rod or electrode dilution was found to be the major factor which determined the weld metal final microstructure and solidification mode. The findings of this research were found to be in line with the results of many researchers (Schino et al., 2000; Fu et al., 2009; Leone, et al., 1982; Udomphol et al., 2007; Arantes et al., 2007; and Baldev et al., 2006).

4.2.3 EFFECT OF ELECTRODE TYPES ON WELD METAL COMPOSITION AND CRCKING PROPENSITY

The results of chemical analysis (presented in Table 4.11) carried out on the weldments showed that electrode types have effect on the weld metal composition. The TIG autogeneous weldment had nearly the same composition and Chromium – Nickel equivalence as that of the unwelded parent metal. However, remarkable difference in weld metal constitution was observed in the joints produced from the various electrodes relative to the Chromium – Nickel equivalence of the parent material. The results of Chromium – Nickel equivalence for the respective joints were found to be slightly more or less, and yet in agreement with the Welding Research Council (1992), Hammar and Svenson (1979), and Schaeffler’s (1949) equations. The results showed that solidification cracking of the weld joints were
sensitive to Cr eq. / Ni eq. ratio and solidification mode of the welds. E 308 – 16/12 (lime-titania), TIG, E 308 – 16/12 (rutile), E 308 – 16/10 (rutile) welds with primary ferrite – austenite solidification modes and 1.5<\frac{\text{Cr eq.}}{\text{Ni eq.}}< 1.9, are immune to solidification cracking in the order of decreasing resistance to solidification cracking respectively. E 312 – 16/10 weld with ferrite solidification mode and \frac{\text{Cr eq.}}{\text{Ni eq.}}>1.9 has low susceptibility to solidification cracking, whilst E 310 – 16/10 weld with primary austenite solidification mode, \frac{\text{Cr eq.}}{\text{Ni eq.}}< 1.5, and (P+S) wt. % = 0.015, may be somewhat susceptible to solidification cracking. Filler rod or electrode dilution is one of the factors which determined the final weld metal composition and solidification mode. Since Solidification cracking is sensitive to weld metal composition and solidification mode, it therefore follows that the type of electrode used during welding of ASS materials, determines the weld metal solidification cracking propensity.

These results were compared with the cracking susceptibility of 300 series stainless steel based on Cr – Ni equivalence according to Hammar and Svenson (1979), and found to be consistent and also in line with the findings of Arantes et al. (2007); Baldev et al. (2006); Korinko et al.(2001); and Brooks et al. (1991) who affirmed that the propensity for solidification cracking in austenitic stainless steel is sensitive to the Cr eq. / Ni eq. ratio, (P+S) wt. % and ferrite number of the weld
metal and maintained that weld metal with solidified FA mode in the range of 1.5<
< 1.9 are immune to solidification cracking, while those in the region of >1.9 and < 1.5, have low resistance and susceptible to solidification cracking respectively. Generally, it was found that (P+S) wt. % values were less than 0.02 in the final composition of the respective welded joints, which is below the critical level suggested by Arantes et al., 2007; necessary to induce cracking.

The results also suggest that the type of electrode coating has effect on the weld metal properties. The electrodes used for the welding were designated ‘-16’ which denotes rutile coating for stainless steel electrodes. Rutile coatings are titania-type based electrodes containing little proportion of other additives. However, E 308 – 16/12 (lime-titania) electrodes were coated with titanium calcium and contains lime which makes it distinct from the rutile category. The presence of lime (which is a slag former) in E 308 -16/12 (lime-titania) electrode was relevant in slowing down the cooling rate of both the weld pool and the just solidified weld metal of the resultant weldment. This suggests the reason for the slight difference observed in properties (such as ductility and strain hardening exponent) of weldments produced from the E 308 – category of welding electrodes. Consequently, the weldment produced from E 308-16/12 (lime-titania) electrode has a higher ductility of about 36% (in terms of percentage elongation) compared to 26% and
18% obtained from weldments produced from E 308-16/10 (rutile) and E 308-16/12 (rutile) electrodes respectively. This result is confirmed in the micrograph of E 308-16/12 (lime-titania) weldment which suggest that the ferrite dendrite had more time for growth in the region where delta ferrite is most stable (due to slower cooling rate offered by lime in the electrode coating) compared to the micrographs of E 308-16/10 (rutile) and E 308-16/12 (rutile) weldments.
CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION OF RESULTS AND FINDINGS

The cracking of austenitic stainless steel (ASS) material during welding was successfully reviewed while investigating the microstructural propensity of an ASS component to solidification cracking.

The effect of electrode type on the solidification cracking susceptibility of ASS weld metal was studied and established. The influence of welding electrode on the strain hardening exponent of an ASS material was carefully studied. The 304H stainless steel material was analysed in order to determine its chemical composition and then welded. The welding operation was carried out using five different categories of stainless steel electrodes and a non-consumable electrode (which served as the control) in a Tungsten Inert Gas (TIG) welding process, to produce the specimens.

Metallurgical as well as some aspect of mechanical behavior of the fabricated ASS components were investigated as the weldments were subjected to tensile test, metallographic test and chemical analysis. In each specimen, the ratio, solidification mode and morphology of the as-weld microstructure were determined. From the results generated thereof, the effect of the electrode types on
the solidification cracking susceptibility of the 304H steels were evaluated. Furthermore, the strain hardening coefficient for each of the specimens was determined from the tensile test results, and the effect of strain hardening coefficient was established.

It was found that fabricated ASS components produced from E 308 – 16/12 (rutile); E 308 – 16/10 (rutile); E 308 – 16/12 (lime-titania) electrodes and TIG joints (all having FA duplex mode of solidification and ratio of Cr to Ni equivalence in the range 1.5< <1.9) are immune to solidification cracking. The E 308 – 16/12 (lime-titania) electrode (having ferrite number (FN) of 10) was observed to impact the highest resistance to cracking, followed by TIG joints (with FN of 8), E 308 – 16/12 (rutile) with FN=6 and E 308 – 16/10 (rutile) with FN=5.5 in that order. ASS components fabricated from E 312 – 16/10 electrode (produced a ratio of about 2.01 which is greater than 1.9, and ferrite number of about 53 in the completed weld which is beyond 35% stipulated by Hull (1967) as necessary cause a shift from immunity zone to crack susceptible zone) solidified with a ferrite mode and was found to show little resistance to solidification cracking. The E 310 – 16/10 electrode solidified with austenite mode and was found to be somewhat liable to solidification cracking since it produced a ratio of about 1.01, which is less than 1.5 the value suggested by (Arantes, et al., 2007; Shankar,
et al., 2003; Brooks, et al., 1991; and Scherer, et al., 1941) to prevent solidification cracking in the completed weld metal. Comparing the results obtained from tensile tests, it was discovered that the use of E310 – 16/10 electrode (which gave a strain hardening coefficient (n) of value 0.44) in the fabrication of ASS components has the capacity of increasing the strain hardening coefficient of the parent material thereby allowing for more plastic deformation prior to necking during subsequent forming operation. However, within the limits of the experimental conditions, TIG welded joints (which gave an ‘n’ value of 0.38) as well as joints produced from E308 – 16/12 (rutile) with n=0.41, E308 – 16/10 (rutile) with n=0.38, E 308 – 16/12 (lime-titania) with n=0.35, and E312 – 16/10 (n=0.40) electrodes were discovered to reduce the strain hardening exponent and hence ductility of austenitic stainless steel fabricated components.

5.2 CONTRIBUTION TO KNOWLEDGE

From careful observations, results and analysis of the data generated in this research work, it can be concluded that contribution to knowledge has been made as follows:

i. The presence of lime in ASS welding electrode may increase the ferrite content of the completed weld.

ii. ASS components fabricated with E 310 – 16 (gauge 10) welding electrode are more useful in metal forming processes.
5.3 RECOMMENDATIONS

From the findings made in this research work, it is recommended that:

i. The use E 308 – 16/12 (lime-titania) electrode in the fabrication of ASS material is necessary to overcome solidification cracking. This is because E 308 – 16/12 (lime-titania) imparts the greatest resistance to solidification cracking in ASS weld metal, even though E308-16 (rutile) gauges 12 and 10 welding electrodes, as well as TIG joints gave similar results.

ii. E 310 – 16/10 electrode is not suitable for welding 304H stainless steels considering the weldability problems associated with solidification cracking.

iii. Where high formability is sought, E310 – 16/10 welding electrode may be useful since it has the highest strain hardening coefficient of 0.44.

iv. Where the application of ASS fabricated component requires high tensile strength, E 312 – 16/10 welding electrode should be used.

v. Scanning electron microscope (SEM) is recommended for studying segregation and probing the as-weld microstructure.

vi. It is also recommended for further studies to consider the contribution of constraint imposed by thick sections to solidification cracking propensity of ASS weldments.
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APPENDIX A

DEFINITION OF TERMS

AISI: American Iron and Steel Institute.

Arc Welding: A fusion welding process in which coalescence of the metal is achieved by the heat from an electric arc between an electrode and the workpiece.

ASS: Austenitic stainless steel.

Austenitic stainless steel: Stainless steels with composition in the range of 16 – 26% Cr., 8 – 30% Ni., and small amount of various other alloying additions.

Austenite (Ƴ): FCC crystal structure of iron which is stable at temperature range of 910°C – 1400°C.

Autogenous Welding: A welding process involving no filler addition or with filler metal of matching composition with the base metal.

AWS: American Welding Society.

Cr.eq.: Chromium equivalent.

**Delta Ferrite (δ):** BCC crystal structure of iron which is stable at high temperatures close to the melting temperature.
Electrode: Welding rod which supplies heat to the workpiece. Consumable types melts in the arc heat during arc welding and fills the joint to produce the weld metal.

E 312 – 16 /10: 312 – 16 gauge 10 stainless steel electrode classified by AWS standard.

E 310 – 16 /10: 310 – 16 gauge 10 stainless steel electrode classified by AWS standard.

E 308 – 16 /12(Lime-titania coated): 308 – 16 gauge 12 stainless steel electrode with a titanium-calcium coating type as classified by AWS standard.

E 308 – 16 /10(Rutile coated): 308 – 16 gauge 10 stainless steel electrode with a titanium oxide base coating as classified by AWS standard.

E 308 – 16 /12(Rutile coated): 308 – 16 gauge 12 stainless steel electrode with a titanium oxide base coating as classified by AWS standard.

Ferrite Number (FN): A measure of the amount of delta ferrite content retained in the final microstructure of the weld metal.

HAZ: Heat Affected Zone – the region of the weld joint which has experienced peak temperatures high enough to cause microstructural changes but insufficient to cause melting.
Microfissuring: Cracks of microscopic dimensions which occur in the weld metal during cooling.

Microstructure: Totality of the phases, grain size and shape, their distribution and volume fraction of the phases present in the weld or cast structure.

NDT: Non – Destructive Tests

Ni.eq.: Nickel equivalent.

SMAW: Shielded Metal Arc Welding also known as Manual Metal Arc Welding – A welding process in which heat required for melting is generated from an arc struck between a consumable coated ( with flux ) electrode and the workpiece.

Solidification: Phase transformation from liquid to solid state.

Solidification Cracking: Fractures at the interdendritic and/or intergranular weld metal boundaries in the solidification process, during which the liquid phase of the mushy melt becomes rich in impurities.

Susceptibility: The tendency to occur or the propensity for something to happen.

TIG Welding: Tungsten Inert Gas Welding – A welding process in which the heat necessary to melt the metal is provided by a very intense electric arc which is struck between a non – consumable Tungsten electrode and the workpiece.
Weld: A union between pieces of metal at faces rendered plastic or liquid by heat or pressure or both.

Weld Cracks: Fracture – type interruptions either in the weld itself or in the base metal adjacent to the weld.

Weld Decay: Carbide precipitation occurring during cooling at the HAZ, leading to the depletion of chromium and intergranular attack.

Weld Dilution: Loss of specific materials at the fusion zone as the parent material mixes with the filler metal (or electrode).

Weldability: The capacity of a metal or a combination of metals to be welded into a suitable design structure and for the resulting weld joint to possess the required metallurgical properties necessary to perform satisfactorily in service.

Weldment: The assemblage of parts joined by welding.

Weld Joint: The junction of the edges or surfaces of parts that have been joined together by welding.

Weld Metal: A solidified structure of the base metal and the filler metal. It may also be regarded as the Fusion Zone.
APPENDIX B

CALCULATION OF Cr\text{eq} and Ni\text{eq} FOR EACH WELD METAL

ACCORDING TO THE 1992 WRC MODEL EQUATION

Cr\text{eq} for E308-16/12 (Rutile) weldment:

\[ \text{Cr}_{eq} = \text{Cr} + \text{Mo} + 0.7\text{Nb} \]

\[ \text{Cr}_{eq} = 17.15 + 0.133 + 0.7(0.027) \]

\[ \text{Cr}_{eq} = 17.3019 \]

Ni\text{eq} for E308-16/12 (Rutile) weldment:

\[ \text{Ni}_{eq} = \text{Ni} + 35\text{C} + 20\text{N} + 0.25\text{Cu} \]

\[ \text{Ni}_{eq} = 7.19 + 35(0.071) + 20(0) + 0.25(0.292) \]

\[ \text{Ni}_{eq} = 7.19 + 2.485 + 0 + 0.073 \]

\[ \text{Ni}_{eq} = 9.748 \]

\[ \text{ratio} = 1.775 \]
(p + S) = 0.0061 + 0.0110 = 0.0171

Cr_{eq}, Ni_{eq}, and (P + S) values for E308-16/10 (Rutile) weldment:

\[ Cr_{eq} = Cr + Mo + 0.7Nb \] \hspace{1cm} (1)

\[ Cr_{eq} = 17.02 + 0.166 + 0.7(0.026) \]

\[ Cr_{eq} = 17.2042 \]

\[ Ni_{eq} = Ni + 35C + 20N + 0.25Cu \] \hspace{1cm} (2)

\[ Ni_{eq} = 7.21 + 35(0.073) + 20(0) + 0.25(0.411) \]

\[ Ni_{eq} = 7.21 + 2.555 + 0 + 0.1028 \]

\[ Ni_{eq} = 9.8678 \]

\[ \frac{Cr_{eq}}{Ni_{eq}} = 1.7435 \]

\[ \text{ratio} = 1.7435 \]

(p + S) = 0.0010 + 0.0084 = 0.094

Cr_{eq}, Ni_{eq}, and (P + S) values for E308-16/12 (Lime-titania) weldment:

\[ Cr_{eq} = Cr + Mo + 0.7Nb \] \hspace{1cm} (1)

\[ Cr_{eq} = 19.57 + 0.232 + 0.7(0.029) \]
\[ \text{Cr}_{eq} = 19.8223 \]

\[ \text{Ni}_{eq} = \text{Ni} + 35\text{C} + 20\text{N} + 0.25\text{Cu} \quad \text{........................................(2)} \]

\[ \text{Ni}_{eq} = 8.74 + 35(0.074) + 20(0) + 0.25(0.246) \]

\[ \text{Ni}_{eq} = 8.74 + 2.59 + 0 + 0.0615 \]

\[ \text{Ni}_{eq} = 11.3915 \]

\[ \text{ratio} = 1.7401 \]

\[ (p + S) = 0.0010 + 0.0076 = 0.0086 \]

Cr\(_{eq}\), Ni\(_{eq}\), and (P + S) values for E310-16/10 weldment:

\[ \text{Cr}_{eq} = \text{Cr} + \text{Mo} + 0.7\text{Nb} \quad \text{.................................................(1)} \]

\[ \text{Cr}_{eq} = 23.85 + 0.157 + 0.7(0.029) \]

\[ \text{Cr}_{eq} = 24.0273 \]

\[ \text{Ni}_{eq} = \text{Ni} + 35\text{C} + 20\text{N} + 0.25\text{Cu} \quad \text{..............................................(2)} \]

\[ \text{Ni}_{eq} = 17.99 + 35(0.135) + 20(0) + 0.25(0.152) \]

\[ \text{Ni}_{eq} = 17.99 + 4.725 + 0 + 0.038 \]
\[ \text{Ni}_{\text{eq}} = 22.753 \]

\[ \text{-} = \frac{\text{-}}{1.0560} \]

\[ \text{ratio} = 1.0560 \]

\[ (p + S) = 0.0010 + 0.0140 = 0.015 \]

\text{Cr}_{\text{eq}}, \text{Ni}_{\text{eq}}, \text{ and } (P + S) \text{ values for E312-16/10 weldment:}

\[ \text{Cr}_{\text{eq}} = \text{Cr} + \text{Mo} + 0.7\text{Nb} \]

\[ \text{Cr}_{\text{eq}} = 26.71 + 0.064 + 0.7(0.047) \]

\[ \text{Cr}_{\text{eq}} = 26.71 + 0.064 + 0.0329 \]

\[ \text{Cr}_{\text{eq}} = 26.8069 \]

\[ \text{Ni}_{\text{eq}} = \text{Ni} + 35\text{C} + 20\text{N} + 0.25\text{Cu} \]

\[ \text{Ni}_{\text{eq}} = 9.73 + 35(0.092) + 20(0) + 0.25(0.079) \]

\[ \text{Ni}_{\text{eq}} = 9.73 + 3.22 + 0 + 0.01975 \]

\[ \text{Ni}_{\text{eq}} = 12.9698 \]

\[ \text{-} = \frac{\text{-}}{2.0669} \]

\[ \text{ratio} = 2.0669 \]
(p + S) = 0.0010 + 0.0130 = 0.014

Cr\textsubscript{eq}, Ni\textsubscript{eq}, and (P + S) values for TIG:

Cr\textsubscript{eq} = Cr + Mo + 0.7Nb .................................................. (1)

Cr\textsubscript{eq} = 18.45 + 0.174 + 0.7(0.021)

Cr\textsubscript{eq} = 18.6387

Ni\textsubscript{eq} = Ni + 35C + 20N + 0.25Cu ........................................... (2)

Ni\textsubscript{eq} = 8.79 + 35(0.06) + 20(0) + 0.25(0.190)

Ni\textsubscript{eq} = 8.79 + 2.1 + 0 + 0.0475

Ni\textsubscript{eq} = 10.9375

\begin{align*}
\text{ratio} &= \frac{\text{Cr}_{eq}}{\text{Ni}_{eq}} = \frac{18.6387}{10.9375} = 1.7041
\end{align*}

\text{ratio} = 1.7041

(p + S) = 0.0022 + 0.0046 = 0.0068

CALCULATION OF Cr\textsubscript{eq} and Ni\textsubscript{eq} FOR THE WELDMENTS ACCORDING TO HAMMER AND SVENSON EQUATIONS OF 1979

According to Hammer and Svenson (1979)
\[ \text{Cr}_{eq} = \text{Cr} + 1.37\text{Mo} + 1.5\text{Si} + 2\text{Nb} + 3\text{Ti} \] …………………………………… (3)

\[ \text{Ni}_{eq} = \text{Ni} + 0.31\text{Mn} + 22\text{C} + 14.2\text{N} + \text{Cu} \] …………………………………… (4)

\[ \text{Cr}_{eq}, \text{Ni}_{eq}, \text{and } (\text{P} + \text{S}) \text{ values for } \text{E308-16/12 (Rutile) weldment:} \]

\[ \text{Cr}_{eq} = \text{Cr} + 1.37\text{Mo} + 1.55\text{Si} + 2\text{Nb} + 3\text{Ti} \]

\[ \text{Cr}_{eq} = 17.15 + 1.37(0.133) + 1.5(0.69) + 2(0.027) + 3(0.024) \]

\[ \text{Cr}_{eq} = 17.15 + 0.18221 + 1.035 + 0.054 + 0.072 \]

\[ \text{Cr}_{eq} = 18.4932 \]

\[ \text{Ni}_{eq} = \text{Ni} + 0.31\text{Mn} + 22\text{C} + 14.2\text{N} + \text{Cu} \]

\[ \text{Ni}_{eq} = 7.19 + 0.31(1.22) + 22(0.071) + 14.2(0) + 0.292 \]

\[ \text{Ni}_{eq} = 7.19 + 0.3782 + 1.562 + 0.292 \]

\[ \text{Ni}_{eq} = 9.4222 \]

\[ \frac{\text{Cr}_{eq}}{2} = 9.246 \]

\[ \text{ratio} = 1.9627 \]

\[ (\text{P} + \text{S}) = 0.0171 \]
Cr_{eq}, Ni_{eq}, and (P + S) values for E308-16/10 (Rutile) weldment:

\[ Cr_{eq} = Cr + 1.37Mo + 1.55Si + 2Nb + 3Ti \]

\[ Cr_{eq} = 17.02 + 1.37(0.166) + 1.5(0.63) + 2(0.026) + 3(0.019) \]

\[ Cr_{eq} = 17.02 + 0.22742 + 0.945 + 0.052 + 0.057 \]

\[ Cr_{eq} = 18.3014 \]

\[ Ni_{eq} = Ni + 0.31Mn + 22C + 14.2N + Cu \]

\[ Ni_{eq} = 7.12 + 0.31(1.18) + 22(0.073) + 14.2(0) + 0.411 \]

\[ Ni_{eq} = 7.12 + 0.3658 + 1.606 + 0.411 \]

\[ Ni_{eq} = 9.5928 \]

\[ \frac{Cr_{eq}}{Ni_{eq}} = 1.9078 \]

\[ \text{ratio} = 1.9078 \]

\[ (P + S) = 0.0094 \]
\[ \text{Cr}_{eq}, \text{Ni}_{eq}, \text{and (P + S) values for E308-16/12 (Lime-titania) weldment:} \]

\[ \text{Cr}_{eq} = \text{Cr} + 1.37\text{Mo} + 1.55\text{Si} + 2\text{Nb} + 3\text{Ti} \]

\[ \text{Cr}_{eq} = 19.57 + 1.37(0.232) + 1.5(0.49) + 2(0.029) + 3(0.011) \]

\[ \text{Cr}_{eq} = 19.57 + 0.31784 + 0.735 + 0.058 + 0.033 \]

\[ \text{Cr}_{eq} = 20.7138 \]

\[ \text{Ni}_{eq} = \text{Ni} + 0.31\text{Mn} + 22\text{C} + 14.2\text{N} + \text{Cu} \]

\[ \text{Ni}_{eq} = 8.74 + 0.31(1.39) + 22(0.074) + 14.2(0) + 0.246 \]

\[ \text{Ni}_{eq} = 8.74 + 0.4309 + 1.628 + 0.246 \]

\[ \text{Ni}_{eq} = 11.0449 \]

\[ \frac{\text{Cr}_{eq}}{\text{Ni}_{eq}} = \frac{20.7138}{11.0449} = 1.8754 \]

\[ \text{ratio} = 1.8754 \]

\[ \text{(P + S)} = 0.0086 \]

\[ \text{Cr}_{eq}, \text{Ni}_{eq}, \text{and (P + S) values for E310-16/10 weldment:} \]

\[ \text{Cr}_{eq} = \text{Cr} + 1.37\text{Mo} + 1.55\text{Si} + 2\text{Nb} + 3\text{Ti} \]

\[ \text{Cr}_{eq} = 23.85 + 1.37(0.157) + 1.5(0.51) + 2(0.029) + 3(0.425) \]
\[ \text{Cr}_{eq} = 23.85 + 0.21509 + 0.765 + 0.058 + 1.275 \]

\[ \text{Cr}_{eq} = 26.1631 \]

\[ \text{Ni}_{eq} = \text{Ni} + 0.31\text{Mn} + 22\text{C} + 14.2\text{N} + \text{Cu} \]

\[ \text{Ni}_{eq} = 17.99 + 0.31(1.87) + 22(0.135) + 14.2(0) + 0.152 \]

\[ \text{Ni}_{eq} = 17.99 + 0.5797 + 2.97 + 0.152 \]

\[ \text{Ni}_{eq} = 21.6917 \]

\[ \frac{\text{Cr}_{eq}}{\text{Ni}_{eq}} = 1.2061 \]

\[ \frac{\text{Ni}_{eq}}{\text{Ni}_{eq}} = 1.2061 \]

\[ (p + S) = 0.015 \]

\[ \text{Cr}_{eq}, \text{Ni}_{eq}, \text{and} (p + S) \text{ values for E312-16/10 weldment:} \]

\[ \text{Cr}_{eq} = \text{Cr} + 1.37\text{Mo} + 1.55\text{Si} + 2\text{Nb} + 3\text{Ti} \]

\[ \text{Cr}_{eq} = 26.71 + 1.37(0.064) + 1.5(0.91) + 2(0.047) + 3(0.016) \]

\[ \text{Cr}_{eq} = 26.71 + 0.08768 + 1.365 + 0.094 + 0.048 \]

\[ \text{Cr}_{eq} = 28.3047 \]

\[ \text{Ni}_{eq} = \text{Ni} + 0.31\text{Mn} + 22\text{C} + 14.2\text{N} + \text{Cu} \]
\[ \text{Ni}_{\text{eq}} = 9.73 + 0.31(1.32) + 22(0.092) + 14.2(0) + 0.079 \]

\[ \text{Ni}_{\text{eq}} = 9.73 + 0.4092 + 2.024 + 0.079 \]

\[ \text{Ni}_{\text{eq}} = 12.2422 \]

\[ \frac{\text{ratio}}{\text{ratio}} = 2.3121 \]

\[ (p + S) = 0.014 \]

Cr\(_{\text{eq}}\), Ni\(_{\text{eq}}\), and (P + S) values for TIG weld metal:

\[ \text{Cr}_{\text{eq}} = \text{Cr} + 1.37\text{Mo} + 1.55\text{Si} + 2\text{Nb} + 3\text{Ti} \]

\[ \text{Cr}_{\text{eq}} = 18.45 + 1.37(0.174) + 1.5(0.376) + 2(0.021) + 3(0.0010) \]

\[ \text{Cr}_{\text{eq}} = 18.45 + 0.23838 + 0.564 + 0.042 + 0.003 \]

\[ \text{Cr}_{\text{eq}} = 19.2974 \]

\[ \text{Ni}_{\text{eq}} = \text{Ni} + 0.31\text{Mn} + 22\text{C} + 14.2\text{N} + \text{Cu} \]

\[ \text{Ni}_{\text{eq}} = 8.79 + 0.31(1.62) + 22(0.06) + 14.2(0) + 0.19 \]

\[ \text{Ni}_{\text{eq}} = 8.79 + 0.5022 + 1.32 + 0.19 \]

\[ \text{Ni}_{\text{eq}} = 10.8022 \]
CALCULATION OF $Cr_{eq}$ and $Ni_{eq}$ FOR THE WELDMENTS ACCORDING TO SCHAEFFLER (1949) EQUATION

According to Schaeffler (1949):

$$Cr_{eq} = Cr + Mo + 1.5Si + 0.5Nb \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots (5)$$

$$Ni_{eq} = Ni + 0.5Mn + 30C \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots (6)$$

$Cr_{eq}$, $Ni_{eq}$, and $(P + S)$ values for E308-16/12 (Rutile) weldment:

$$Cr_{eq} = Cr + Mo + 1.5Si + 0.5Nb$$

$$Cr_{eq} = 17.15 + 0.133 + 1.5(0.69) + 0.5(0.027)$$

$$Cr_{eq} = 17.15 + 0.133 + 1.035 + 0.0135$$

$$Cr_{eq} = 18.3315$$

$$Ni_{eq} = Ni + 0.5Mn + 30C$$

$$Ni_{eq} = 7.19 + 0.5(1.22) + 30(0.071)$$
\[ \text{Ni}_{eq} = 7.19 + 0.61 + 2.13 \]

\[ \text{Ni}_{eq} = 9.93 \]

\[ \frac{1}{\text{Ni}_{eq}} \cdot 1.8461 \]

\[ \text{ratio} = 1.8461 \]

\[ (p + S) = 0.00171 \]

\[ \text{Cr}_{eq}, \text{Ni}_{eq}, \text{and (P + S)} \text{ values for E308-16/10 (Rutile) weldment:} \]

\[ \text{Cr}_{eq} = \text{Cr} + \text{Mo} + 1.5\text{Si} + 0.5\text{Nb} \]

\[ \text{Cr}_{eq} = 17.02 + 0.166 + 1.5(0.63) + 0.5(0.026) \]

\[ \text{Cr}_{eq} = 17.02 + 0.166 + 0.945 + 0.013 \]

\[ \text{Cr}_{eq} = 18.144 \]

\[ \text{Ni}_{eq} = \text{Ni} + 0.5\text{Mn} + 30\text{C} \]

\[ \text{Ni}_{eq} = 7.21 + 0.5(1.18) + 30(0.073) \]

\[ \text{Ni}_{eq} = 7.21 + 0.59 + 2.19 \]

\[ \text{Ni}_{eq} = 9.99 \]

\[ \frac{1}{\text{Ni}_{eq}} \cdot 1.8162 \]

\[ \text{ratio} = 1.8162 \]
ratio = 1.8162

(p + S) = 0.0094

$\text{Cr}_{eq}$, $\text{Ni}_{eq}$, and $(P + S)$ values for E308-16/12 (Lime-titania) weldment:

$\text{Cr}_{eq} = \text{Cr} + \text{Mo} + 1.5\text{Si} + 0.5\text{Nb}$

$\text{Cr}_{eq} = 19.57 + 0.232 + 1.5(0.49) + 0.5(0.029)$

$\text{Cr}_{eq} = 19.57 + 0.232 + 0.735 + 0.0145$

$\text{Cr}_{eq} = 20.5515$

$\text{Ni}_{eq} = \text{Ni} + 0.5\text{Mn} + 30\text{C}$

$\text{Ni}_{eq} = 8.74 + 0.5(1.39) + 30(0.074)$

$\text{Ni}_{eq} = 8.74 + 0.695 + 2.22$

$\text{Ni}_{eq} = 11.655$

$ratio = 1.7633$

$(p + S) = 0.0086$
Cr$_{eq}$, Ni$_{eq}$, and (P + S) values for E310-16/10 weldment:

\[
Cr_{eq} = Cr + Mo + 1.5Si + 0.5Nb
\]

\[
Cr_{eq} = 23.85 + 0.157 + 1.5(0.51) + 0.5(0.029)
\]

\[
Cr_{eq} = 23.85 + 0.157 + 0.765 + 0.0145
\]

\[
Cr_{eq} = 24.7865
\]

\[
Ni_{eq} = Ni + 0.5Mn + 30C
\]

\[
Ni_{eq} = 17.99 + 0.5(1.87) + 30(0.135)
\]

\[
Ni_{eq} = 17.99 + 0.935 + 4.05
\]

\[
Ni_{eq} = 22.975
\]

\[
\frac{Cr_{eq}}{Ni_{eq}} = 1.0788
\]

\[
\frac{Cr_{eq}}{Ni_{eq}} \text{ ratio} = 1.0788
\]

(P + S) = 0.015

Cr$_{eq}$, Ni$_{eq}$, and (P + S) values for E312-16/10 weldment:

\[
Cr_{eq} = Cr + Mo + 1.5Si + 0.5Nb
\]

\[
Cr_{eq} = 26.71 + 0.064 + 1.5(0.91) + 0.5(0.047)
\]
\[ \text{Cr}_{\text{eq}} = 26.71 + 0.064 + 1.365 + 0.0235 \]
\[ \text{Cr}_{\text{eq}} = 28.1625 \]
\[ \text{Ni}_{\text{eq}} = \text{Ni} + 0.5\text{Mn} + 30\text{C} \]
\[ \text{Ni}_{\text{eq}} = 9.73 + 0.5(1.32) + 30(0.092) \]
\[ \text{Ni}_{\text{eq}} = 9.73 + 0.66 + 2.76 \]
\[ \text{Ni}_{\text{eq}} = 13.15 \]
\[ \text{ratio} = \frac{9.73 + 0.66 + 2.76}{9.73 + 0.5(1.32) + 30(0.092)} = 2.1416 \]
\[ (p + S) = 0.014 \]

\text{Cr}_{\text{eq}} , \text{Ni}_{\text{eq}} , \text{and} (p + S) \text{ values for TIG weld metal:}

\[ \text{Cr}_{\text{eq}} = \text{Cr} + \text{Mo} + 1.5\text{Si} + 0.5\text{Nb} \]
\[ \text{Cr}_{\text{eq}} = 18.45 + 0.174 + 1.5(0.3760) + 0.5(0.021) \]
\[ \text{Cr}_{\text{eq}} = 18.45 + 0.174 + 0.564 + 0.0105 \]
\[ \text{Cr}_{\text{eq}} = 19.1985 \]
\[ \text{Ni}_{\text{eq}} = \text{Ni} + 0.5\text{Mn} + 30\text{C} \]
\[ \text{Ni}_{\text{eq}} = 8.79 + 0.5(1.62) + 30(0.06) \]
\[ \text{Ni}_{\text{eq}} = 8.79 + 0.81 + 1.8 \]
\[ \text{Ni}_{\text{eq}} = 11.4 \]

\[ \text{ratio} = 1.6841 \]

\[ (p + S) = 0.0068 \]

C_{\text{eq}}, \text{Ni}_{\text{eq}} \text{ and } (p + S) \text{ values of the unwelded parent metal according to the WRC model equation}

\[ \text{Cr}_{\text{eq}} = \text{Cr} + \text{Mo} + 0.7\text{Nb} \]
\[ \text{Cr}_{\text{eq}} = 18.55 + 0.166 + 0.7(0.027) \]
\[ \text{Cr}_{\text{eq}} = 18.7349 \]

\[ \text{Ni}_{\text{eq}} = \text{Ni} + 35\text{C} + 20\text{N} + 0.25\text{Cu} \]
\[ \text{Ni}_{\text{eq}} = 8.72 + 35(0.057) + 20(0) + 0.25(0.111) \]
\[ \text{Ni}_{\text{eq}} = 8.72 + 1.995 + 0 + 0.02775 \]
\[ \text{Ni}_{\text{eq}} = 10.7428 \]
\[ \text{ratio} = 1.7439 \]

\[ (p + S) = 0.023 + 0.0075 = 0.0305 \]
APPENDIX C

WRC 1992 CONSTITUTION DIAGRAM SHOWING THE SOLIDIFICATION MODE FOR EACH OF THE WELD METALS.

Figure A: WRC-1992 Constitution diagram showing the solidification mode of Type 304H Stainless Steel weld with E 308 - 16/12 (Rutile) Electrode

Figure B: WRC-1992 Constitution diagram showing the solidification mode of Type 304H Stainless Steel weld with E 308 - 16/10 (Rutile) Electrode
Figure C: WRC-1992 Constitution diagram showing the solidification mode of Type 304H Stainless Steel weld with E308-16/12 (Lime-titania) Electrode

Figure D: WRC-1992 Constitution diagram showing the solidification mode of Type 304H Stainless Steel weld with E310-16/10 Electrode
Figure E: WRC-1992 Constitution diagram showing the solidification mode of Type 304H Stainless Steel weld with E312-16/10 Electrode.

Figure F: WRC-1992 Constitution diagram showing the solidification mode of Type 304H Stainless Steel TIG weld.
APPENDIX D

Photograph of the weldments

FIGURE G: E 308 – 16/12 (RUTILE) WELD

FIGURE H: E 308 – 16/10 (RUTILE) WELD
FIGURE I: E 308 – 16/12 (LIME-TITANIA) WELD

FIGURE J: E 310 – 16/10 WELD
FIGURE K: E 312 – 16/10 WELD

FIGURE L: TIG WELD
Scanned section of a typical weldment

FIGURE M(a): Scanned section of a typical weldment

FIGURE M(b): Scanned section of a typical weldment

FIGURE M(c): Geometric determination of filler dilution

filler dilution = \frac{B+C}{A+B+C} \times 100 (%)
APPENDIX E

Tensile test specimens

FIGURE N: WELDED JOINTS FOR TENSILE TEST
APPENDIX F

MICROGRAPHIC TEST RESULTS

Micrographic test result for E 312 – 16/10 specimen
Micrographic test result for E 310 – 16/10 specimen
Micrographic test result for E 308 – 16/12 (lime-titania) specimen
Micrographic test result for E 308 – 16/10 (rutile) specimen
Micrographic test results for E 308 – 16/12 (rutile) specimen and the parent material.
Micrographic test result for TIG specimen
