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Effect of Pre and Post-Heattreament on the Heat-Affected-Zone(HAZ) of Austenitic Stainless -Steel

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Abstract

Stainless Steel is an important class of engineering alloys which are iron-base alloys grouped as iron-chromium-nickel alloys used in both wrought, cast and fabricated form for a wide range of applications and in many industries. Residual stresses in weld joints can be reduced by heat treatment

The goal of this research work carried out by Legend Builders Limited in collaboration with the Lagos state Laboratory test Centre, Centre for Energy and Research Development(CERD) Osun chapter and Universal Steels Limited Lagos. This project is aimed to improve the performance of austenitic stainless steels weldment used in Universal Steels Limited, joined using Shielded Metal Arc Welding (SMAW) welding with stainless steel electrodes at constant welding current, through preheating and stress relieving post weld heat treatment by determining the effect of preheating temperature on the microstructure of heat affected zone, the effect of post weld; annealing, normalizing and quenching on the microstructure of heat affected zone, hardness value of the heat affected zone.

The result shows that the post weld heat treatments; annealing, normalizing and quench hardened generally decreases the hardness values of the stainless steel and by extension improve the mechanical properties of the steel weldment e.g. strength, toughness, etc. Increase in annealing temperature also improves the mechanical properties of the stainless steel and decrease the hardness values.

Language: English Keywords: HAZ

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1 Introduction

Legend Builders Ltd is an architectural, building construction and consulting company based in Lagos, Nigeria which serves as the leading company of this project under the supervision of Mr Ugochukwu Ernest, the CEO of legend builders LTD; a seasoned Architect, a builder, registered member Nigeria institute of Architect, (MNIA) and a member of the Nigeria institute of builders. Legend Builders Ltd was established in Nigeria under the authority of the corporate affairs commission of the Federal Republic of Nigeria in 2003. Legend builders majorly deal with designs, design projects, contracting projects, consulting and construction management. Since its inception, the company has maintained its stand on making sure its image is being protected by making sure all its projects are compliant with the federal and state building legislation which has continued to increase its client list and projects ranging from plant designs, estate constructions and road constructions.

The goal of this research work carried out by Legend Builders Limited in collaboration with Centre for Energy and Research Development(CERD) Osun chapter, Universal Steels Limited Lagos, and Lagos State Material Testing Centre, is aimed to improve the performance of austenitic stainless steels weldment used in Universal Steels Limited (Universal Steels Limited is a company with immerse experience in production, distribution, sales and marketing of goods ranging from iron rods to steels bars and stainless steel products), joined using Shielded Metal Arc Welding (SMAW) welding with stainless steel electrodes at constant welding current, through preheating and stress relieving post weld heat treatment by determining the effect of preheating temperature on the microstructure of heat affected zone, the effect of post weld; annealing, normalizing and quenching on the microstructure of heat affected zone, hardness value of the heat affected zone.

Welding is a fabrication process whereby two or more workpieces are joined together by causing fusion state so that bonding followed by an inter atomic penetration takes place at their original boundary surfaces after the work pieces is cooled to an ambient temperature. During the fabrication process, welding is the most commonly used method of joining items together which is an important operating and maintaining processes in the petroleum and chemical processing industries which is distinct from other lower temperature metal-joining processes like soldering and brazing[1]**.** The development of residual stresses approaching or even exceeding the yield stress during fabrication processes is possible when welding thick sections due to the temperature of the molten weld pool during the process ranging as high as and beyond 2000 ^{o}C, which causes a heat increase that is rapid and instantaneous within the welded zone and the heat affected zone(HAZ)[2]. These residual stresses and macro structure changes, combined with operating stresses, can lead to catastrophic failure of the pressure vessels.[2]

For certain industry sectors such as Petrochemical, Chemical, Oil and Gas, etc., the existence of residual stress of this magnitude is completely unacceptable and the need to avoid or minimize the magnitude of environmental cracking, fatigue and the effect of residual tensile stresses in that regard is essential. Preheating of a weldment is advantageous to prevent the formation of martensite to avoid possible cracking or brittle fracture, to increase the weld productivity, to improve the weld speed, to restore the macro structure and to get rid of every possible water vapor that may cause hydrogen embrittlement which may also result in cracking**.** Post weld heat treatment (PWHT) is commonly used for stress relieving, control hardness and enhance material strength on completion of fabrication of welded structures[3]**.** Post weld heat treatment basically refers to the process of reheating a weld below the lower transformation temperature in a controlled manner, giving the macrostructure enough time to regain its original state and removing residual stress.

Residual stresses in weld joints cannot only be reduced by heat treatment but also by mechanical stress relieving methods such as peening, hammering, surface rolling of the weld-bead area and by plastically deforming the structure by small amount. Post weld heat treatment is also very helpful because it softens or tempers any hard martensite or bainite that has formed in the heat affected zone (HAZ), while also improving the diffusion of hydrogen out of weld metal.[3]

However, post weld heat treatment does not always have a positive effect and can cause distortion and degradation of the microstructure. Stress relieving heat treatments are generally avoided unless specified as mandatory by Codes and/or Standards, because of the high cost involved and potential adverse consequence of incorrect post weld heat treatment procedure. The welding process generally involves melting and subsequent cooling, and the result of this thermal cycle is distortion if the welded item is free to move or residual stress if the item is securely held. There comes a point when the amount of residual stress can create potential problems, either immediately or during the life of the welded structure, and it needs to be reduced or removed.[3]

1.1 Purpose and Methodology

The goal of this project is to improve the performance of austenitic stainless steels weldment, joined using Shielded Metal Arc Welding (SMAW) welding with stainless steel electrodes at constant welding current, through preheating and stress relieving post weld heat treatment. The specific objectives are to:

i Determine the effect of preheating temperature on the microstructure of heat affected zone,

ii Determine the effect of post weld; annealing, normalizing and quenching on the microstructure of heat affected zone,

iii Determine the effect of objectives (i) and (ii) on the hardness value of the heat affected zone.

Iv Determine a suitable heat treatment process and ideal temperature to improve the mechanical properties of stainless steel type without altering the corrosion resistance stainless steel properties.

1.2 Scope of the Research

Previous Research revealed that pre-heating and post-weld heat treatment affects the microstructure and by extension mechanical properties; toughness, ductility, hardness and fatigue life of heat affected zone of low carbon steel. Despite the high demand of austenitic stainless steels because of it high corrosion resistance, the effect of preheating temperature and post-weld heat treatment of its microstructure and hardness on the heat affected zone of its weld structure have not been studied in detail. The use of gas heating nozzles for preheating will not be considered in this work due to financial constraints and unavailability of necessary equipment. The scope of this project is limited to conducting investigations on the effect of Preheating temperature and Post Weld Heat Treatment on the Microstructure and Hardness on the HAZ of an austenitic stainless steel, using Shielded Metal Arc Welding (SMAW) with stainless steel electrodes.

2 Theory

2.1 Steel

The basic chemical elements can be divided into metals and non-metals. Metal are elements that readily forms positive ions(cations) and has metallic bond. Examples of metals are aluminium, copper, iron, tin, gold, lead, silver etc.[4] Metals are mostly solid at room temperature except for mercury and few others and has properties such as electric and heat conductivity, shiny appearance, high melting point, heavier, harder compared to non-metals.[5] Among all the metals, iron is second only to aluminium in natural abundance, making up 4.7 percent of the earth's crust, and occurring mainly as its various oxides. The main product made from iron is steel and cast iron, the least expensive and most widely used of all metals. Metals are pure while metal alloys are combination or mix of two or more metals melt together. Metal alloys are classified as ferrous/nonferrous and subdivided according to the diagram below.[6]

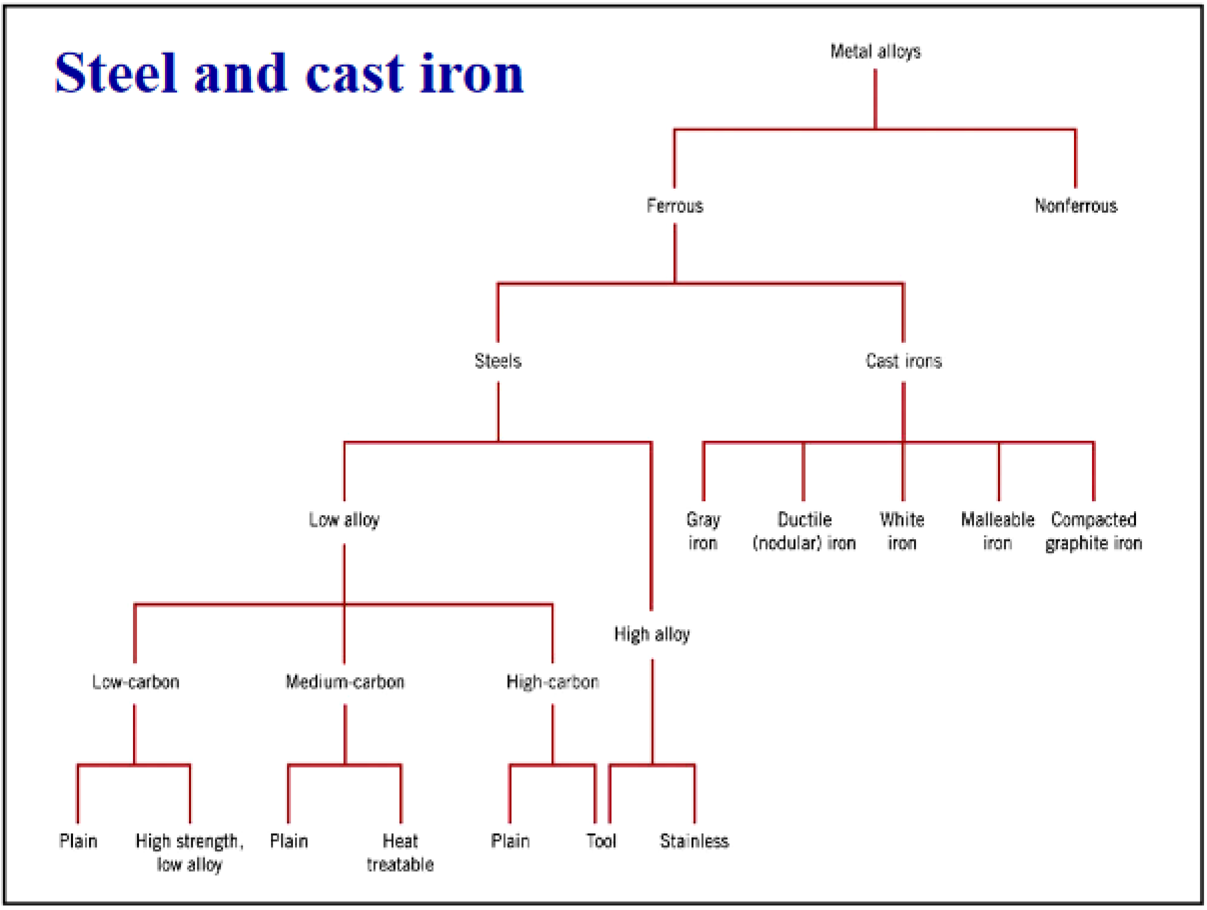

Figure 1. *A classification of metal alloys*

Steel is an alloy of iron and carbon with not more than 2.01 percent carbon. It may also contain other elements, such as Manganese, Aluminium, Boron, Copper etc. Steel are grouped as low alloy; low carbon steel (<0.35% carbon by weight), medium carbon steel (0.35%-0.5% carbon by weight) and high carbon steel (0.5% -1.5% carbon by weight) and high alloy such as stainless steel and tool steel.[5] Whereas pure iron is a relatively soft metal that rusts easily, steel can be hard, tough, and corrosion resistant. Steel is the primary and most common industrial construction material used to make almost everything from skyscraper girders, automobiles, and appliances to thumb tacks and paper clips, steel is one of the world's most vital materials and can be subdivided into the followings.[7]

2.1.1 Low Carbon Steel:

This is a type of steel that contains majorly iron and a low amount of carbon (<0.35 wt%) which is the largest amount of steel produced and used in industrial application. It includes structural steels of buildings and buildings. It contains only small amount of other alloying elements. These types of steels are not quench hardened, ductile and are most times referred to as mild steel. [8]

2.1.2 Medium Carbon Steel:

This is a type of steel that contains iron as the main element with up to 0.35% to 0.5% carbon weight and up to 3% by weight of other elements like manganese, nickel, chromium, molybdenum or other elements. Medium alloy steels can be quenched hardened, and the added alloying elements are primarily to improve hardenability. [8]

2.1.3 High Carbon Steel:

This is a type of steel with approximately 5%-10% by weight consisting of alloying elements other than carbon. They are mostly used in smallest amount and they are referred to as tool steels which are commonly used for hammers, pick-axes, and cutting tools like knives and chisels. [8]

2.2 Stainless Steels

Iron and the most common iron alloy, steel, are poor materials from a corrosion viewpoint relatively since they rust in air, corrode in acids and scale in furnace atmospheres.[9] Stainless Steels are an important class of engineering alloys which are iron-base alloys grouped as iron-chromium-nickel alloys used in both wrought and cast form for a wide range of applications and in many industries[10]. Stainless steels are based on the iron-chromium, iron-chromium-carbon, and iron-chromium-nickel systems, but may contain many other alloying additions that alter their microstructures and/or properties.[9] The stainless nature of these steels arises primarily from the addition of chromium in quantities greater than 12 wt%. This level of chromium ensures that a continuous layer of protective chromium-rich oxide forms on the surface. In practice, however, stainless steels may contain as little as 9wt% Cr and be subject to general corrosion (rusting) at ambient temperatures. Few stainless steels contain more than 30 wt% Cr or less than 50 wt% Fe.[9]

Stainless steels do not rust in sea water, are resistant to concentrated acids, do not scale at temperature up to 1100^{o}C and are used extensively in the power generation, pulp and paper, and chemical processing industries, but are also chosen for use in many everyday household and commercial products.[11] The widespread use of stainless steels and their importance in critical industrial technologies has led to considerable investigation of the weldability and service integrity of these steels.[11] The wide range application of stainless steel is because of a good combination of good mechanical properties and manufacturing characteristics.

However, the usage of stainless steel is small compared with that of carbon steels but exhibits a steady growth in contrast to the constructional steels[11].

2.2.1 Selection of Stainless Steels

Fundamentally, the selection of a type of stainless steel will depend on the application requirement. environment, expected part life and extent of acceptable corrosion are few criteria that determines what type of stainless to use. In most cases, the primary factor is corrosion resistance, followed by tarnish and oxidation resistance while other factors include the ability to withstand pitting, crevice corrosion and intergranular attack.[12] The austenitic/higher chromium stainless steels, usually required in very high or very low temperatures, are generally more corrosion resistant than the lower chromium ferritic or martensitic stainless steels.[12]

Another factor to be considered when selecting stainless steels is called sensitization. Ferritic stainless steels and some austenitic stainless steels, which contain appreciable free carbon (greater than about 0.04%C) can be rendered sensitive to intergranular corrosion in the heat-affected zone (HAZ) of a weld.[12] This sensitization occurs where a peak temperature of about 900 to 1600 F (482^{o}C to 871^{o}C) is reached in the HAZ. Chromium carbides precipitate on grain boundaries, and in the process of doing so, chromium as an alloy element is depleted in the metal adjacent to the grain boundaries. Then, in corrosive service, this Cr-depleted metal is selectively attacked. Low welding heat input can limit, but not eliminate, sensitization. The best methods of preventing sensitization are selection of very low carbon base metal (less than 0.03%C) or selection of a grade stabilized with titanium or niobium (also known as columbium), such as types 321 or 347. However, sensitization is almost never a weld metal problem, it is largely a heat-affected zone problem.[12]

2.2.2 Classification of Stainless Steel

Historically, stainless steels have been classified by microstructure and are described as ferritic, martensitic, austenitic, or duplex (austenitic and ferritic). In addition, many precipitation-hardenable (PH) martensitic, semi austenitic, and austenitic stainless steels exist and are normally classified separately as PH stainless steels;[12]

1. **Martensitic Stainless Steels:**

   These are essentially alloys of chromium and carbon that possess a body-centered cubic (bcc) or body-centered tetragonal (bct) crystal (martensitic) structure in the hardened condition. They are ferromagnetic and hardenable by heat treatments, generally resist relatively mild corrosive environments and the chromium content of these materials generally ranges from 11.5 to 18 wt%, and their carbon content can be as high as 1.2 wt%. The chromium and carbon contents are balanced to ensure a martensitic structure after hardening.[13] The limitations on the alloy content required to maintain the desired fully martensitic structure restrict the obtainable corrosion resistance to moderate levels. In the annealed condition, martensitic stainless steels have tensile yield strength of approximately 275 MPa and can be moderately hardened by cold working. To obtain useful properties and prevent cracking, the weldable martensitic usually require preheating and post weld heat treatment.[12]

2. **Ferritic Stainless Steels:**

   Ferritic stainless steel consists of iron-chromium alloys with body-centered cubic crystal structures. They can have good ductility and formability, but high-temperature strengths are relatively poor when compared to austenitic grades. Some ferritic stainless steel (such as types 409 and 405) used, for example, in mufflers, exhaust systems, kitchen counters and sinks, cost less than other stainless steels.

Other more highly alloyed steels low in C and N (such as types 444 and 261) are costlier, but are highly resistant to chlorides. While these alloys have useful properties in the wrought condition, welding is known to reduce toughness and ductility and corrosion resistance because of grain coarsening and formation of martensite [20], [12]

3. **Austenitic Stainless Steels:**

These types of stainless steels exhibit a single-phase, face-centered cubic (fcc) structure that is maintained over a wide range of temperatures. This structure results from a balance of alloying additions that stabilize the austenite phase from elevated to cryogenic temperatures. Austenitic stainless steels are the most weldable of the stainless and can be divided rather loosely into three groups: common chromium-nickel (300 series), manganese-chromium-nickel-nitrogen (200 series) and specialty alloys. Austenitic is the most popular stainless-steel group and is used for numerous industrial and consumer applications, such as in chemical plants, power plants, food processing and dairy equipment.

Though generally very weldable, some grades can be prone to sensitization of the weld heat-affected zone and weld metal hot cracking. The austenitic stainless steels were developed for use in both mild and severe corrosive conditions. They are also used at temperatures that range from cryogenic temperatures, where they exhibit high toughness, to elevated temperatures of nearly 600 °C (1110 °F), where they exhibit good oxidation resistance. Because the austenitic materials are nonmagnetic, they are sometimes used in applications where magnetic materials are not acceptable [21], and where alloying additions and specific alloy composition can have a major effect on weldability and the as-welded microstructure.[12]

4. **Duplex stainless steels (DSS):**

These categories are used in chemical plants and piping applications, the duplex stainless steels are developing rapidly today and have a microstructure of approximately equal amounts of ferrite and austenite. Duplex stainless steels typically contain approximately 22-25% chromium and 5% nickel with molybdenum and nitrogen. Although duplex and some austenitics do have similar alloying elements, duplexes have higher yield strength and greater stress corrosion cracking resistance to chloride than austenitic stainless steels.[12]

5. **Precipitation-hardening (PH) Stainless Steels:**

   These are iron-chromium-nickel alloys with corrosion resistance with high strengths that are obtained by carrying a precipitation hardening process on a martensitic or austenitic matrix with one or more of the following elements; copper, aluminium, titanium, niobium (columbium), and molybdenum. Precipitation-hardening steels can be grouped into three types martensitic, semi-austenitic, and austenitic--based on their martensite start and finish (Ms and M_f) temperatures and resultant behaviour upon cooling from a suitable solution treatment temperature.[12]

2.3 Micro structural Development of Austenitic Stainless Steels

Although austenitic stainless steels are predominantly austenitic, they often contain small amounts of body-centered cubic (bcc) ferrite, particularly in the weld metal. This ferrite is often described as "delta" ferrite, because it forms at elevated temperatures and is distinguished from "alpha" ferrite, which is the low-temperature form in iron-base alloys. The term ferrite will refer to high-temperature delta ferrite, unless noted otherwise. These alloys also may contain martensite, although the presence of this phase is unusual and limited to special composition and temperature ranges, forming only because of plastic deformation.[14]

2.4 Corrosion Behaviour of Austenitic Stainless Steels

Austenitic stainless-steel weldments are often subject to corrosive attack. The nature of this attack is a function of weld thermal history, service temperature and environment, and stress level (both residual and applied). Four general types of corrosive attack are associated with this.[15] Which are;

i inter-granular attack

ii stress-corrosion cracking

iii Pitting and crevice corrosion

iv Microbiologically influenced corrosion

2.5 Weld Thermal Treatments of Austenitic Stainless Steels

Because the austenitic stainless steels do not experience a martensitic transformation upon cooling, there is generally no benefit derived from the use of preheat or inter-pass temperature control during multi-pass welding. In fact, these thermal treatments may increase the degree of sensitization by reducing cooling rates and allowing more time for carbide precipitation. Preheat and inter-pass heating can also increase distortion and cracking susceptibility.

Post weld heat treatment (PWHT) is often required to relieve residual stresses in austenitic stainless-steel weldments, particularly in thick sections. Because the coefficient of thermal expansion(CTE) value and the elevated-temperature yield and creep strengths of austenitic materials are significantly greater than for ferritic materials, the magnitude of residual stresses is generally larger. Although the effect of residual stresses from welding is typically not as severe as when less-ductile materials are used, they may still affect mechanical properties and corrosion behaviour. PWHT is particularly critical when machining must be performed after welding, because significant distortion may occur. [22]

2.6 Shielded Metal-Arc Welding (SMAW)

Shielded metal arc-welding (SMAW) is a manual welding process involving the use of flux-covered consumable electrodes. Electric arc is generated by touching the tip of the coated electrode against the work piece and withdrawing it quickly to a distance sufficient enough to maintain the arc. The heat generated is utilized in melting a portion of the coated electrode and the base metal. During welding, the flux combusts or decomposes to provide a gaseous shield for the weld puddle, electrode tip and the surrounding area. The shielding thus prevents air from reacting with the molten weld metal, reducing oxide and nitride formation as well as hydrogen absorption. [23]

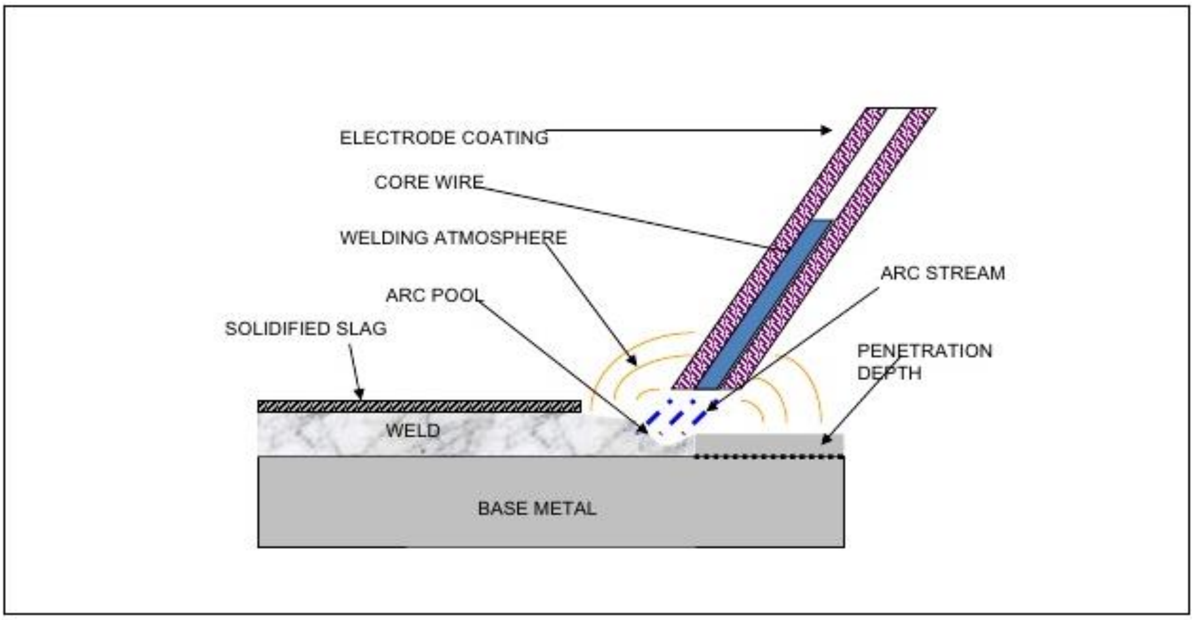

Figure 2. *SMAW Welding Process*

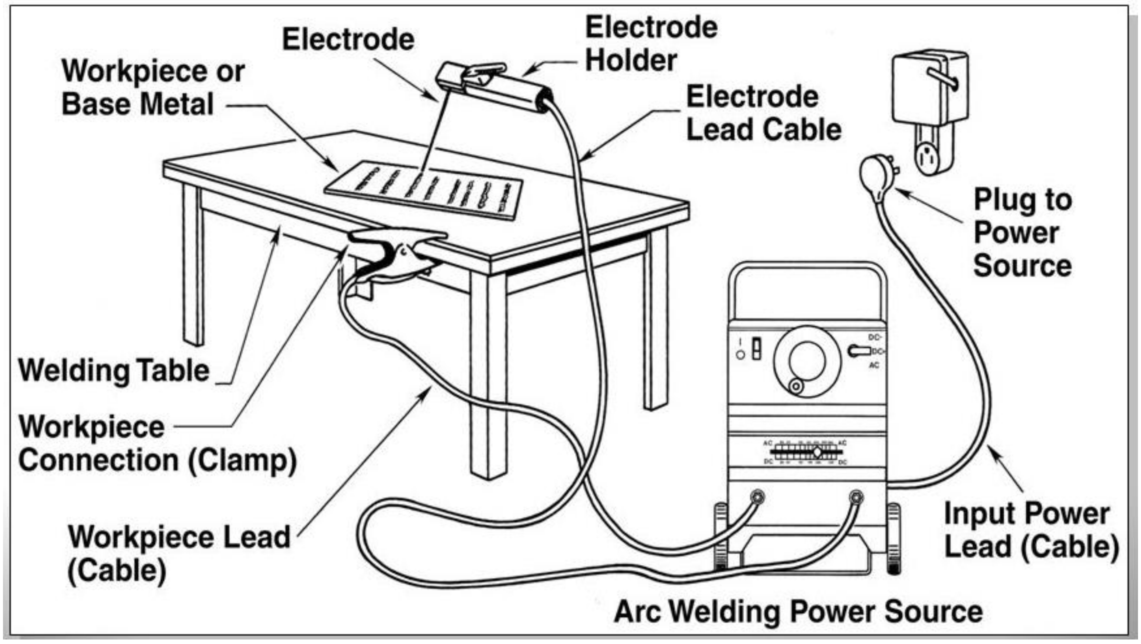

Figure 3. *SMAW Welding Component*

The welding current of SMAW process involves the use of alternating current (AC), direct current (DC) or a combination of both AC and DC. Direct current, DC, can be either straight polarity (when the electrode is negative) or reverse polarity (when the electrode is positive). The choice here mainly depends on the type of electrode used and the availability of the equipment. Some of the advantages of SMAW process over other welding processes are; cheapest common arc welding equipment to purchase, it is used to weld ferrous and non-ferrous metal, all position welding, ideally suited for outdoor work, highly portable and consumables and equipment are readily available. [24]

For AC welding, the cable length is more critical than for DC welding because the voltage drop in long cables added to that at the arc can overlap the power source or prevent its developing sufficient voltage for a proper arc. When low current values are used with small-diameter welding wire, DC surpasses AC. All classes of covered electrodes are satisfactory for DC welding. [24]

However, only AC/DC-rated electrodes with coverings specifically formulated for alternating current should be used with AC welding. DC current is preferable for welding sheet metal because of the steady, easily started arc. AC current is well suited for welding thick sections using large-diameter electrodes and maximum current levels because arc blow is rarely a problem with AC welding current. It's easier to maintain a short arc with DC than with AC. [24] Especially when the arc must be crowded into a molten puddle. More weld spatter is produced with AC welding partly because of the pulsating nature of the current. Because the use of lower current is possible with Dc welding, DC is somewhat easier to use for out-of-position welding on thicker sections and there is a practical limit to the amount of current that may be used. Usually, the covered electrodes are about 9-18 inches long, and if the current is raised too high, electrical resistance heating within the unused length of electrode will become so great that the coating ingredients may overheat and breakdown, potentially resulting in weld quality degradation. [24]

2.7 Development of Residual Stresses During Welding

Residual stresses are stresses that would exist in a body if all external loads are removed. They are sometimes called internal stresses. Thermal stresses are residual stresses that exist in a body that has been previously subjected to non-uniform temperature changes, such as those during welding. Detrimental residual stresses commonly result from such differential cooling. [25] During welding, the region near the weld is hot while the regions remote from the weld are still cool. As the weld region cools, its tendency to undergo thermal contraction is resisted by the material outside the weld. This results in the weld metal being left in a state of residual tension parallel to the weld. Residual stresses due to welding are of magnitude roughly equal to the yield strength of the base material. [26]

2.8 Stress Relieving Annealing

Annealing is a controlled cooling process that involves heating the weld metal to elevated temperatures and then slowly cooling the work piece to attain a high degree of softness in the weld. Several types of annealing process exist. These includes full annealing, spherodizing annealing, and Process/Stress Relieving Annealing. Process or Stress Relieving annealing can be used to relief internal stresses in weld metal. These stresses are developed during welding, cold working, machining and other forming processes. Annealing, just like normalizing heat treatment helps to relieve internal stresses and reduce the chances for distortion and cracking of weld metal [26], [27], [28], [29

The aim of stress-relieving heat treatment is not only to relax internal stresses but also to improve the microstructure and impact properties of heat affected zone (HAZ) and weld metal, to improve dimensional stability and increase resistance against stress corrosion [30], [31]. In process/stress relieving annealing, the part is heated to only 595˚C - 700˚C. The part is then slowly cooled in the furnace. Most of the internal stress is removed but not all of it. [30] Process annealing is a good option when time is more important than full softening. It is a practical and economic solution as the part is heated to a temperature that is below the lower transformation temperature, thus relieving stresses without taking a great deal of time. The temperature reached during stress relief treatment has a far greater effect in relieving stresses than the soaking time. [32] The closer the temperature is to the critical or recrystallization temperature, the more effective it is in the removal of residual stresses. [33] Recommendations on Post Weld Heat Treatment (PWHT) are usually dependent upon specific alloys and filler metals involved, but also on thickness and restraint of welded joints. [33] Other factors that influence PWHT are dimensions, joint design, welding parameter and the likely mechanism of failure. To remove residual stresses in a material, elastic strains must be converted to plastic strains. During a stress relief anneal, the elastic strains in the material are converted to plastic stains by creep. [34] Higher temperatures accelerate the process. However, the driving force for additional creep decreases as the magnitude of the residual stresses diminishes, and the process of stress relief slows down. For this reason, complete stress relief is not possible during conventional stress-relief annealing. [34] Three thermally active and overlapping stages exist during annealing. These stages include; recovery, recrystallization and grain-growth. [35]

2.9 Normalizing

This is a type of heat treatment process whereby steel is heated to a temperature corresponding to its hardenability temperature and holding it for some minutes and then allowed to cool in air. The cooling or holding time can vary from 10 minutes to 30 minutes. This kind of heat treatment refines the grain of the steel that has become coarse-grained because of previous heating to high temperature. Normalizing is basically applied to carbon and low -alloy steels. However, the normalization of hyper-eutectoid steels is also possible for special cases.[16]

2.10 Quench Hardening

Quench hardening is a mechanical process in which steel and cast-iron alloys are strengthened and hardened. This is done by heating the material to a certain temperature, depending on the material and then cooled rapidly in a quenching media such as oil, water or other medium to obtain certain properties. This produces a harder material by either surface hardening or through-hardening varying on the rate at which the material is cooled. The material is then often tempered to reduce the brittleness that may increase from the quench hardening process. Items that may be quenched include gears, shafts, and wear blocks. This type of heat treatment prevents undesired low temperature processes such as phase transformation from occurring. [17]

2.11 Weld Metal Microstructure

The microstructure of a weld consists of three regions: a fusion zone (material that has been melted); a heat affected zone (material that was not melted, but whose microstructure has been altered); and the base metal. [36], [28] Generally, steel weld metal microstructure is a complex mixture of two or more constituents, such as pro-eutectoid ferrite, polygonal ferrite, aligned and non-aligned plate ferrite, ferrite carbide aggregates and acicular ferrite. [37] Upper and lower banites, martensites and the A-M (austenite with martensite) microstructure may sometimes be formed. [38] This complex microstructure mixture causes variation in the properties of the weld. The properties of the welds often cause more problem than the base metal properties and in many cases, they govern the overall performance of the structure. [39] A way to unify the structure of the welds is by heat treatment. [40]

Weld microstructures are examined using standard specimen removal and preparation techniques, with some concessions made for their inhomogeneous nature. Similarly, the parameters used to characterize the weld microstructures, such as grain size, grain morphology, and the amount of the various phases or micro constituents present, are those used to characterize monolithic materials. [21] Micro-structural characterization of welds has two purposes: to evaluate the microstructure with respect to properties and to relate the microstructure to the process used. The goal is to optimize the process to produce the most desirable microstructure. In general, the effects of a process and parameters on microstructure are due to the compositional and thermal effects. The compositional effects are largely limited to the fusion zone. Thermal cycles affect both the fusion zone and HAZ. In welds, a large amount of acicular ferrite is associated with high toughness levels, whereas martensitic or bainitic microstructures have much lower toughness levels. Bainite and martensite are also associated with higher effective cooling rates, so decreasing the weld metal manganese content, or reducing the cooling rate with increased heat input or preheat, will increase the amount of acicular ferrite and improve weld metal toughness. [21]

2.12 Chemical Reaction during Welding

High-cellulose electrodes used in SMAW contain much cellulose, in the electrode covering. The covering decomposes upon heating to produce a gaseous shield rich in hydrogen, for instance 41% Hydrogen, 40% CO, 16% moisture, and 3% Carbon dioxide in the case of

AWS E6010 electrodes. Low-Hydrogen electrodes on the other hand contain much Calcium Carbonate in the electrode covering. The covering decomposes during welding to produce a gaseous shield low in hydrogen. [41] Oxygen, nitrogen and hydrogen can dissolve in the weld metal during welding. These elements usually come from; air, the consumables such as the shielding gas and the flux, or the work piece such as the moist or dirt on its surface. The properties of the resultant welds are significantly affected by nitrogen, oxygen and hydrogen. In steel welds, nitrogen increases strength but reduces toughness while oxygen reduces toughness but improves it when acicular ferrite is promoted. Hydrogen on the other hand induces hydrogen cracking. However, in austenitic or duplex stainless-steel welds, nitrogen reduces ferrites and promotes solidification cracking. Carbon dioxide produced by the decomposition of carbonate or cellulose in the electrode covering, can potentially increases the weld oxygen level. Self-shielding arc welding uses strong nitride formers such as Al, Ti, and Zr in the electrode wire alone to protect against nitrogen. [41]

2.13 Hardness Testing

The Hardness Test is extremely useful in material selection because it provides a hardness value which indicates how easily a material can be machined and how well the material will wear.[18] Mechanical properties vary across varying microstructures of the welded region. Hardness testing of welds allows local regions and individual microstructures to be compared for strength, especially as strength is correlated to hardness. Hardness testing is widely used as a rapid measurement of mechanical strength across the weld regions. Macro-hardness testing of welds requires preparation of a small region of the weld surface. The major techniques are Brinell Hardness test method(HB), Microhardness testing by Knoop and Vickers Hardness Test method(HV) and Rockwell testing(HRC).[18] The Brinell testing technique uses a spherical indenter to produce indentations of 2 to 6mm diameter and mostly applied to any metallic material and is the method most commonly used to test castings and forgings that have a grain structure too coarse for other metal hardness testing methods while the Rockwell testing technique uses a diamond penetrator or sphere to produce smaller indentation which is visible, unaided.

The Rockwell Hardness Test and Superficial Rockwell are performed on castings, forgings and other relatively large metal products and samples because the tests produce a large visible indentation. The Rockwell method uses several different loads for different hardness scales thus, making it possible for a weld to require different hardness scales for different regions.[18] Microhardness testing by Knoop and Vickers Hardness Test methods measure small samples or small regions in a sample. They are often used to measure surface or coating hardness on carburized or case-hardened parts, as well as surface conditions such as grinding burns or decarburization. (Vickers is also available on the macro scale to 50 kg.)[18]

Figure 4. *Brinell Hardness Machine*

Macro-hardness testing results can be limited by the micro structural gradients around the welds. A hardness value may represent hardness for one uniform microstructure or an average over the regions deformed by the indenter. [42] Welds and Heat Affected Zones (HAZs) often have gradients of microstructure and chemistry that can cause variations in hardness across the indentation. [42] Interpretation of the hardness from the impression may be made more difficult if there is a large gradient in the hardness of the weld metal under the indenter. This often result in noncircular Brinell impressions and Rockwell tests with the deepest point not under the deepest point of the indenter.

Micro-indentation hardness traverses are often used to determine the variation of hardness within the weld, across the fusion line, and across the HAZ. Micro-indentation hardness testing using an indenter requires an even smaller region of the surface to be used than the macro-hardness testing, though the surface preparation requirements are more stringent as the cross sections of the weld metal under examination must be ground, polished, and sometimes etched. Brinell hardness test is performed on a work piece made of the desired material which is fixed on the plate form of the Brinell hardness testing machine. Afterwards, a small ball usually of 10 mm diameter, made of tungsten carbide is used to apply the load of about 3000 kg on the work piece. Load is applied for certain duration and then removed.

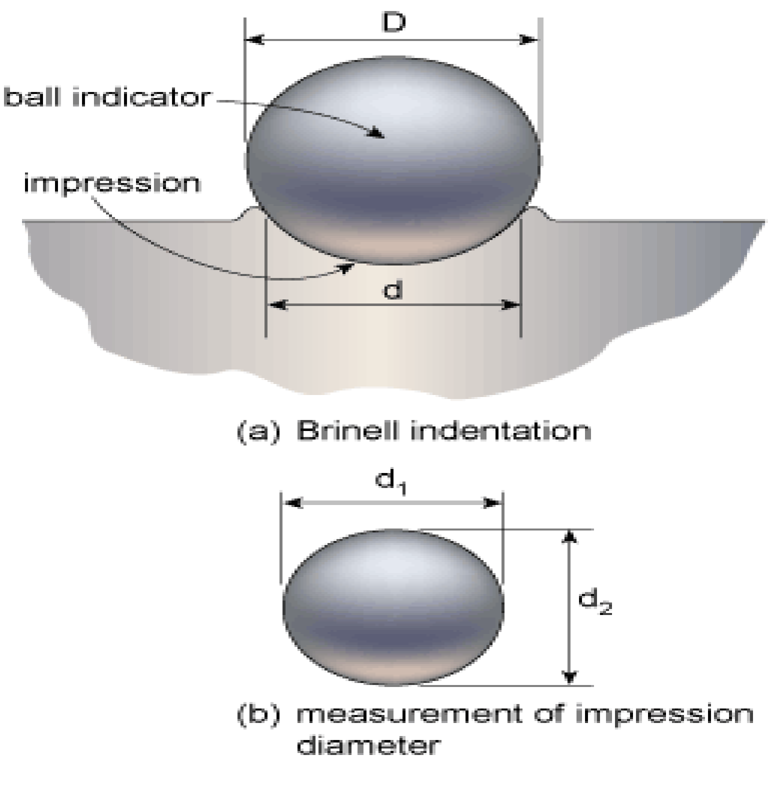

Figure 5. *Brinell Hardness Measurement*

Due to such high load, the ball penetrates the outer surface of the work piece and upon removal make cavity at that position. The diameter of the cavity is measured from at least two positions and these positions should be at right angle to each other.[19] The diameter measured is then compared with the standard table provided with Brinell hardness machine table where the diameter reading is converted into the Brinell hardness number of the material. Cavity diameter measured from the Brinell hardness machine is converted into the Brinell hardness number or manually by the help of formula below;

$$HB = \frac{2F}{\pi * \mathrm{D}(D - \sqrt{\mathrm{D} - \mathrm{d}})}$$

Where D is the ball diameter, d is the impression diameter, F s the load, HB is the Brinell hardness value.

3 Materials and Methods

3.1 Sample collection

The austenitic stainless-steel sheet plate used for this research work was obtained from Owode Onirin Lagos State, Nigeria with the chemical composition as given in fig. 4.0, and E6006 stainless steel welding consumable electrodes.

3.1.1 Sample preparation

Twenty-six pieces of sized 3cm by 3cm was cut out from an austenitic stainless-steel sheet using hark saw. Hand filling was used to file the cut samples to enhance smooth surface for welding.

3.2 Welding process and Heat Treatment

Shielded metal arc welding (SMAW) methods was used in joining the metal at constant welding current set to 100A with stainless steel electrodes of code AWS E6013. A pair of each pieces was welded as received to serve as the control sample. Six pieces was welded at an ambient temperature, and then each of the three pairs was heated to a respective temperature 550°C, 650°C and 750°C respectively prior to welding and allows cooling to ambient temperature. Six pieces of the samples was heated to temperature 550°C and welded, and then each of the three pairs was subjected to a respective post-weld heat treatment; annealing, normalizing and quench hardening respectively. Another six pieces of the samples was heated to 650°C, welded, and then each of the three pairs welded was subjected to a respective post-weld heat treatment; annealing, normalizing and quench hardening respectively.

Finally, the remaining six pieces was heated to temperature 750°C and welded, and then each of the three pairs of the samples was subjected to a respective post-weld heat treatment; annealing, normalizing and quench hardening. AWS E6013 electrodes were used with d.c arc welding process. Welding current of 100A was used with a terminal voltage of 80V.

3.3 Metallography

The welded samples were cut with a hark saw such that the heat affected can be prepared for metallography and hardness test. The heat affected zone, after cut was mounted using metal rod of 3cm long with super glue. These mounted samples were subjected to gentle grinding on abrasive silicon carbide papers of successive finer grades; 240, 320, 400 and 600 lubricated with water. The specimens were polished on a 150mm rotating disc of a METASERV universal polisher. Haven obtained mirror-like surfaces; the polished samples were etched (chemical technique used to show features of metals at microscopic levels to predict and explain the physical properties and performance failures of a given sample of metal.) using 2% Nital (nitic acid and alcohol). The etched specimens were then rinsed in running water after 7 seconds and then surface cleaned with compressed air to prevent oxidation. The etched specimens were observed on the Olympus metallurgical microscope with a minisee optical viewing system connected to the USB port of a computer in the Department of Materials Science and Engineering of the Obafemi Awolowo University, Ile-

Ife. Micro examination was carried out on a higher magnification of 200X and images captured for metallographic analysis. These images are as presented in Fig.4.30 to Fig.5.20.

3.4 Hardness Testing

The polished surfaces of all the prepared samples were subjected to hardness tests using Brinell hardness testing machine. The diameter of the dent made by the diamond indenter were measured (as presented in Table4.0) and converted to the Brinell hardness number, and corresponding Vickers hardness value using the standard conversion chart as shown in appendix 1.

4 Results and Discussion

4.1 Results

The composition of the austenitic stainless-steel sheet plate used in this work is given in Table 1 which was a composition test analysed at the Centre for energy and research development. The stainless-steel sheet plates were of 3cm by 3cm sized. The Brinell Hardness values of the heat affected zone of austenitic stainless steel of the control sample welded at ambient temperature, heated to various temperature and then normalized is shown in Table 2, while the Brinell hardness values of the heat affected zone of austenitic stainless-steel samples preheated to various temperatures, welded and then subjected to various post weld heat treatment is shown in Table 3.

Table 1. *Chemical Composition of as-received Austenitic stainless steel (in wt. (%)).*

C	**Si**	**S**	**P**	**Mn**	**Ni**	**Cr**	**Mo**	**V**	**Cu**
0.0313	1.0101	0.0301	0.0452	2.0241	8.0213 -12.12	18.23 - 19.65	2.012 - 2.961	0.0034	0.2193

W	**As**	**Sn**	**Co**	**Al**	**Pb**	**Ca**	**Zn**	**Fe**
0.0044	0.0060	0.0162	0.0091	0.0050	0.0046	0.0007	0.0057	64.0683

Table 2. *The Brinell Hardness values of the heat affected zone of austenitic stainless steel of the control sample welded at ambient temperature, heated to various temperature and then normalized.*

Ambient Temperature	**550^0C**	**650^0C**	**750^0C**
HV:292	HV:270.2	HV:312.8	HV:328
HRC:29	HRC:26	HRC:33.03	HRC:33.03
HB: 277	HB:258	HB:308	HB:311

Table 3. *The Brinell hardness values of the heat affected zone of austenitic stainless-steel samples preheated to various temperatures, welded and then subjected to various post weld heat treatment.*

Pre-heating Temperature	**Annealed**	**Normalized**	**Quench Hardening**
550^0C	HV: 253.5	HV: 261.0	HV: 366.975
550^0C	HRC: 23.125	HRC: 24.95	HRC: 38.75
550^0C	HB: 241.0	HB: 248	
650^0C	HV: 234.0	HV:271.0	HV: 301.975
650^0C	HRC: 22.30	HRC: 26.95	HRC: 30.925
650^0C	HB: 223	HB: 257.0	HB: 285.0
750^0C	HV:228.90	HV:276.7	HV:295.450
750^0C	HRC:20.55	HRC:27.80	HRC:29.325
750^0C	HB: 217	HB: 262	HB: 280.0

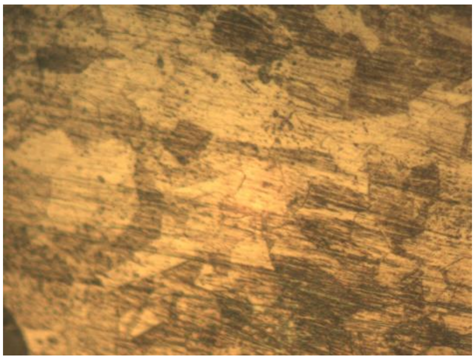

Figure 6. *Micrograph of HAZ of the control sample subjected to 100A welding current (X200)*

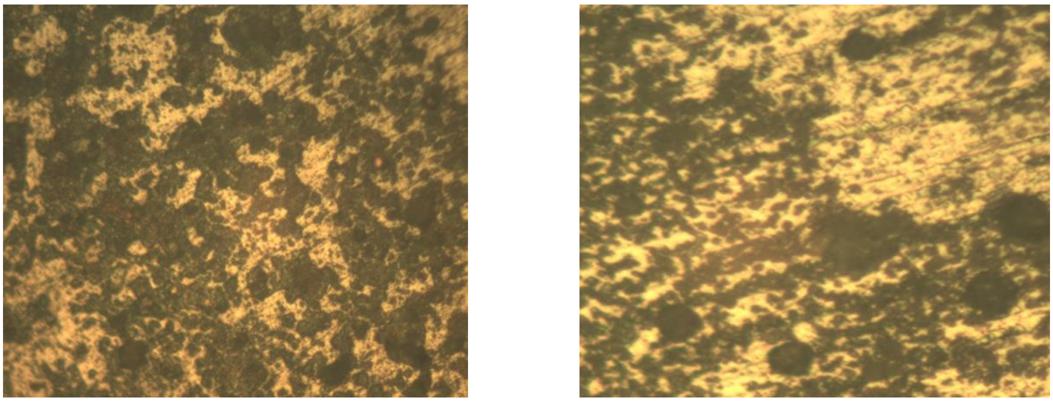

Figure 7. *Micrograph of HAZ of sample heated to 550^{0}C and 650^{0}C, welded at ambient temperature, and then normalized respectively*

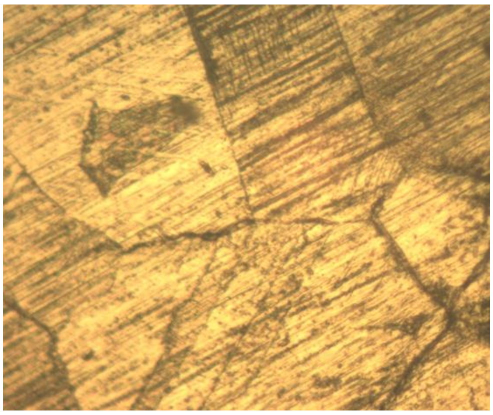

Figure 8. *Micrograph of HAZ of sample heated to 750^{0}C, welded at ambient temperature, and then normalized*

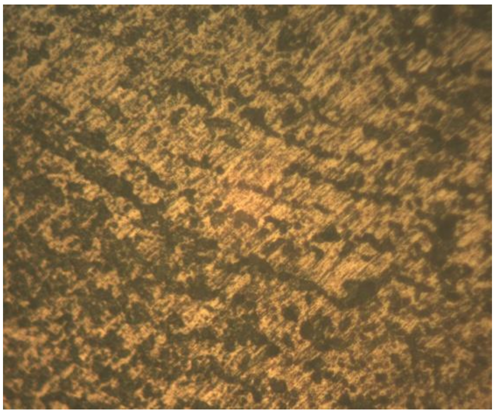

Figure 9. *Micrograph of HAZ of sample pre-heated to 550^{0}C, welded and then normalized*

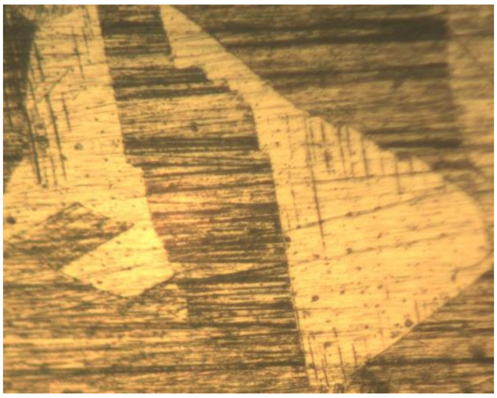

Figure 10. *Micrograph of HAZ of sample preheated to 550^{0}C, welded and then annealed*

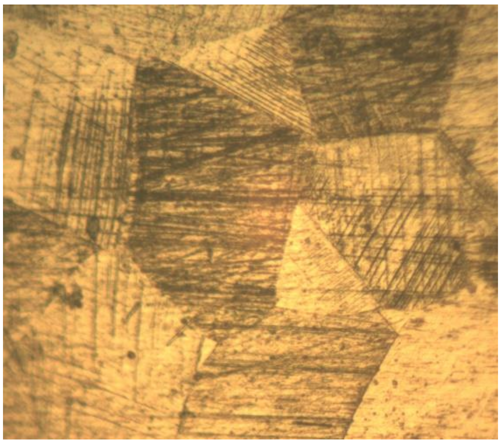

Figure 11. *Micrograph of HAZ of sample preheated to 550^{0}C, welded and then quench hardened*

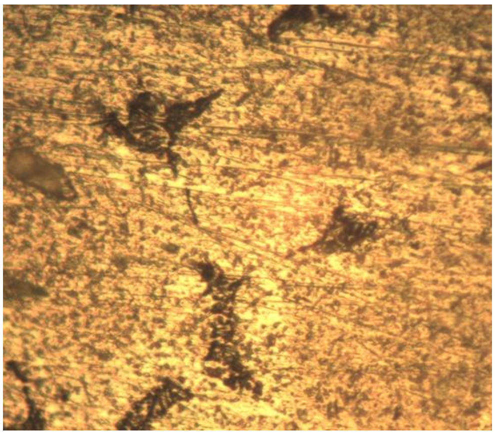

Figure 12. *Micrograph of HAZ of sample preheated to 650^{0}C, welded and then quench hardened*

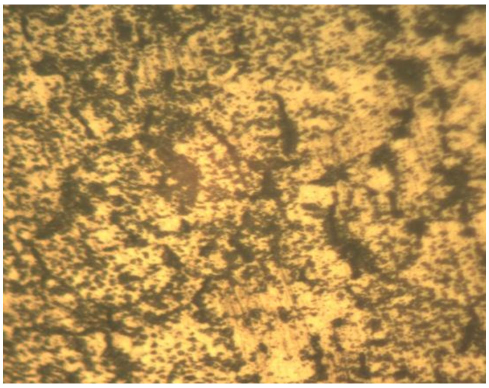

Figure 13. *Micrograph of HAZ of sample preheated to 650^{0}C, welded and then annealed*

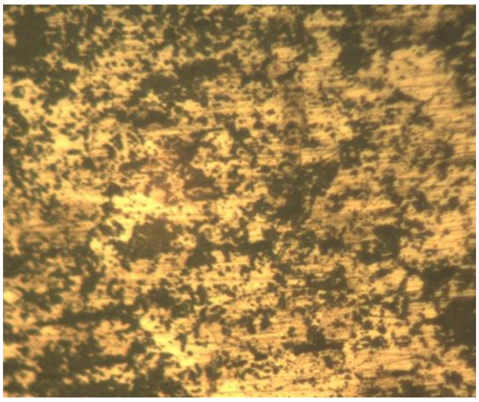

Figure 14. *Micrograph of HAZ of sample preheated to 650^{0}C, welded and then normalized*

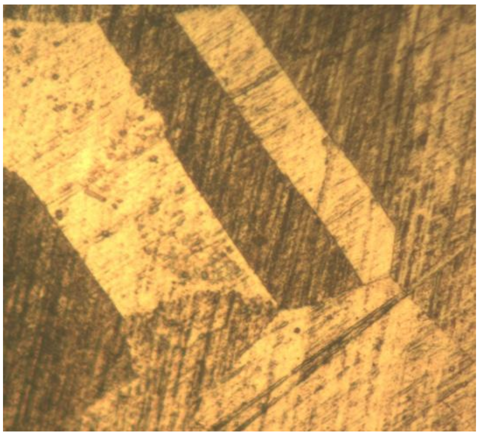

Figure 15. *Micrograph of HAZ of sample preheated to 750^{0}C, welded and then annealed*

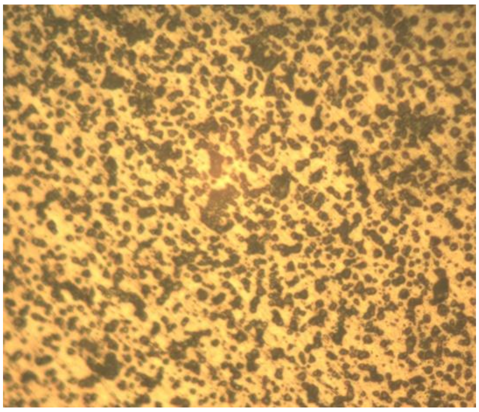

Figure 16. *Micrograph of HAZ of sample preheated to 750^{0}C, welded and then normalized*

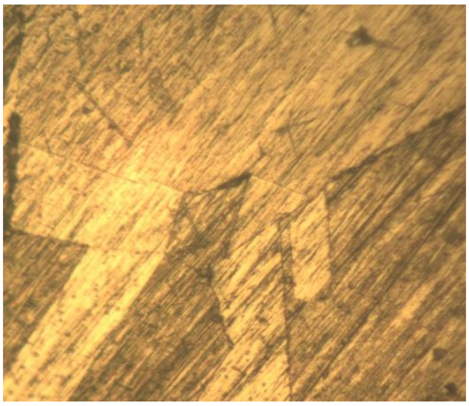

Figure 17. *Micrograph of HAZ of sample preheated to 750^{0}C, welded and then quench hardened*

4.2 Discussion of Results

Increasing the temperature of the samples welded at ambient temperature preheated at 550^{0}C, 650^{0}C 750^{0}C and then normalized, led to an increase in the hardness values and increase the level of residual stress in the weld metal.

The samples preheated to 550^0,650^0, 750^0 and annealed were observed to have low hardness values which will result in low tensile strength and toughness**.** This is due to the reduction in stress levels of the heat affected zone. During the stress relief annealing process, the elastic strains in the zone were converted to plastic strain due to high temperature accelerated process.

The samples heated to 650^0C welded and then normalized, annealed and quenched hardened were generally characterized by minimal hardness values. This is due to softening effect of the ferrite matrix which arises from liberation of trapped carbon atoms in the super saturated ferrite during annealing as depicted in the microstructure of the annealed samples which clearly identifies ferrite and pearlite. The carbon atoms are liberated by a diffusion controlled process which precipitates a second phase, an iron-carbon compound with formula Fe_3C (cementite). [40] This is an evidence as depicted in the micrographs of the annealed samples.

The improvement in the mechanical properties of the stainless steel is a result of a shift in the internal structure of the steel, where the ferrite phase shift within coarse pearlite to ferrite amidst smooth pearlite in the alloy that has been treated thermally and turning successive layers of rough carbides to soluble soft granules in a phase of austenite because of its stability and lack of full transformation to pearlite which can be seen by observing the image of the microstructure.
However, as depicted in the microstructure, the samples heated to 650^0C, welded and normalized, annealed and quench hardened obey the Hall petch equation. i.e. the finer the grains size led to increase in the yield strength.

5 Conclusion and Recommendation

From the result obtained, there were slight environmental and laboratory inconsistencies which altered the result of the laboratory experiment. It could be seen from Table 4.0 to 4.2 that Post weld heat treatments; normalizing and quench hardened generally increases the hardness values of the stainless steel and by extension improve the mechanical properties of the steel e.g. strength, toughness while the annealed samples reduces the hardness value and therefore reduces the mechanical properties of the steel. Also, there is an increase in tensile strength which has been improved due to the reduction in the size of the granules, which led to increased grain boundaries and which also increases the fatigue life of the thermally treated alloy**.**

Furthermore, increase in annealing temperature also improve the mechanical properties of the stainless-steel weldment and decrease the hardness values of Universal Steels Ltd stainless-steel products. Due to the initial closure of the stainless-steel production line, the success of this project will gear up a good start up for a better productivity and efficiency at Stainless Steel production line of Universal Steels Limited.

Having attained the aim of this research work, I hereby recommend that the effect of pre-heating and post weld heat treatment on microstructure and hardness of the heat affected zone of austenitic stainless steel on the wear and tear properties, tempering effect, and shock resistance of the steel should be investigated with a more efficient method and techniques such as Thermo-mechanical simulator, which will foster the efficiency and better productivity of stainless steel product and application in different sectors in Nigeria.

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Appendix 1

Table 4: Standard Hardness Conversion Chart

Hardness Conversions Chart

Brinnel Hardness HB	Vickers Hardness HV	Rockwell Hardness HRC	Rockwell Hardness HRB	Tensile Strength ksi	Brinnel Hardness HB	Vickers Hardness HV	Rockwell Hardness HRC	Rockwell Hardness HRB	Tensile Strength ksi
321	339	34	108	158	174	182	-	88	84
311	328	33	108	154	170	178	-	87	82
302	319	32	107	150	166	175	-	86	80
293	309	31	106	146	163	171	-	85	78
285	301	30	105	142	159	167	-	84	77
277	292	29	104	138	156	163	-	83	76
269	284	28	104	135	153	160	-	82	75
262	276	27	103	131	149	156	-	81	74
255	269	25	102	125	146	153	-	80	72
248	261	24	101	121	143	150	-	79	71
241	253	23	100	119	140	147	-	78	70
235	247	22	99	117	137	143	-	76	67
229	241	21	98	113	134	140	-	75	66
223	234	-	97	110	131	137	-	74	65
217	228	-	96	107	128	134	-	73	64
212	222	-	95	102	126	132	-	72	63
207	218	-	95	100	124	129	-	71	62
202	212	-	94	98	121	127	-	70	60
197	207	-	93	96	118	124	-	69	59
192	202	-	92	94	116	122	-	68	58
187	196	-	91	90	114	119	-	67	57
183	192	-	90	89	111	117	-	66	56
179	188	-	89	87	-	-	-	-	-