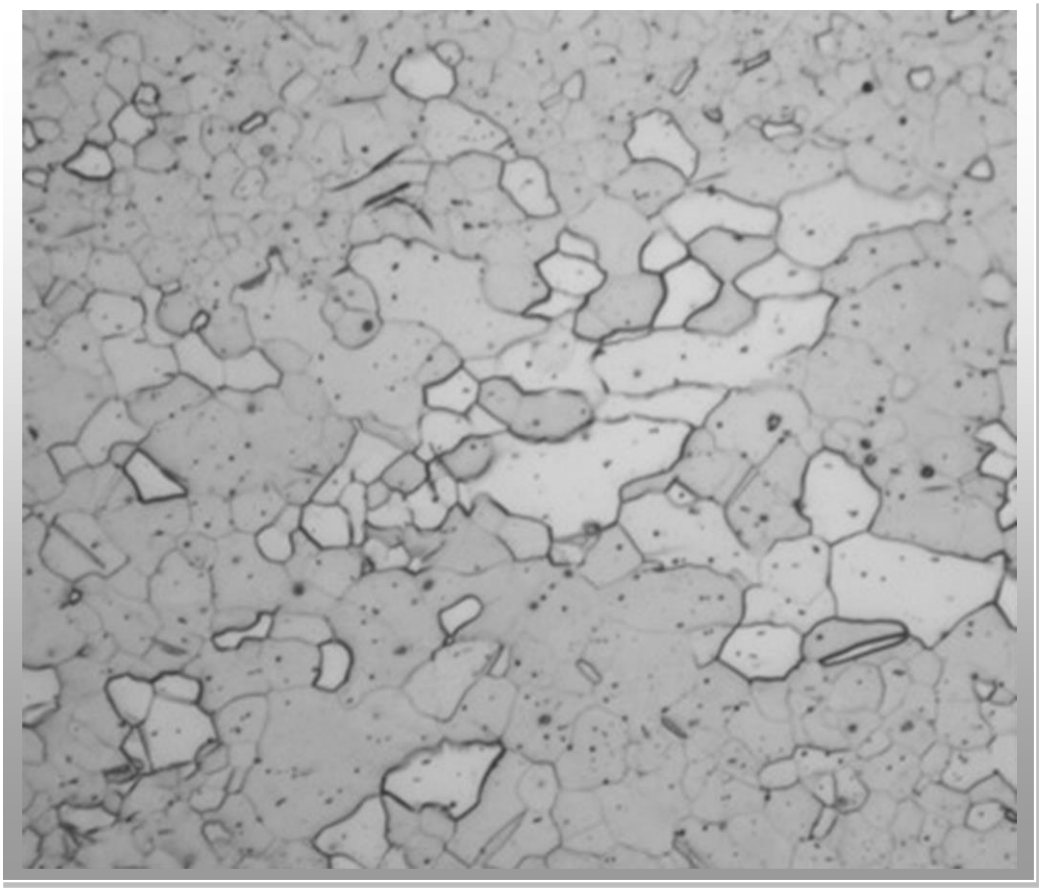
THE EFFECTS OF ELECTRIC POWER ARC INPUTS ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 0.4%C STEEL



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DEDICATION

This work is dedicated to my dear parents Chief and Mrs. Jacob Ikeh and to Almighty God.

ACKNOWLEDGEMENT

All praises and thanks belong to Almighty God, whose immense peace, mercy, blessings, and favor of good deeds have enabled me to accomplish this project.

Sincere thanks and acknowledgment to my great parents for their kind support, guidance, prayers, and good upbringing in the fear of God; May almighty God reward them handsomely with sound health.

I sincerely and thankfully acknowledge Professor B.O. Onyekpe and Awheme Ogehenerobo for their support, guidance, and stupendous supervision of this work. I thank him for sparing his precious time to go through this work and for making valuable corrections therein. He has been a source of inspiration and encouragement throughout this program. It is an honor, indeed to work under his supervision.

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TABLE OF CONTENT

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

NOMENCLATURE

A_1 - Lower Transformation Temperature
A_2 - Upper Transformation Temperature
ASM - American Society for Metals
HAZ - Heat Affected Zone
PM - Parent Metal
SMAW - Shielded Metal Arc Welding
HRC - Rockwell Hardness Number
WM - Weld Metal
AWS - American Welding Society
NDT - Non Destructive Test

ABSTRACT

An investigation of the effect of electric arc power inputs on the microstructure and mechanical properties of welded 0.4% carbon steel was studied using shielded metal arc welding (SMAW) process with E6013 electrode. The as-received ribbed steel form was firstly cut and machined to standard configurations for both tensile, hardness and impact tests. The power inputs controlled by the welding current, arc voltage, welding speed and electrode diameter were used in this investigation. The current was varied while maintaining a constant arc voltage of 40 volts, welding speed of 3.2mm/sec and electrode gauge of 3.2mm. The currents were varied at 100A low heat input, dual current of 100A & 125A for medium heat input and 125A for high heat input to give a varying amount of heat inputs. Microstructural analysis and mechanical tests were carried out on the specimens forboth the welded and the controlled specimens to determine the mechanical properties of the specimens. The results showed that the selected welding parameters had significant influence on the mechanical properties and micro-constituent of the welded samples. Increasing the welding current from 100A-125A caused a corresponding increase in the temperature of the welded joint which affected the microstructure of the welds. The weld microstructure was controlled mainlyby the cooling cycle. At 100A (i.e. with low level of current) the time for solidification was less. This rapid cooling promoted smaller grains. At 125A, the time required for solidification increases and therefore cooling rate slowed down which yielded coarse grains. On the mechanical properties, the results indicated that the joints made by using low heat input exhibited higher tensile strength (515.90 Mpa) and from scanning electron microscopy (SEM) of tensile test fractured surface exhibited ductile failure, higher hardness strength (179.5 HRC) andimpact toughness value of (6.5 Joules) than those welded with medium and high heat inputs respectively which exhibited brittle failure as the heat inputs increases as shown from the SEM image.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Medium carbon steels with carbon composition ranging from 0.25 to 0.5%C are heat treatable steels and can be successfully welded by all of the arc welding process provided suitable welding procedures and precautions are adopted or followed. The high carbon content of these steels, along with manganese greater than 1% makes these steels hardenable and weldable, thereby changing phases on cooling to form hard microstructure, for this reason, they are commonly used in the quenched and tempered condition for such applications or production of machine parts such as: bolts, crankshaft, gears, axles, rail road rails, spanner, hammer heads and heavy duty forging (Onyekpe, 2002). Because of the greater likelihood of martensite formation during welding and the higher hardness of the martensite formed, preheating is necessary. Procedures should be used to reduce the likelihood of hydrogen induce cracking by using low-hydrogen consumable or contaminants on the parent material. The high strength level of these steels may require the use of an alloy electrode to match with the base metal (ASM International, 1991). Preheating is usually done to raise the temperature of the weld area so that the weld does not cool too quickly after welding. This protects the material being welded from various adverse effects that can be carried by the normal rapid cooling cycle created by the welding process (Ameh, 2011). Preheating is carried out for the following reasons:

i. Slow down the cooling rate
ii. Reduced shrinkage stress and welded distortion
iii. Promote fusion
iv. Remove moisture

Welding joint can be made with any of the following geometrics butt joint, square butt, single 'V', double 'V' butt, butt weld with backing material, single 'U', double 'U' and horizontal butt weld depending on the thickness of the material, (Radhakrishan, 2007).

Welding involves the operation of joining two pieces of metal by the application of intense heat, pressure or both to melt the edges of the metals so that they fuse permanently (Parma,2010). 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 stresses if the items are securely held or the internal forces still remain. There comes a point when the amount of residual stresses can create potential problems either immediately or during the life of the welded structure and it needs to be reduced or removed, the process termed stress relieving (tempering) is applied; (welding technology institute of Australia, 2003). Also welding, more than any fabrication process exposes the part to rapid and extreme changes that can lead to cracks in the weldment (Desia, 2010). Usually, the rapid heating and cooling characteristics of welding produces a hard microstructure in the heat affected zone (HAZ), one factor responsible for deterioration and properties of welded joint.

Structure of steel consists of the macro and micro structure. The micro structure is the structure that is visible with the help of the enchant chemical which is being poured on the surface of the polished steel (Mbah, 2003). The visible macro-structure is the parent metal, the heat affected zone, the fusion zone (Roger, 2008). The parent metal is the normal unaffected part of the metal whose structure was not altered. The heat affected zone (HAZ); which is the area of the base material of metal that has had its microstructure and properties altered by welding or heat intensive cutting operation. The fusion zone (FZ) is where melting and solidification takes place and the principle controls the size and shape of the grain, segregation and distribution of inclusion and porosity. The microstructure which shows the way the atoms and phases are arranged. This can only be detected by the use of the metallurgical microscope (Choudary, 2007). The internal structure of the plain carbon steel that has been tempered is different from that which has been welded. Also, there is difference in the structure of that which is cooled with normal air that which is quenched in water (Adibe, 2000).

Mechanical properties of welded joints, the properties related to stress and strain are most often measured to show that such a weld and other similar welds will serve their purpose under loading conditions. Mechanical properties are such properties as strength, hardness and toughness, which not only influence the service life of a component but choice of manufacturing process for that component (Choudary, 2007).

Materials are tested for the following reasons (Rajput, 1999):

i. To check chemical composition
ii. To determine suitability of a material for a particular application
iii. To determine data; that is, force deformation (or stress) values to draw up sets of specifications upon which the engineer base his design.

iv. To determine the surface or sub-surface defects in welded materials.

More rarely, several welds are compared to see which welding techniques, process, or chemistries provides the best combination of mechanical properties (ASM International, 1991). Mechanical testing is classified as destructive and non-destructive testing. In destructive testing, the component or specimen either breaks or remain no longer useful for further use and it includes tensile test, hardness test, fatigue test, creep test and impact test.

Tensile tests are carried out to determine the ultimate tensile strength, yield strength and ductility of materials. The test is carried out on a bar of uniform cross section, usually circular (but in some cases flat) in testing machine, which indicates the tensile load being applied. For the very small strain involved in the early part of the test, the elongation of measured length (called the gauge length) is recorded by extensometer (Onyekpe, 2002). The tensile testing machine is designed to elongate the specimen at a constant rate and to continuously and simultaneously measure the instantaneous applied load and resulting elongations. A stress-strain test typically takes several minutes to perform and is destructive, that is, the test specimen is permanently deformed and usually fractured (Callister, 2007).

Hardness represents the resistance of material to indentation and involves the measurement of plastic deformation caused when a loaded ball or diamond is applied to the surface of the material (Onyekpe, 2002). Hardness testing of weld provides an indication of two parameters, significant to the determination of successful weld joint and they are:

i. Strength
ii. Microstructure of a known material.

Welding can impose a variety of thermal cycle on steel at various location that produce:

i. Undesirable hard microstructure susceptible to cracking and brittle fracture
ii. Excessively soft microstructure susceptible to plastic collapse under load.

The factors that can influence the resultant hardness includes: pre-heat, weld heat input, cooling rate, total thickness at the weld, alloy content of the steel, alloy content of any flux and the original micro-structural condition of the steel. The hardness can therefore be a useful indicator to determine if the thermal cycle induced by welding has rendered the heat affected zone (HAZ) adjacent to the weld susceptible to cracking or plastic collapse (Welding Technology of Australia, 2006).

There are various methods to measure hardness:

i. Brinell Hardness
ii. Rockwell Hardness
iii. Vickers Pyramid Hardness

In non-destructive test, the component does not break and so even after being tested, it can be used for the purpose for which it was made. The test includes (Rajput, 1999):

i. X-ray radiography
ii. Gamma radiography
iii. Magnetic Particle inspection
iv. Electrical particle inspection
v. Electrical method
vi. Ultrasonic testing

This work seeks to investigate the effect of electric arc power inputs on the microstructure and mechanical properties for service condition from welded, As- received (parent material) of the medium carbon steel weldment.

1.2 Statement of the Problem:

Welding of medium carbon steel is more difficult than welding of low carbon steels because of the greater tendency of martensite formation in the heat affected zone (HAZ) and this makes the weldment susceptible to hydrogen induced cracking and therefore leads to catastrophic failure. Research has shown that medium carbon steel fail in the industry due to poor choice of welding parameters and welding practice and as a result leads to gaseous molecule entrapment, irregular grain sizes and internal stress in weldment and heat affected zone which affects its mechanical properties when subjected in service i.e. under load bearing capacity. It is therefore necessary to investigate the effect of electric power arc inputs on the microstructure and mechanical properties on this steel, so that adequate measures can be adopted to improve the mechanical and micro-structural properties when subjected in service under load bearing capacity.

1.3 Aim and Objectives of the Study

1.3.1 Aim of the Study:

To investigate the effect of electric arc power inputs on the microstructure and mechanical properties of welded medium carbon steel.

1.3.2 Objectives of the Study:

i. To determine the effect of varying electric current inputs on the mechanical properties of welded medium carbon steels.
ii. To determine the effect of varying electric current inputs on the microstructure of welded medium carbon steel
iii. To determine the effect of varying electric current inputs on the fracture toughness of welded medium carbon steel

1.4 Scope:

The research will involve:

i. Determination of chemical analysis of the steel being investigated
ii. Cutting and machining the steel to prepare the joint geometry
iii. Welding the samples with metal-arc welding machine using mild steel electrodes with similar chemical composition with parent material
iv. Micro-structural examination of as-received, as-welded materials
v. Determination of the mechanical properties of each of the samples.

CHAPTER TWO

LITERATURE REVIEW

2.1 Welding

Welding is a process of joining two or more pieces of the same or dissimilar materials to achieve complete coalescence. It is the only method of developing monolithic structures and it is often accomplished by the use of heat or pressure (Parma, 2010). Although, in its present form, it has been used since about beginning of 20th century but it is fast replacing other joining process like reverting and bolting (Khan, 2007). In recent days, welding is used extensively for fabrication of vastly different components including critical structures. Welding processes is commonly used in joining sheet metals (Mohammed et al, 2013), the heat is produced after the electrical energy has been converted to light energy which passes through the flux to the electrode to strike an arc, and the light energy is converted to heat energy which helps in welding.

A welded joint is obtained when two clean surfaces are brought into contact with each other and either pressure or heat, or both are applied to obtain a bond. The tendency of atoms to bond is the fundamental basis of welding (Mohammed et al, 2013). Welding is used as a fabrication process in the industry. It is an important means of fabrication and repairing products. It is used extensively for fabrication of vastly different components including critical structures like boilers, pressure vessels, ships, off-shore structure, bridges, storage tanks, pipelines, missile and rocket parts, nuclear reactors, fertilizers and chemical plants, earth moving equipment, automobile bodies in heavy plate, pipe and tube fabrication industries. The process is efficient, economical and dependable means of joining metals. The process finds its application in air, underwater and in space; it is the only process which has been tried in space (Khan, 2007). For satisfactory weld to be obtained, it is desirable to have the following condition (Zakaria, 2010):

i. A source of energy to create union by fusion or pressure
ii. A method for removing surface contaminants
iii. A method for protecting metal from atmospheric contamination
iv. A control of weld metallurgy

Modern welding technology started just before the end of the 19th century with the development of methods for generating high temperature in localized zones. Welding generally requires a heat source to produce a high temperature zone to melt the material, though it is possible to weld two metal pieces without much increase in temperature. There are different methods and standard adopted and there is still a continuous search for new and improved methods of welding. As the demand for welding new materials and larger thickness components increases, mere gas flame welding which was first known to the welding engineer is no longer satisfactory and improved methods have been developed (Radhakrishan,2007).

American Welding Society (AWS) has given letter designation to various welding processes.

2.2 Shielded Metal Arc Welding

Shielded metal arc welding (SMAW) also known as manual metal arc welding (MMAW), flux shielded arc welding or informally as stick welding, is a manual arc welding process that uses a consumable electrode covered with flux to lay the weld. Here an electric current, in the form of either alternating current or direct current from welding power supply is used to form an electric arc between the electrode and the metal to be joined. The workpiece and the electrode melt forming a pool of molten metal (weld pool) that cools to form a joint. As the weld is laid, the flux coating of the electrode disintegrates, giving off vapors that serve as a shielded gas and providing a layer of slag, both of which protect the weld area from atmospheric contamination (Eroglu et al, 2000).

a. Operation

To strike the electric arc, the electrode is brought into contact with the workpiece by a very light touch with the electrode to the base metal, and then is pulled back slightly. This initiates the arc and then the melting of workpiece and the consumable electrode, and causes droplet of electrode to be passed from the electrode to the weld pool. As the electrode melts, the flux covering disintegrates, giving off shielded gases that protect the weld area from oxygen and other atmospheric gases (Prasad and Dwivedi, 2011). In addition, the flux provides molten slag which covers the filler metal as it travels from the electrode to the weld pool. One part of the weld pool, the slag floats to the surface and protects the weld from contamination as it solidifies. Once hardened, it must be chipped away to reveal the finished weld. As welding progresses and the electrode melts, the welder must periodically stop welding to remove the remaining electrode stub and insert new electrode into the electrode holder (Prasad and Dwivedi, 2011).

b. Equipment

Shielded metal arc welding equipment typically consist of a constant current welding power supply with an electrode and electrode holder, a ground clamp and a welding cables (also known as welding leads) connecting the two. The power supply is SMAW has constant current output, ensuring that the current (and thus the heat) remains relatively constant, even if the arc distance and voltage change (Parma, 2010).

c. Quality

The most common problems associated with shielded metal arc welding includes: weld spatter, porosity, poor fusion, shallow penetration and cracking. Weld spatter, while not affecting the integrity of the weld, damages its appearance and increases cleaning cost. It can be caused by excessively high current, along arc or arc blow, a condition associated with direct current characterized by the electric arc being deflected away from the weld pool by magnetic forces. Arc blow can also cause porosity in the weld, as can joint contamination, high welding speed, and a long welding arc, especially when low hydrogen electrodes are used. Another defect affecting the strength of the weld is poor fusion, though it is often easily visible. It is caused by low current, contaminated joint surfaces or the use of an improper electrode (Roger, 2008). Shallow penetration, another detriment to weld strength, can be address by decreasing welding speed, increasing the current or using a smaller electrode. Any of these weld-strength-related defects can make the weld prone to cracking, but other factors are involved as well (Juan, 2003).

d. Application and Materials

Shielded metal arc welding is one of the world’s most popular welding processes, accounting for over half of all welding in some countries, because of its versatility and simplicity; it is particularly dominant in the maintenance and repair industry and is heavily used in the construction of steel structures and industrial fabrication. SMAW is often used to weld carbon steel, low and high allow steel, stainless steel, cast iron and ductile iron (Momoh and Akinribide, 2013).

e. Shielded Metal Arc Welding (SMAW) Electrodes

The electrode is coated in a metal mixture called flux, which gives off gases as it decomposes to prevent weld contamination, introduces deoxidizers to purify the weld, causes weld protecting slag to form, improves the arc stability and provides alloying elements to improve the weld quality.

Electrodes can be divided into three groups, those designed to melt quickly are called fast-filled electrodes, those designed to solidify quickly are called fast-freeze electrodes, and intermediate electrodes go by the name fill-freeze or fast- freeze electrodes. Fast- fill electrodes are designed to melt quickly so that the welding speed can be maximized, while fast-freeze electrodes supply filler metal that solidifies quickly, making welding in a variety of positions possible by preventing the weld pool from shifting significantly before solidifying (Bayaraktar et al, 2007).

f. Electrode Classification

There are various electrodes specification systems used in different countries. The most important ones are (Eroglu et al, 2000):

i. International standard organization (ISO) coding system
ii. American welding society(AWS) coding system
iii. British standard institute (BSI) coding system
iv. Indian standard (IS) institutional coding
v. Standard organization of Nigeria (SON)

As shown in table 2.1, In AWS classification, and a four –digit number is used, preceded by the letter E (indicating a covered arc welding electrode). The first two digits indicate the minimum tensile strength of the weld metal deposited in thousands of pounds force per square inch (psi)(Davies, 1993). The third digit indicates the welding positions in which the electrode can be used satisfactorily and the last two digits together indicate current conditions and type of covering (Eroglu et al, 1999).

Table 2.1: Third digit and welding position in AWS electrode classification (Khan, 2007)

Third digit	**Position**
1	F,H,V,OH
2	F,H-fillet
3	F, H, V-down. OH

2.2.1 Welding Techniques

Successful manual metal arc welding techniques depends on the following factors

a. **Selection of electrode**

The selection of an electrode is straight forward, in that it is only a matter of selecting an electrode of similar composition to the parent metal (Asibeluo and Emifoniye, 2015).

b. **Size of electrode**

The size of the electrode generally depends on the thickness of the section being welded, and the thicker the section the larger the electrode required. In the case of light sheet, the electrode size used is generally slightly larger than the work being welded (Dodo et al, 2016).

c. **Welding current**

Correct current selection for a particular job is an important factor in arc welding. With the current set too low, difficulty is experience in striking and maintaining the arc, the electrode tends to stick to the work, penetration is poor and beads with a distinct rounded profile will be deposited (Oluwasegun et al, 2016). Excessive current is accompanied by overheating of the electrode. It will cause undercut and burning through of the material, and will give excess spatter. Normal current for a particular job may be considered as the maximum, which can be used without burning through the work, overheating the electrode or producing a rough spatter surface (i.e. the current in the middle of the range specified on the electrode package is considered to be optimum), (Roger, 2008). In the case of welding machine with separate terminals for different size electrode, the welding lead is connected to the correct terminal for the size electrode being used.

d. **Arc length**

To strike an arc the electrode is gently scraped on the work until the arc is established. An arc length is the shortest arc that gives a good surface to the weld. An arc too long reduces penetration, produces spatter and gives rough surface finish to the weld. An excessively short arc causes sticking of the electrode and rough deposits that are associated with slag inclusions (Roger, 2008)

e. **Electrode angle**

The angle that the electrode makes with the work is important to ensure a smooth, even transfer of metal (Roger, 2008).

f. Correct travel speed

The work is welded at a speed that will give the size of run required. At the same time, the electrode is fed downwards to keep the correct arc length at all times. Correct travel speed for normal welding application varies between approximately 100 and 300mm per minute, depending on electrode size, size of run required and the amperage used. Excessive travel speed leads to poor fusion, lack of penetration. While too slow a rate of travel will frequently lead to arc instability, slag inclusions and poor mechanical properties (Roger, 2008).

g. Correct work preparation

The method of preparation of component to be welded will depend on equipment availability and relative costs. Methods may include sawing, punching, shearing, machining, flame cutting and others (Zakaria, 2010)

2.3 Welding Metallurgy

During welding, the material to be welded experiences a thermal cycle; the material is heated rapidly and cools at a somewhat slower rate. In both solid state and fusion welding, the temperature cycle strongly influences the structure and properties of the material; however, there are distinctions between the two cases. In fusion welding, the maximum temperature exceeds locally the melting point and a weld pool is formed, while the un-molten material reaches a maximum temperature, which depends on the distance from the fusion boundary. During cooling phase of the welding process, the liquid weld metal solidifies again forming the weld metal (Radhakrishan, 2007).

2.3.1 Weld metal (WM), Heat affected zone (HAZ), and Parent metal (PM)

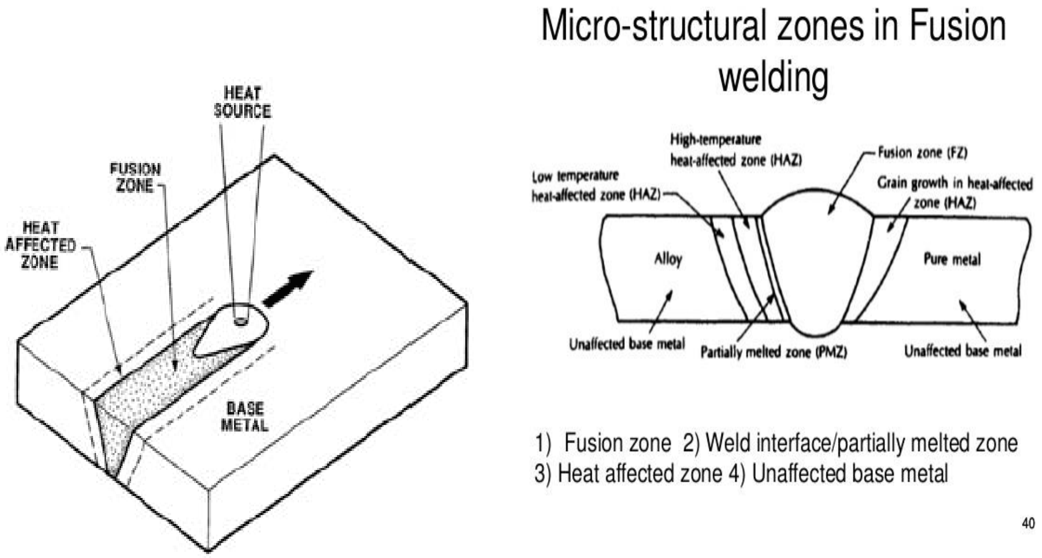


Figure 2.1Different Welded Zones of Carbon Steel (Parma, 2010)

Welding results in development of temperature gradient which varies from the highest temperature encountered in the center of the weld pool to the ambient temperature along the transverse direction to the weld axis (Parma, 2010).

The welded joint, although actually a single integral structure, may be considered to consist of three distinct zones that merge into one another: the weld metal (WM), the heat affected zone (HAZ) and the base or parent metal (PM), (Parma, 2010).

a. The Weld Metal (wm) Zone

This is the result of melting which fuses the base metal and filler metal to produce a zone with a composition that is most often different from that of the base metal (Davies, 1993).

b. Heat Affected Zone (HAZ)

HAZ is that portion of the parent metal that has not melted, but whose mechanical properties or microstructure has been altered by the welding or heat intensive cutting operations. The micro-structural changes that occur depend on the material composition, the peak temperature encountered and the cooling rate. The heat from the welding process and subsequent re-cooling causes this change from the weld interface to the termination of sensitizing temperature in the base metal (Roger, 2008). The extent and magnitude of property change depends primarily on the base material, the weld filler metal, and the amount and concentration of heat input by the welding process. The thermal diffusivity of the base materials plays a large role if the diffusivity is high, the material cooling rate is high and the HAZ is relatively small. Alternatively, a low diffusivity leads to slower cooling and a larger HAZ. The amount of heat inputs during welding process also plays an important role as well, as processes like oxy-fuel welding use high heat input and increases the size of HAZ. Processes like laser beam welding and electron beam welding give a highly concentrated, limited amount of heat, resulting in small HAZ. Arc welding falls in between the two extremes, with the individual processes varying somewhat in heat input. To calculate the heat input for arc welding procedures, the following formula is used:

$$Q = \left(\frac{V \times I \times 60}{S \times 1000}\right) \times Efficiency \qquad (2.1)$$

Where *Q= heat input* (KJ/mm), *V= voltage* (v), *I= Current* (A) and *S= welding speed* (mm/min).

The efficiency is dependent on the welding process used, with shielded metal arc welding having a value of 0.75≈ 0.8, gas metal arc welding and submerged arc welding is of value 0.9, and gas tungsten arc welding is 0.8 (Mohammed et al, 2013).

Usually, the rapid heating and cooling characteristics of welding produce a hard microstructure in the HAZ, one factor responsible for property deterioration of welds. Steels that tend to produce hard welding HAZ are hard to fabricate and thereby hard to use (Abioye, 2017). The HAZ in a carbon steel can be related to the Fe-C equilibrium phase diagram, if the kinetic effect of rapid heating during welding on phase transformation is neglected (Ravinder et al, 2016).

The HAZ can be divided into the following subzones (Upadhyaya and Anish, 2006):

i. **Grain Growth Zone**

    a. This region is immediately adjacent to the weld metal zone. In this zone, the parent metal has been heated to a temperature well above upper critical temperature (A_3). This results in grain growth and coarsening of the structure. The size and extent of this zone increases as the cooling rate decrease (Khanna, 2005).

ii. **Grain Refining Zone**

    a. This zone is adjacent to the grain growth zone. In this zone, the parent metal is heated just above (A_3) temperature, where grain refinement is completed and the finest grain structure exist (Khanna, 2005).

iii. **Partially Transformed Zone**

    a. In the zone, the parent material is heated between (A_1) and (A_3) temperatures (Parma, 2010) where partial allotropic transformation takes place (Khanna, 2005).

iv. **Tempered Zone**

    a. In this zone, the parent material is heated to temperature below (A_1)

c. Parent Metal

Parent metal is that portion of the material whose mechanical properties and microstructure has not been altered by the welding and heat intensive cutting operation.

2.3.2 Effect of Heat on the Temperature Gradient across the Weldment.

Immediately after fusion, the temperature of the fusion zone is the highest and decreases due to heat transfer by conduction from the fusion zone to the heat affected zone and the unaffected base metal. The temperature of the heat affected zone and the base metal increases since heat loss by the FZ is equally gained by the HAZ and BM. When a material is subjected to heat, the heat flows so that the body and the surroundings reach the same temperature, at this point, they are in thermal equilibrium. Such spontaneous heat transfer always occurs from region of high temperature to the region of low temperature as described in the second law of thermodynamics (Choudary, 2007). From the temperature measurement, more heat is quickly given out in low heat inputs, followed by the medium heat inputs and then high heat inputs.

2.3.3. Metallurgical and Mechanical Properties of Weldment

Metallurgical characteristics of the weld metal as well as heat affected zone (HAZ) are very important because this directly influence the weld mechanical properties and joint performance. It is well known that the microstructure of base metal as well as (HAZ), are somewhat different with respect to distributions of pearlite, ferrite, and grain size depending on the weld condition adopted (Apurv and Jatti, 2014). In a pass of welding current, the material is rapidly heated to the maximum temperature and allowed to cool more slowly by conduction of heat into the bulk of the parent metal. Phase changes occur depending on the temperature reached. Sufficiently far from the weld pool, the material remains unaffected. The region next to the fusion zone where micro-structural changes occur but no melting of base metal has affected is known as the heat affected zone (HAZ). Such micro-structural changes can affect the mechanical properties of the weld and need to be controlled. The weld metal microstructure is controlled mainly by the cooling cycle. At lower energy input (i.e. with low level of current), the time for solidification is less. The rapid cooling promotes smaller grains. With higher energy input, the time required for solidification decreases, and therefore cooling rate slows down which yields coarse grains. Coarse grain in the microstructure indicates lower hardness and low tensile strength (Abioye, 2017). Mechanical properties are important characteristics of the weldment that must confirm to the application feasibility as well as functional requirement of the welded joint. These include hardness, impact strength (toughness), yield strength, ultimate tensile strength, percentage elongation, resistance to wear and corrosion. These mechanical properties greatly depend on weld microstructure, which in turn related to cooling condition, composition of base metal, electrode composition. However, welding process parameters also have direct/indirect influence on weld mechanical properties and microstructure (Asibeluo and Emifoniye, 2015).

2.3.4 Micro-structural Development in Steel Weldment

The mechanical performance of the weldment particularly with reference to its strength and toughness will depend upon the type of microstructure obtained in the weld metal and HAZ.

Some or combination of the following microstructures may be encountered in weld metal and HAZ of steel weld (Parma, 2010):

i. Delta ferrite
ii. Grain boundary ferrite
iii. Ferrite side plates
iv. Lath ferrite
v. Acicular ferrite
vi. Pearlite
vii. Bainite
viii. Martensite
ix. Retained austenite

Some of these are shown in Figure 2.2

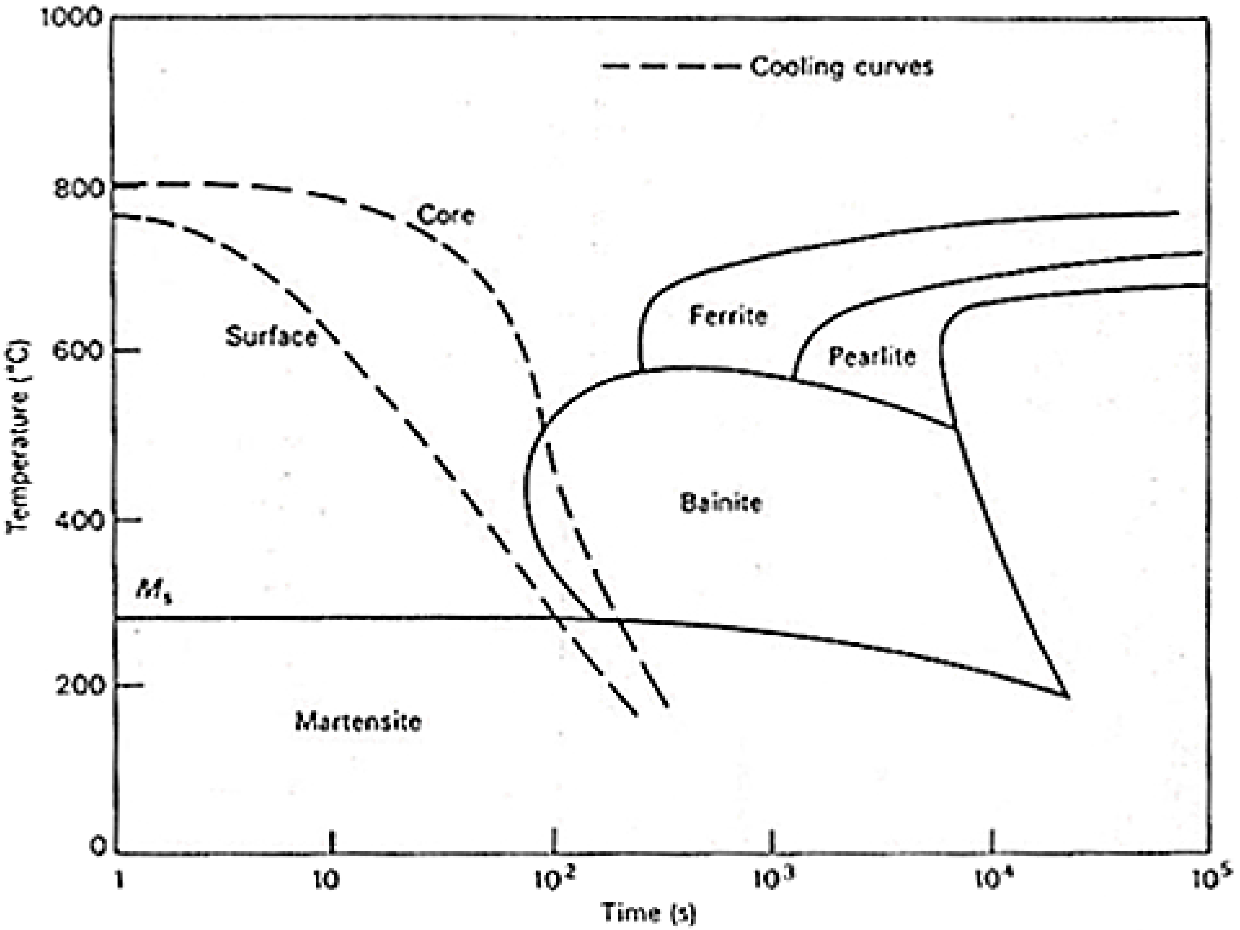


Figure 2.2 schematic of weld CCT diagram showing selected microstructure (ASM International, 1991)

2.3.5 Weldability

Weldability also known as joinability of materials refers to the suitability of a material to produce sound and reliable welded joints. A material's weldability is used to determine the welding process and to compare the final weld quality to other materials. The term is used to describe the ease with which a metal can be welded to produce a weldment of acceptable quality. The weld quality is usually judge from the standpoint of mechanical properties (Dodo et al, 2016):

i. The strength of the joint must be at least as great as that of the parent metal;

ii. The fracture ductility of the weld metal and heat affected zone (HAZ) must be sufficient to ensure that the brittle fracture properties of the structure in service are limited by these factors alone;

iii. The fatigue properties of the joint should not be impaired by the metallurgical condition of the weld metal or HAZ;

iv. The metallurgical condition of the joint should not impair the behavior of the structure during service as a result of localized corrosion, etc.

The metal which can be welded to fit the above criteria with no special precautions to prevent discontinuities or other difficulties is considered to have good weldability (Tarik, 2013).

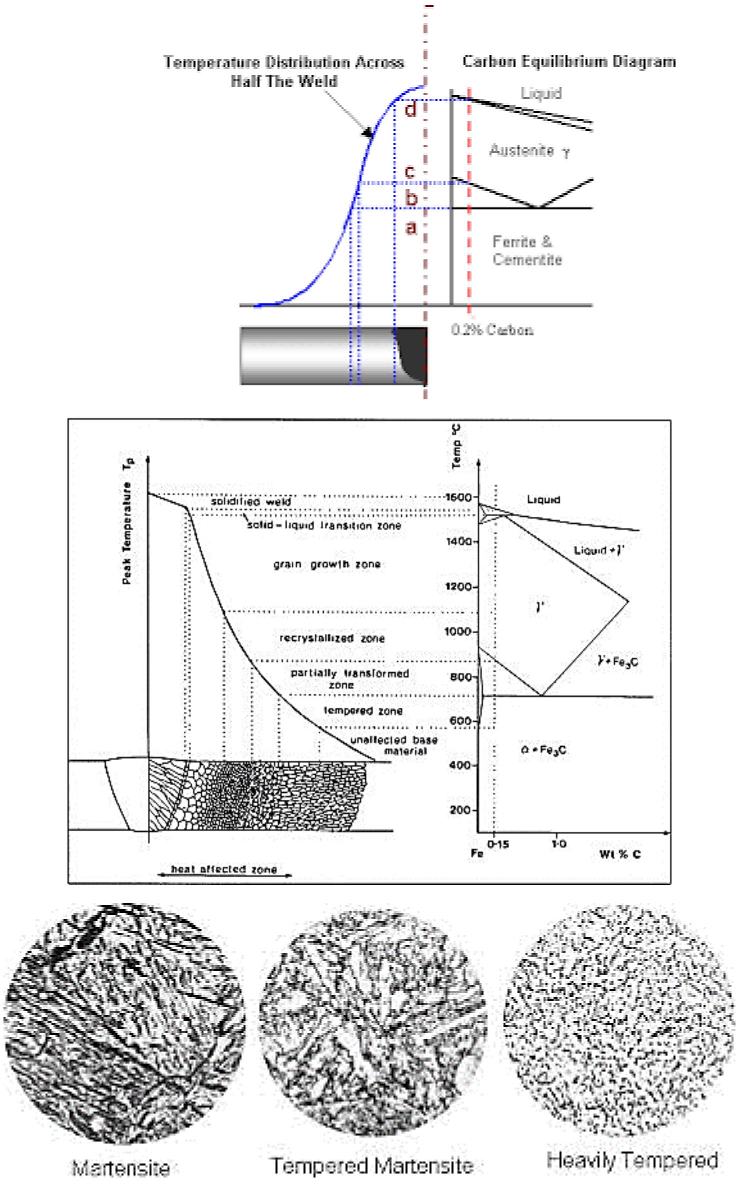
a. Weldability of medium carbon steel

Welding of medium and high carbon steels is more difficult than welding lower carbon steels because of the greater tendency of martensite formation in the HAZ and hence hydrogen cracking (Choudary, 2007). A pronounced change in weldability of carbon steel takes place when the carbon content is 0.3%. Medium carbon steels have fair weldability and preheat and post weld heat treatments are frequently required to avoid the formation of large amount of hard martensite in the HAZ.

b. Hardenability of Steel

Hardenability is the potential of steel to form hard microstructures (martensite). Also refers to the potential for any steel to harden on cooling and, as the carbon content of the steel increases towards 0.8%, so the potential of the steel to harden increases. Increasing the alloy content of the steel also increases the hardenability; i.e. hardenability is a function of carbon content and other alloying elements and the grain size of austenite. The relative importance of the various alloying elements is calculated using the equivalent carbon content of the material (Choudary, 2007). While hardness and strength may be desirable in a welded steel structure, martensite can be brittle and susceptible to cracking, and is also known that the potential brittleness of the material also increases as hardenability increases. While hardness is actually achieved in steel with known hardenability depends on the maximum temperature to which it is heated and the cooling rate from the temperature. During welding, the parent material close to the weld will be heated to temperatures near melting point, while further away it will remain at ambient temperature. The cooling rate depends on the mass of the material, its temperature, and the heat input. Therefore, welding hardenable steel, the hardness in the HAZ depends on the cooling rate; the faster the cooling rate, the harder the microstructure produced and the more susceptible it is to cracking. Changes in phases determines how hard steel must be, the starting point is austenite and is as follows:

i. Rapid quenching transforms austenite phase to martensite phase; a hard nut brittle structure.
ii. Slower cooling rate will promote formation of bainite and/or other softer phases
iii. Cooled even more slowly, a soft structure of ferrite plus cementite, called pearlit results.



Martensite Tempered Martensite Heavily Tempered

Figure 2.3 Variation of Temperature from the Centre of the Weld to the Base Material and the Resultant Martensite Structure (Lancaster, 1987)

c. Carbon Equivalent

Carbon has the greatest effect on the hardenability of steel, but other alloying elements may be added to increase its hardenability. This addition effectively reduces the critical cooling rate and the temperature at which the austenite to martensite transformation takes place, making it easier for martensite to form at slower cooling rates. The alloying elements that have greatest influence on hardenability of steels are manganese, molybdenum, chromium, vanadium, nickel, copper, silicon, but their effect are negligible to carbon effect. The carbon equivalent describes the influence of these elements on the hardenability in terms of the effect that carbon has. It can be expressed as follows (Asibeluo and Emifoniye, 2015):

$$\text{CE} = \%\text{C} + \left(\frac{\%Mn+\%Si}{6}\right) + \left(\frac{\%Cr+\%Mo+\%V}{5}\right) + \left(\frac{\%Cu+\%Ni}{15}\right) \tag{2.2}$$

The carbon equivalent is used mainly for estimating preheats. Preheat is necessary to slow down the cooling rate sufficiently to reduce hardening in the HAZ of welds in susceptible carbon and low alloy steels. This, in turn helps to prevent subsequent HAZ hydrogen cracking. The overall effect is to improve the weldability of steel being welded or at least to overcome the weldability problems presented by it.

2.3.6 Residual Stresses and Distortion in Welding

Due to the non-homogeneous heating and cooling of the workpiece during welding, residual stresses will be introduced into the workpiece, which may lead to plastic deformation and distortion. Residual stresses and distortion are closely related. Generally speaking, minimizing the distortion of workpiece, for instance by clamping device, will result in an increase of residual stresses. Residual stresses are stresses that remain in a solid material after the original cause of the stresses has been removed (Abioye, 2017). These stresses are internal stresses i.e. the stresses are not due to external forces. Therefore, the stresses have to be in equilibrium. This means that the tensile stresses in specific part of the workpiece have to be compensated by residual stresses in other parts (Radakhrishan, 2007). Residual stresses can occur through a variety of mechanism including inelastic (plastic) deformations, temperature gradient (during thermal cycle) or structural changes (phase transformation). Heat from welding may cause localized expansion, which is taking up during welding by either the molten metal or the placement of parts being welded. When the finished weldment cools, some area cools and contract more than others, leaving residual stresses (Rajput, 1999).

Residual stresses have a negative influence on the integrity of the welded joint. The promote weld cracking and may cause distortion. Distortion in a weld results from the expansion and contraction of the weld metal and adjacent base metal during the heating and cooling cycle of the welding process. Distortion also refers as any unwanted physical change or departure from specification in a fabricated structure or component, as a consequence of welding (Parma, 2010).

The following types of distortion may be observed in welding (Radakhrishan, 2007):

i. Transverse distortion
ii. Longitudinal distortion
iii. Rotational distortion
iv. Angular distortion
v. Bending distortion
vi. Buckling

a. Methods of Relieving or Controlling Welding Residual Stresses

Various methods are available to reduce the level of residual stresses in weld joints:

i. Preheating
ii. Post-weld heat treatment
iii. Peening
iv. Overloading
v. Vibratory stress relief, etc

The most common method is thermal stress relief. This method makes use of the fact that the yield stress of metal decreases as the temperature is raised. Therefore, the temperature is raised until the yield stress has fallen to a low value at which residual stresses are no longer supported (Khan, 2007)

2.4 Weld Defect

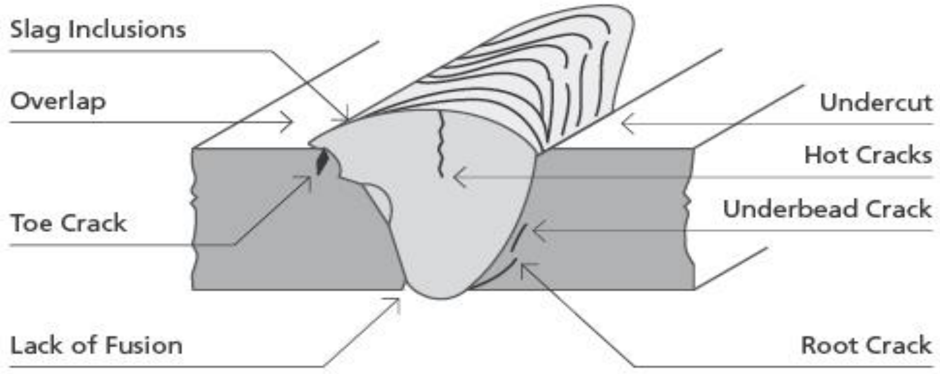


Figure 2.4 Sections of Weld Defect (Khanna, 2005)

Weld defect is any flaw that compromises the usefulness of the weldment. Weld defect are potentially disastrous as they can all give rise to high stress intensities which may result in sudden unexpected failure below the design load or in case of cyclic loading; failure after fewer load cycle. These defects weaken the weld, they reduce the quality of the weld and eventually causes failure or weld cracking. During fusion welding, different weld defects can be formed which under specific condition may impair the integrity and reliability of the welded joint (Roger, 2012). The most important weld defects are: cracks, pores, inclusions, lack of penetrations and undercuts.

a. Cracks

These are longitudinal shrinkage stresses acting on weld metal of low ductility. Cracks can also be said as linear ruptures of metal under stress. Cracks are by far most dangerous weld defects and can occur about everywhere in a weld: In the weld metal, the plate next to the weld metal or in any other piece affected by the intense heat of welding. The major classes of crack are: Hot crack, cold crack, crater crack, hat crack, spatter, micro fissures and lamellar tearing (ASM International, 1993).

i. Hot Crack

Hot cracking, also known as solidification cracking, can occur with all metals, and happens in the fusion zone of a weld. To diminish the probability of this type of cracking, excess material restraint should be avoided, and a proper filler material should be utilized. Other causes include too high welding current, poor joint design that does not diffuse heat, impurities (such as sulfur and phosphorus), preheating, and speed is too fast, or long arcs. Hot cracks are formed at high temperature, usually several hundred degrees below the melting point or solidus temperature of the alloy. Two types of hot cracks may be distinguished: solidification crack and liquation crack.

Solidification crack occurs in the weld metal when the metal is very hot; just below the solidus temperature. Such cracks are inter-dendritic, following the random path of grain boundaries. In most cases solidification cracks are formed in the centre line of the weld (centre line crack). Liquation cracks occur in the heat affected zone when a low melting phase is present at the grain boundaries. During welding the phases may melt and depending on the surface tension may spread out as a film on the grain boundaries. In this way, the structure is weakened and stresses due to shrinkage may cause cracking (Radakhrishan, 2007).

ii. Crater crack

Crater crack occurs when a crater is not filled before the arc is broken. This causes the outer edge of the crater to cool more quickly than the crater which creates a sufficient stress to form a crack. This crack occurs at the end point of weld when welding is being stopped before using up the electrode. This crack causes other cracks to take place (Adibe, 2000).

iii. Hat crack

Hat crack is a type of crack based on the shape of the cross-section of the weld, because the weld flares out at the face of the weld. The cracks start at the fusion line and extend up through the weld. They are usually caused by too much voltage or not enough speed (Juan, 2003).

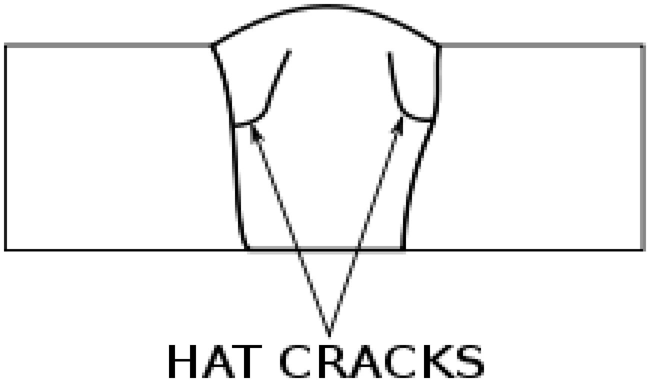


Figure2.5 Cross-Section of Hat Weld (Roger, 2008)

iv. Microfissures

Microfissures are cracks of microscopic dimension. They are cracks that occur in the area of partial melting and the HAZ adjacent to the fusion line. Because no material can be purified to the state where it solidifies truly as an invariant, all materials have a temperature region of stable two-phase coexistence of solid and liquid. In fusion welding, this manifests itself in the formation of a zone of partial melting at temperature below the alloy liquidus. The extent of this zone may be enlarged by the presence of chemical in-homogeneity in a material. Local chemical variations will result in local variations in the melting point (Tarik, 2017).

v. Lamellar Tearing

Is type of welding defects that occurs in rolled steel plates that have been welded together due to shrinkage forces perpendicular to the faces of the plate; it occurs at welded joint at the point of high stress concentration. The tearing always lies within the base metal, generally outside the HAZ and parallel to the weld fusion boundary (Ravinder et al, 2016). The problem is caused by:

i. Sulfurous inclusions in the material
ii. Presence of hydrogen in the alloy
iii. By elongated non-metallic inclusion arrays in rolled plate
iv. By welds that subject the base metal to the tensile loads in the HAZ or through direction of the rolled steel.

The defect can be mitigated by:

i. By keeping the amount of sulfur in the steel alloy below 0.005%.

ii. By design, low inclusion plate or use of casting/forgings

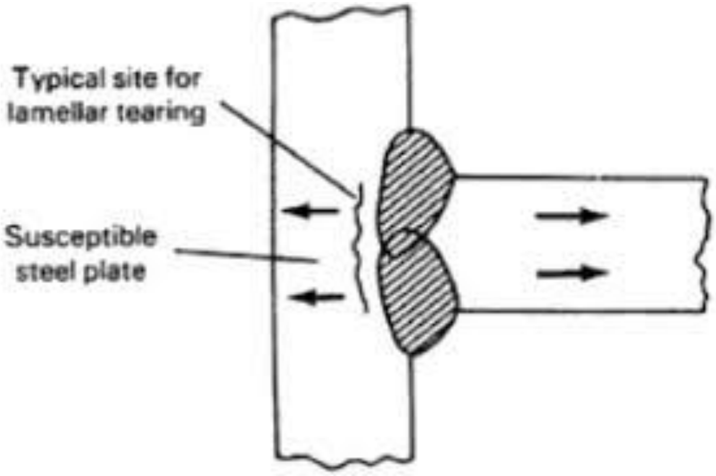


Figure 2.6: Typical Location of Lamellar Tearing (Roger, 2008)

b. Porosity

Porosity (tiny holes in the weld) is gas pockets in the weld metal that may be scattered in small clusters or along the entire length of the weld. Porosity weakens the weld in approximately the same way that slag inclusion does (Ravinder et al, 2016). The problem is caused by:

i. Excessive welding current
ii. Rust, grease, oil or dirt on the surface of the base metal
iii. Excessive moisture in the electrode coatings
iv. Impurities in the base metal
v. To short an arc length
vi. Travel speed too high, which causes freezing of the weld puddle before gases can escape.

The defects can be mitigated by:

i. Lowering the welding current
ii. Cleaning the surface of the base metal
iii. Re-drying electrodes
iv. Changing to a different base metal with different composition
v. Using a slightly longer arc length
vi. Lowering the travel speed to let gases escape
vii. Preheating the base metal, using a different type of electrode, or both.

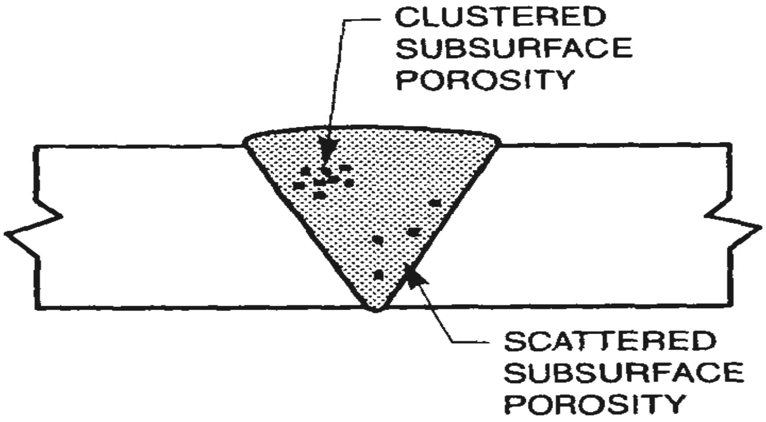


Figure 2.7 Typical Location of Porosity in the Weld (ASM International, 1993)

c. Slag Inclusion

This refers to non-metallic solids trapped in the weld deposit, or between the weld metal and base metal that produces a weaker weld. Slag is normally seen as elongated lines either continuous or discontinuous along the length of the weld. It can also be referred as the solidified remaining flux after the weld area cools. However, they are generally derived from electrode covering or fluxes employed in arc welding operations (Ameh, 2011). The problem is caused by:

i. Low amperage
ii. Improper techniques
iii. Slow travel speed in vertical down
iv. Welding in an area that is too tight
v. Insufficient cleaning contaminant
vi. Letting slag run ahead of the arc
vii. Too wide a weaving motion
viii. Incorporation of bad tack-welds

The defect can be mitigated by:

i. Increase amperage or preheat
ii. Grind out tight areas to gain access to bottom of joint
iii. A tighter weaving motion

iv. A uniform travel speed
v. Using a smaller electrode

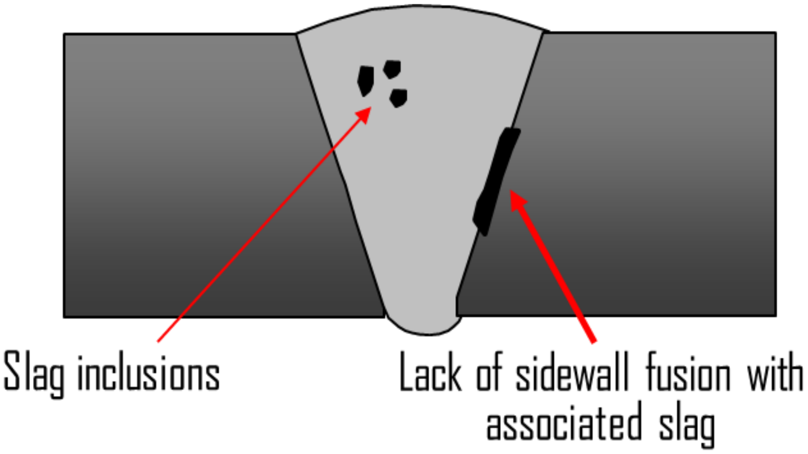


Figure 2.8 Section showing location of slag inclusion in weld metal (Parma, 2010)

d. Lack of Fusion and Incomplete Penetration

This is referred to the poor adhesion of the weld bead to the base metal. It results from improper electrode manipulation and the use of incorrect welding conditions. Fusion refers to the degree to which the original base metal surfaces to be welded have been fused to the filler metal; penetration refers to the degree to which the base metal has been melted and re-solidified to result in a deeper throat that was present in the joint before welding (Bodude and Momoh, 2015). With some joint configuration, the two terms can be used interchangeably. The problem is caused by:

i. Excessive travel speed
ii. Excessive electrode size
iii. Insufficient current
iv. Improper electrode manipulation
v. Excessive arc blow
vi. Poor welder skill
vii. Incorrect inter-run cleaning

viii. Surface contaminant such as oil, oxide or dirt that prevent full melting of the underlying metal.

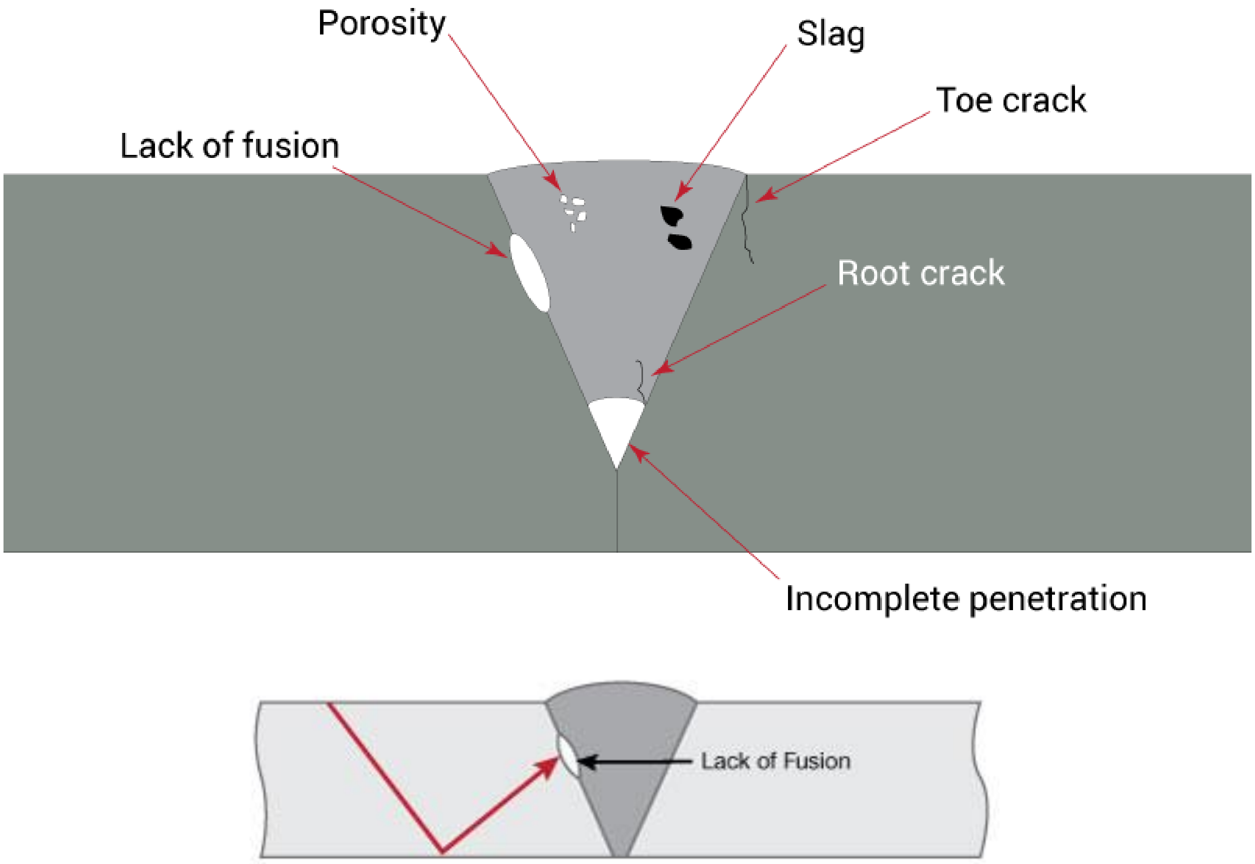


Figure 2.9 Sections Showing Lacks of Fusion and Incomplete Penetration (Desia, 2010)

e. Undercutting

Undercutting is when the weld reduces the cross-sectional thickness of the base metal and which reduces the strength of the weld and workpiece. One reason for this type of defect is excessive current, causing the edges of the joint to melt and drain into the weld; this leaves a drain-like impression along the length of the weld. Another reason is if a poor technique is used that does not deposit enough filler metal along the edges of the weld. A third reason is using an incorrect filler metal because it will create greater temperature gradient between the centre of the weld and the edges. Other causes are; too small electrode angle, a dampened electrode, excessive arc length and slow speed (Nurul et al, 2017).

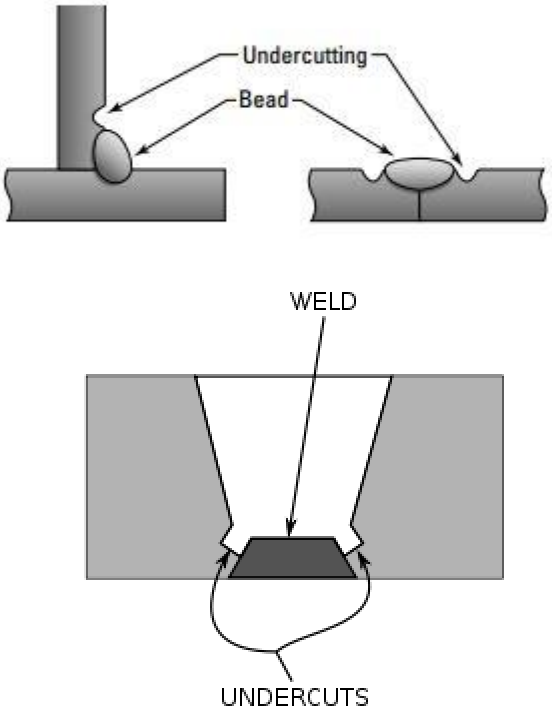


Figure 2.10 Section Portion of Undercutting on the Welded Bead (Davies, 1993)

2.5 Inspection and Testing of Welds

2.5.1 Mechanical Testing of Weld

Mechanical testing or engineering test is performed to determine various mechanical properties of materials. Mechanical testing reveals the properties of a material when force is applied dynamically or statistically. The test shows whether a material or part is suitable for its intended application by measuring properties such as elasticity, strength, hardness, ductility, toughness, brittleness, elongation, fracture toughness, stress rupture and fatigue limit. The mechanical properties of welded joints, the properties related to stress and strain, are most often measured to show that such a weld and other similar welds will serve their purpose under loading. More rarely, several welds are compared to see which welding techniques, processes or chemistries provide the best combination of mechanical properties (Saadat and Mumtaz, 2018). Materials are tested for the following reasons (Rajput, 1999):

i. To check chemical composition

ii. To determine suitability of a material for a particular application
iii. To determine data; i.e. force deformation (stress) values to draw up sets of specifications upon which the engineer base his design
iv. To determine the surface or subsurface defects in welded materials

Mechanical testing is classified as destructive and non-destructive testing.

2.5.1.1 Destructive Testing

Involves physical destruction of the completed weld in order to evaluate its characteristics. A number of destructive weld testing methods are used to determine weld integrity or performance. Typically, they involve sectioning and/or breaking the welded component and evaluating various mechanical and/or physical characteristics. Here, the specimen or component either breaks or remain no longer useful for further use and it includes tensile test, hardness test, fatigue test, creep test and impact test (Wan et al, 2015).

a. Tensile Test

The tensile test of a material is performed to determine:

i. The ultimate tensile strength
ii. Yield strength
iii. Percentage elongation and reduction of area
iv. Proportional and elastic limit and
v. Ductility of materials

The test is carried out on a bar of uniform cross section, usually circular (but in some cases flat) in a testing machine, which indicates the tensile load being applied. For the very small strain involved in the early part of the test, the elongation of a measured length (called gauge length) is recorded by an ‘’extensometer’’ (Onyekpe, 2002). The tensile machine is designed to elongate the specimen at a constant rate, and to continuously and simultaneously measure the instantaneous applied load and the resulting elongations. A stress-strain test typically takes several minutes to perform and is destructive; i.e. the test specimen is permanently deformed and usually fractured (Apurv and Jatti, 2014). The tensile test for a ductile material is generally carried out on universal testing machine on the specimen made from material to be tested. The specimen is held in the jaws of the machine and the load is applied gradually by a hydraulic press, which is measured from the pressure developed inside the cylinder. The function of the oil pump is to supply oil under pressure to the hydraulic cylinder. The reading is noted directly from the load scale.

Different types of tensile test that are carried out to evaluate a weldment include (Parma, 2010):

i. All-weld metal test
ii. Tension-shear test
iii. Transverse butt weld test
iv. Longitudinal butt weld test

b. Hardness test

Hardness represents the resistance of a material to indentation, and involves measurement of plastic deformation caused when a loaded ball or diamond is applied to the surface of the material (Onyekpe, 2002). Hardness testing of welds provides an indication of two parameters significant to the determination of a successful weld joint:

i. Strength
ii. Microstructure of a known material

Welding can impose a variety of thermal cycle on steel at various locations that produce:

i. Undesirably hard microstructures susceptible to cracking and brittle fracture
ii. Excessively soft microstructures susceptible to plastic collapse under load

The factor that can influence the resultant hardness includes: pre-heat, weld heat input, cooling rate, total thickness at the weld, alloy content of the steel, alloy content of any fluxes plus the original micro-structural condition of the steel plus post-weld heat treatment and peening. The hardness can therefore be a useful indicator to determine if the thermal cycle induced by welding has rendered the HAZ adjacent to the weld susceptible to cracking or plastic collapse (Welding Technology Institute of Australia, 2006).

There are various methods to measure hardness.

i. Rockwell Hardness Test

The Rockwell’s Hardness test is generally performed when quick and direct reading is desirable. This test is also performed when the materials have hardness, beyond the range of Brinell’s Hardness Test. It differs from the Brinell’s test that in this test the loads for making indent are smaller and thus make smaller and shallower indents. It is because of this reasons that the Rockwell Hardness Test is widely used in the industry. Several different scales may be utilized from possible combinations of various indenters and different loads, which permit the testing of virtually all metal alloys (as well as some polymers) (Callister, 2007). In this test a standard indenter either of 1.58mm diameter loaded with 100kN or a cone indenter with 120° cone and 150kN is employed. The test has nine scales of hardness (A to H and K). But B and C scales are widely used. The ball indenters are generally, made of hardened tool steel or tungsten carbide. During the test, the specimen is placed on the anvil, and is raised till it comes in contact with the indenter. A minor load of 100kN is applied on the specimen and the small pointer indicate ‘’set’’. The main pointer is also brought to the ‘’set’’ position. The major load is the applied and is allowed to continue for one second. The depth of indentation in mm is read from small pointer (Oluwasegun et al, 2016). The Rockwell Number is obtained mathematically from the relation as:

$$\text{Rockwell B Number, (R.H.B)} = 150 - \frac{Depthofindentationinmm}{0.002} \quad (2.3)$$

$$\text{Rockwell C Number, (R.H.C)} = 100 - \frac{Depthofindentationinmm}{0.002} \quad (2.4)$$

Other methods of hardness test include:

i. Brinell’s Hardness Test

ii. Vickers Hardness Test

c. Impact Test

The impact test is a method for evaluating the toughness and notch sensitivity of engineering materials. It is usually used to test the toughness of metals, but a similar test is used for polymers, ceramics and composites. Here, many machine parts are subjected to suddenly applied load called impact blows. It has been observed that a metal may be hard, strong or of high tensile strength. But it may be unsuitable for uses where it is subjected to sharp blows. The capacity of a metal to withstand such blows without fracture is known as impact resistance or impact strength. It is an indicative of the toughness of the metal i.e. the amount of energy absorbed by the metal during plastic deformation.

There are various methods to measure impact test.

i. Charpy Impact Test

The charpy impact test is a dynamic test in which a test piece U-notched or V-notched in the middle and supported at each end is broken by a single blow of a freely swinging pendulum. The energy absorbed is measured. This absorbed energy is a measured of the impact strength of materials. The charpy impact test is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is the measure of a given material notch toughness and acts as a tool to study temperature-dependent ductile-brittle transition. It is widely applied in industry since it is easy to prepare, conduct and results can be obtained quickly and cheaply (Bodude and Momoh, 2015).

Other methods of impact test are:

ii. Izod impact test

iii. Keyhole impact test.

2.6 Related Literature Review on Effects of Electric Power Arc Inputs on the Microstructure and Mechanical Properties of Weld.

Bodude and Momoh (2015) researched the effect welding parameters on the mechanical properties of welded Low-Carbon Steel using two welding processes: Oxy-Acetylene Welding (OAW) and Shielded Metal Arc Welding (SMAW). Two different edge preparations on a specific, 10-mm thick low-carbon steel, with the following welding parameters: dual welding voltage of 100 V and 220 V, various welding currents at 100, 120 and 150 Amperes and different mild steel electrode gauges of 10 and 12 were investigated. The tensile strength, hardness and impact strength of the welded joint were carried out and he discovered that the tensile strength and hardness reduce with the increase in heat input into the weld. However, the impact strength of the weldment increases with the increase in heat input. It was also discovered that V-grooved edge preparation has better mechanical properties as compared with straight edge preparation under the same conditions. Micro-structural examination conducted revealed that the cooling rate in different media has significant effect on the microstructure of weldment. Pearlite and ferrite were observed in the microstructure, but the proportion of ferrite to pearlite varied under different conditions.

Apurv and Jatti (2014) researched the influence of heat input (controlled by welding current, welding voltage and welding speed) on tensile strength, micro-hardness and microstructure of austenitic 202 grade stainless steel weldments produced by shielded metal arc welding (SMAW). In his research, the base material used in this investigation was Cr-Mn stainless steel, solid electrode was used as filler material. From the experimental results he found out that the increase in heat input affects the micro-constituents of base metal, and heat affected zone (HAZ). Tensile strength decreases with increase in heat input and from scanning electron microscope of tensile test fracture surfaces exhibited ductile and brittle failure. The micro hardness data values decrease with increase in heat input. Optical microscopy shows that smaller dendritic sizes and lesser inter-dendritic spacing were observed in the fusion at low heat input. And long dendritic sizes and large inter-dendritic spacing were observed in the fusion zone of the joint welded at high heat input.

Wan et al (2015) researched the effect of welding heat input on microstructure and mechanical properties at coarse grain heat affected zone of ABS grade steel. The study was carried out to scrutinize the effect of welding heat input to the distribution of microstructure formation and its mechanical properties at coarse grain heat affected zone (CGHAZ) of ABS grade steel. Three heat input combinations which designated as low heat (0.99kj/mm), medium heat (1.22kj/mm) and high heat (2.25kj/mm) was used to weld the specimen by using flux cored arc welding (FCAW) process. He found out that the micro-structural formation at CGHAZ consists of grain boundary ferrite (GBF), widmanstatten ferrite (WF) and Pearlite (P). Significant grain coarsening was observed at the CGHAZ of all the joints and he found out that the extent of grain coarsening at CGHAZ increased along with heat input. The results of the mechanical investigation showed that the joints made by using low heat input exhibit higher hardness and impact toughness value than those welded with medium and high heat inputs. He concluded that higher heat input causes the expansion towards the microstructure grain size, but will lead to lower hardness and affect the toughness value.

Asibeluo and Emifoniye (2015) researched the effect of arc welding current on the mechanical properties of A36 carbon steel weld joints. His research focused on melting the A36 low carbon steel at about 1426-1470˚C with a range of current from 70A-120A. He conducted hardness, impact and micro-structural tests to determine the mechanical properties of the welded joint. He found out that increasing the current from 70A-120A caused a corresponding increase in the temperature of the welded joint which affected the microstructure of the weld and that the weld microstructure was controlled mainly by cooling cycle. The results of his investigations showed that at 70A (with low level of current) the time for solidification was less. The rapid cooling promoted smaller grains. At 120A, the time required for solidification increases and therefore cooling rate slows down which yielded coarse grains. He found out that at 120A, the grain size was coarse with a hardness and toughness value of 60BHN and 11 Joules respectively; which indicated reduced strength and hardness.

Mohammed et al (2013) investigated the mechanical and metallurgical properties of medium carbon steel using shielded metal arc welding process (SMAW) with reference to the weld metal, heat affected zone and parent metal. He found out that shielded metal arc welding of medium carbon steel increased the strength of the welded joint in particular the heat affected zone (HAZ), as revealed by lower impact strength, higher tensile strength and hardness values as compared with the parent and weld metal which he attributed to be because of the fine ferrite matrix and fine pearlite distribution as compared to the weld and parent metal. However, he found out that there was loss of ductility at the welded joint resulting to brittleness of the material.

Oluwasegun et al (2016) evaluated the effects of welding current on the mechanical properties of welded joints between mild steel and low carbon steel. His test specimens were cut, machined and subjected to tensile test, impact toughness test, hardness test and their mechanical properties determined. He found out that as the welding current increases, hardness of the weld increases for the two samples up to 115A and 116A for both mild steel and low carbon steel but shows a decrease with a further increase in welding current. He further stated that the ultimate tensile strength, the yield strength and impact strength decreases with an increase in welding current.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Material

The materials used for this research work is hot rolled ribbed medium carbon steel rod of 16mm diameter and 1m long obtained from Universal Steel Rolling Mill, Ogba-Ikeja, Lagos; Nigeria and the chemical composition of the steel analysis was determined at the same company using the mass analyzer (Chemical composition as shown in Table 4.1). The equipments used for this research work are: mass analyzer, lathe machine, vice, hack saw, variosfabrieken Groningen shielded metal arc welding machine, a low hydrogen electrode having a rating E6013 and a composition of 0.12%C, 0.1%Si and 0.45%Mn. The electrode is coated with titanium-potassium materials which can be operated in all positions. It has a diameter of 3.2 mm and a length of 350 mm which has an advantage of deep penetration and also angle grinding machine, wire brush, file, silicon carbide paper, motor driven polishing machine, enchant chemical, metallurgical microscope with in-built camera, scanning electron microscope, LECO micro-hardness tester, tensile machine and charpy impact testing machine were all used in this project.

3.2 Methods

3.2.1 Sample Preparation

The 16mm ripped medium carbon steels rod was turned (using lathe machines) to 13mm diameter and the welding samples were sectioned using a hacksaw into twelve (12) pieces, three (3) pieces each served as control sample for both the mechanical and micro-structural properties and were un-welded and the other nine (9) were welded. Three (3) of which measured 100mm in length, 80mm gauge length, 6mm diameter for tensile test, three (3) measured 50mm for hardness test and the other three measured 60mm for impact test. The edge that were prepared for the weld geometry is single ‘’V’’ groove butt weld each beveled around the edges with the aid of a grinding machine to an angle of 30˚ to the horizontal. The beveled faces were cleaned properly and smoothened to ensure sound weld. Heat generated was minimized to avoid changes in the microstructure of the specimens and surface uniformity was ensured when using lathe machine. The specimens were machined carefully to the required dimensions for tensile, impact and hardness test analysis.

3.2.2 Welding Process

The welding process used is SMAW with E6013- low hydrogen electrode and with the following welding parameters: Welding currents at 100A, dual welding current of 100A and 125A, and current of 125A respectively, welding voltage of 40V each, a welding speeds of 2.5mm/sec and electrode diameter of 3.2mm. The faces of two pieces of the beveled rods were placed 5mm apart from each other, and welding machine was appropriately set with proper amperage and voltage. The electrode was placed in the holder and the welding machine was turned on. The assembly was tack-welded to ensure alignment and an arc was struck. A single bead was made to ensure uniform fusion of the rods. The weld was de-slagged, cleaned and welded again. The finished bead was spread round the joint to ensure proper weld. After the final welding process, the specimen was allowed to cool on the floor and subsequently a chipping hammer was used to remove the hard slag from the surface of the welds and the specimens were allowed to cool before further investigations were carried out. An analysis of the weldments of medium carbon steel was carried out to determine some mechanical and micro-structural properties with reference to the parent metal, HAZ, and the weld metal as shown in Figure 4.1-4.3 and Plate 4.2-4.11. An alternating current supply is used in filling completely the V-Notch samples which maintains an arc gap of 3mm in between. The welding was carried out at the department of Metallurgical and Materials Engineering Laboratory, University of Nigeria Nsukka (UNN). In accordance with this fundamental fact, three different heat input combinations corresponding to different welding currents were selected for this study, i.e. 100A (low heat input), 112.5A (medium heat input), 125A (high heat input). The reasons for using these specific welding current values are two-fold:

i. Firstly; this spectrum of heat input combinations results in arc energies which are sufficient to cause adequate fusion of the base and weld metal selected for the present study
ii. Secondly; a step increase of 25A was anticipated to be sufficient enough to cause a direct and significant influence on the microstructure and mechanical properties of the welded joint.

The heat inputs were calculated according to the formula as stated in equation 2.1 of literature review.

Table 3.1 Welding process parameters

Heat Type	Voltage (V)	Current (A)	Electrode Gauges (mm)	Welding Speed (mm/sc)	Heat Input (KJ/mm)
Low heat	40	100	3.2	2.5	72
Medium heat	40	112.5	3.2	2.5	81
High heat	40	125	3.2	2.5	90

The samples were clamped firmly on the vice to prevent movement during welding. The completely filled welded joints were thereafter ground with grinding machine in order to level off and clean the weld with the base metal to standard dimension. During and after welding the joints were visually inspected for their quality and it was ensured that all weld beads possessed good geometrical consistency and were free from visible defects like surface porosity, blow holes.

3.2.3 Temperature Measurement Technique

Thermocouple was used to measure the temperature variation across the weld regions. The K-type thermocouple with range of temperature of -200 ˚C to +1350 ˚C was used. The thermocouple was placed at different zones of the weld; immediately after filling the V-notched grove. One at the fusion zone, the others at the heat affected zone and the unaffected base metal and the temperature readings were taken at interval of five seconds until a fairly constant temperature was obtained. Before measuring the temperature of the weld, the initial temperature reading of the thermocouple was noted and recorded.

3.2.4 Micro-structural Examination

The micro-structural examination was carried out as follows: grinding, polishing, etching and microscopic viewing at the department of Metallurgical and Materials Engineering, Enugu State University of Science and Technology.

a. Grinding

Silicon carbide paper was used. Samples for micro-structural examination were ground using a set of abrasive papers rubbed to and fro on the strips. Starting with the roughest cloth (240 grit), and rub until all traces of saw cuts are removed. The specimens were turned through 90° and rubbed on the next (finer) paper (320 grit) until the previous scratches were removed. Next ground on (400 grit) and then on the final one (600 grit) each time turning through 90°.

b. Mechanical Polishing

This was done in two stages, with a coarse and a fine abrasive or polishing agent respectively. The specimen was held against horizontal rotating wheel and polished on a rotating disc of a synthetic velvet polishing cloth impregnated with micron alumina paste and finally polished with diamond paste.

c. Etching

The specimens were then etched with 5ml nitric acid (Nital) and 95ml alcohol by submerging or swabbing with this chemical reagent that removes the surface layer produced on polishing and attacks preferentially grain boundaries and second phase precipitates. The acid is always added to the alcohol and not vice versa. The carbide will show darkened surface.

c. Microscopic Viewing

The samples were illuminated by a reflected light which was mounted on the microscope; the specimens were viewed with an optical microscope through the eyepiece of the microscope so as to determine the microstructure which was subsequently snapped by the attached camera to obtain the micrograph. This was viewed at a magnification of X200. The results are presented in Plate 4.1- 4.7.

3.3 Mechanical Properties

a. Hardness Test

Hardness values of the specimens were determined using LECO micro-hardness tester with a load of 150 kilos and a dwell time of 10secs. Multiple hardness tests were performed on each sample and the average of the best values taken as a measure of the specimen. The LECO micro-hardness tester calculates the hardness values in Rockwell Hardness Number (HRC). This test was carried out at mechanical engineering department, University of Nigeria Nsukka, Enugu, Enugu State Nigeria. The hardness tests for the specimens were evaluated at three points:

- The weld pool region
- The heat affected zone (HAZ)
- The unaffected base metal.

The results are presented in Table 4.4 and in Figure4.1

b. Tensile Test

The tensile tests were conducted on the samples at room temperature using Instron Electromagnetic Testing Machine of ISO 6892 standard at the load of 200KN. The ends of the specimens were gripped in the machine and load was applied until failure occurred. The tensile test specimen has the following dimensions: Length = 100mm, Gauge length = 80mm, Diameter = 6mm, Width of the grip section = 10mm, radius = 10mm. The results are presented in Table 4.5 – 4.9 and Figure 4.2

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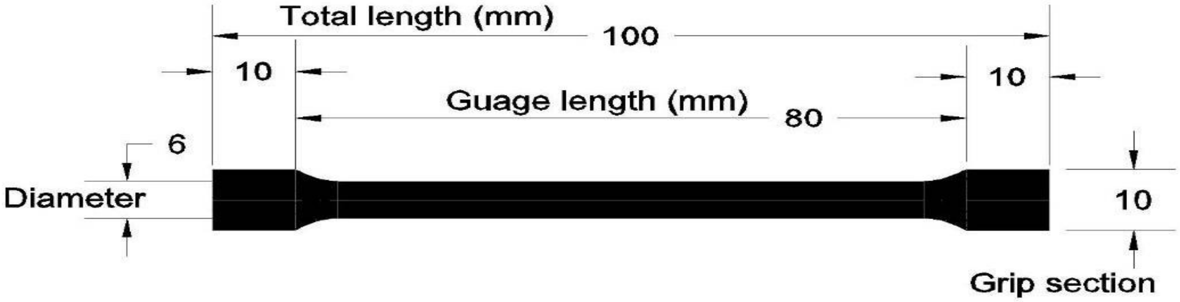

Figure. 3.1 Tensile Test Specimen

c. Impact Test

The impact tests were conducted on the samples at room temperatures using impact testing machine at the department of mechanical engineering workshop, University of Benin. V-notch bevel was made on each of the test samples using an angle grinding machine. The samples were placed horizontally as a simply supported beam between two anvils 40 mm apart in such a way that the striking hammer strikes the specimen on the face which is opposite to the notched. The striking hammer or pendulum was made to fall freely. As the pendulum hits the samples, it destroyed the samples from V-notch. The force applied by the pendulum was calculated by the charpy impact tested and displayed on the LED screen. The results are presented in Table 4.10 and Figure 4.3.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

Table 4.1 Chemical analysis of the steel

Elements	**Compositions (wt %)**
C	0.4155
Si	0.2895
Mn	0.9095
S	0.1130
P	0.0470
Cr	0.1570
Ni	0.1070
Cu	0.3150
Nb	0.0001
Al	0.0085
B	0.0020
W	0.0001
Mo	0.0001
V	0.0001
Ti	0.0075
Fe	97.6285

Table 4.2 Chemical analysis of mild steel electrode

Element	**Compositions (wt %)**
C	0.24
Si	0.19
Mn	0.30
S	0.044
P	0.042
Ni	0.13
Ti	0.015
V	0.006
Nb	0.002
Cr	0.005

Table 4.3 Mechanical properties of as-received steel

PROPERTY	
Yield Strength (Mpa)	515.20
Tensile Strength (Mpa)	550.4
Hardness (HRC)	185.2

Table 4.4 Micro-Hardness Variation at Different Weld Regions

Weld Region	**Low Heat Input 100 A**	**Medium Heat Input 112.5A**	**High Heat Input 125A**
Weld Pool	145.5	132.5	125.5
HAZ	179.5	153.5	137.9
Base Metal	113.5	113.5	113.5

Table 4.5Stress and Strain Values for Control Sample Specimen of Tensile Test

Stress (Mpa)	Strain
0.00	0.00
256.54	0.008
348.41	0.0185
454.20	0.0345
509.22	0.0451
515.20	0.062
539.30	0.0785
550.40	0.14
550.40	0.1245
550.40	0.1345
521.20	0.1435

Table 4.6 Tensile Test Values at High Heat Input (125A)

Stress (Mpa)	Strain
0.00	0.00
7.07	0.0025
60.07	0.0125
120.14	0.025
204.95	0.035
275.62	0.045
325.09	0.055
378.09	0.07
388.69	0.0875
353.36	0.1075

Table 4.7 Tensile Test Values at Medium Heat Input (112.5A)

Stress (Mpa)	**Strain**
0.00	0.00
77.74	0.005
141.34	0.0175
212.01	0.0325
282.69	0.045
353.83	0.0625
402.83	0.085
431.10	0.11
431.10	0.13
402.83	0.14

Table 4.8 Tensile Test Values at Low Heat Input (100A)

Stress (Mpa)	Strain
0.00	0.00
56.54	0.0075
148.41	0.0175
254.42	0.0325
339.22	0.045
424.03	0.06
494.70	0.0775
515.90	0.1
515.90	0.1175
515.90	0.1325
480.57	0.1425

Table 4.9 Summary of Overall Tensile Test Results

Heat Input	Yield Strength (Mpa)	Ultimate Tensile Strength (UTS) (Mpa)
Low	424.03	515.90
Medium	353.36	431.10
High	275.62	388.69

Table 4.10 Impact Test at Different Heat Variations

Impact Conditions	Impact Values Joules (J)
Control	8
Low Heat Inputs (A)	6.5
Medium Heat Input (A)	6.2
High Heat Input (A)	6

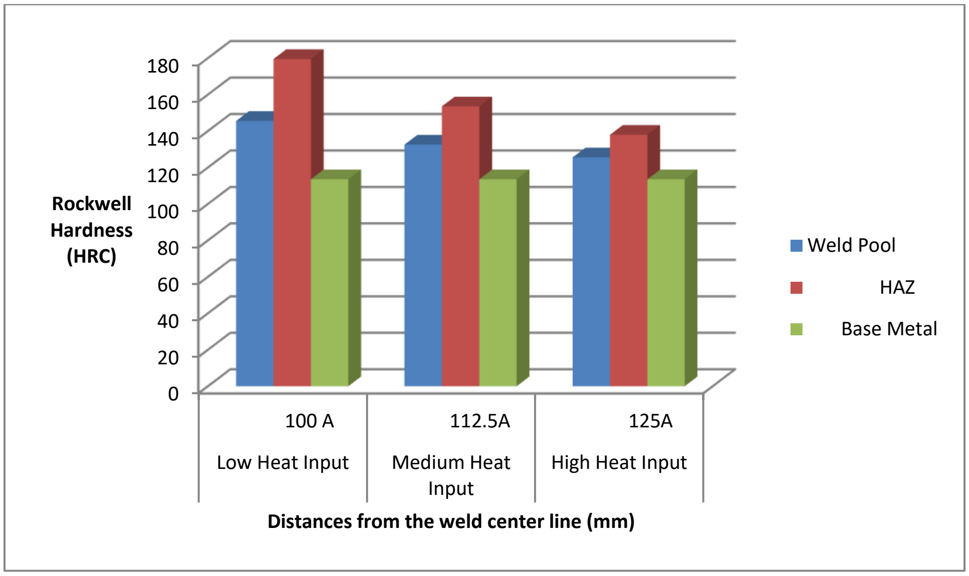

Figure 4.1 Micro-hardness Results at different zones of the weldments with different heat inputs

The hardness test result shows that increase in heat inputs; results in decrease in hardness value

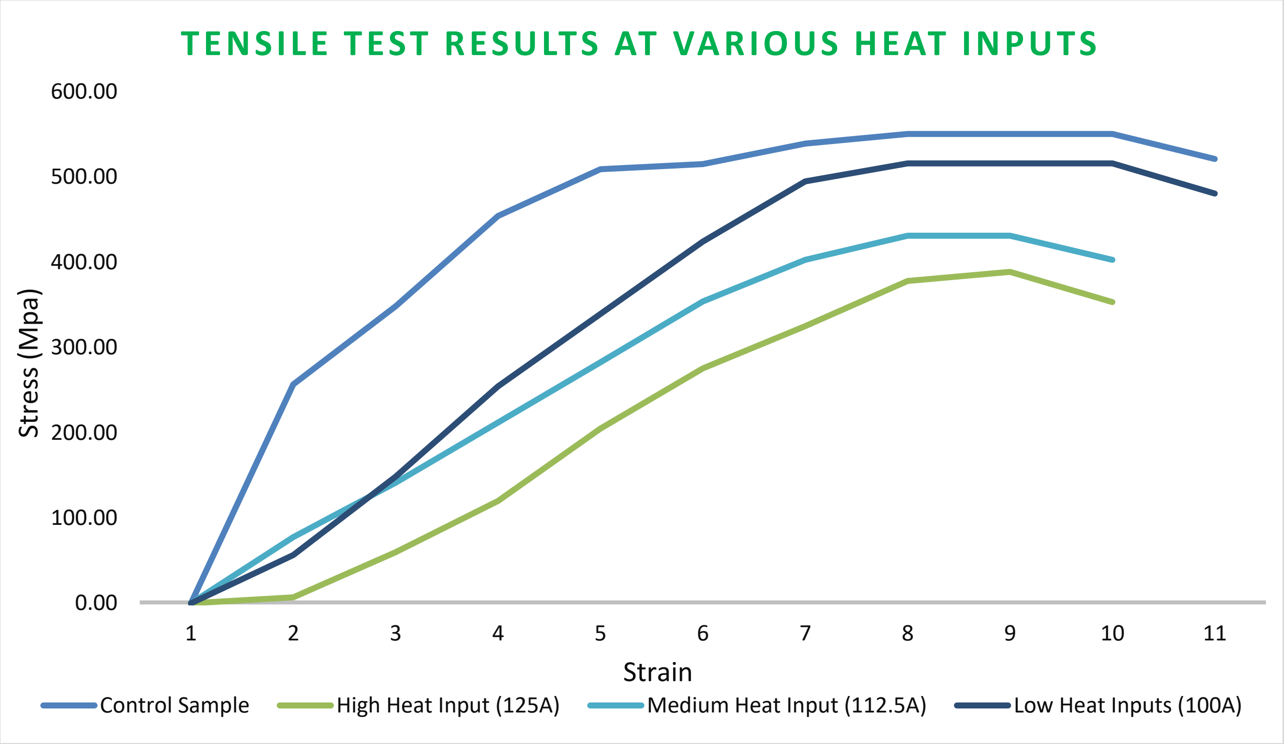

Figure 4.2 Tensile Test Results of the Samples

The higher the heat inputs, the lower the tensile strength, i.e. the tensile strengths are proportionally decreasing with an increase in heat input.

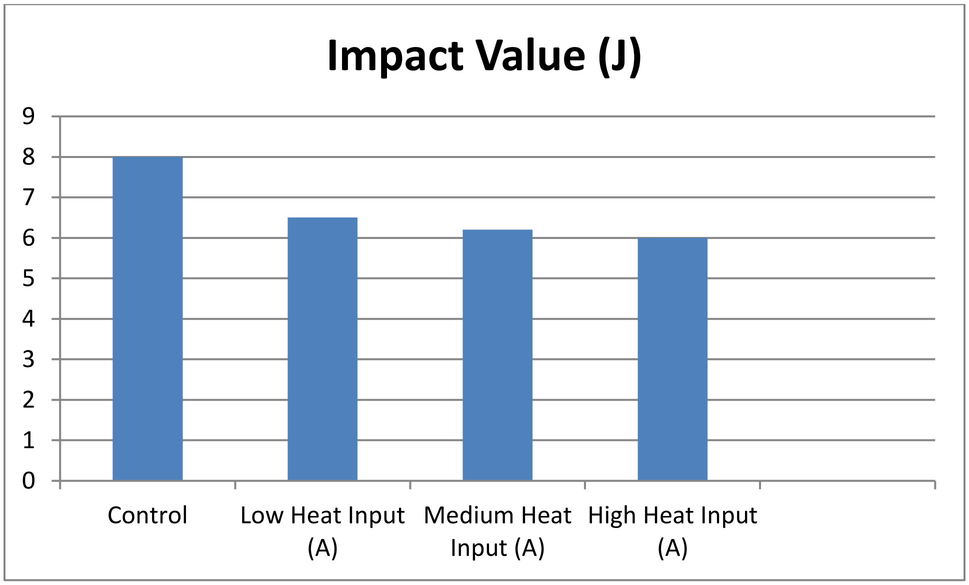

Figure 4.3 Impact Test Results at Different Heat Inputs

The higher the heat inputs, the lower the impact toughness value, i.e. the impact toughness values are proportionally decreasing with an increase in heat input.

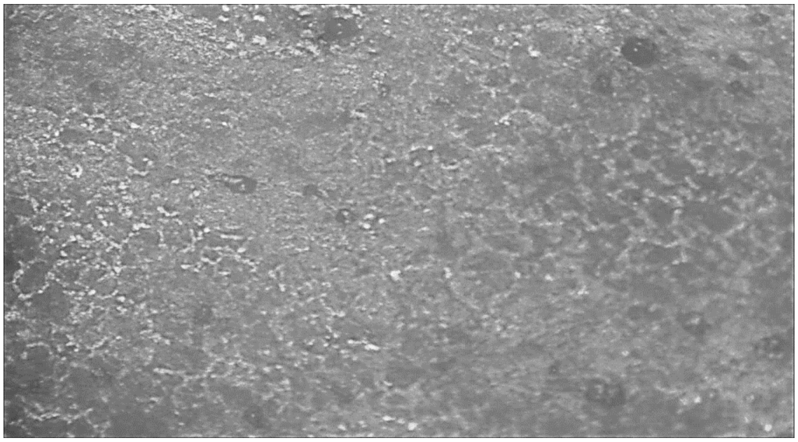

Plate 4.1 Micrograph of Control Steel Specimen at 200X

Here there are evenly distributed fine grain ferrite (white), pearlite and Fe_3C (black).

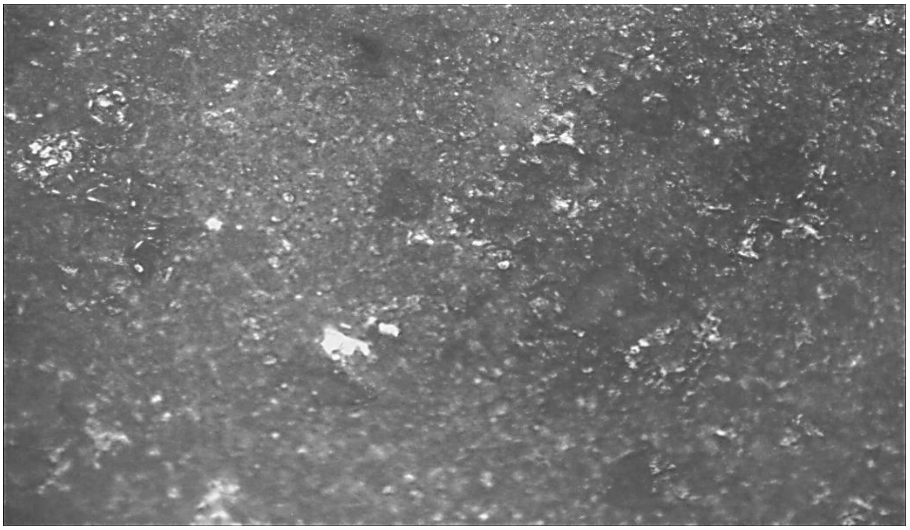

Plate 4.2aMicrograph of Tensile Test Specimen of HAZ for Low Heat Input (100A) at 200X

Here, there is slight increase in grains when compared with the control specimen as a result of applied heat.

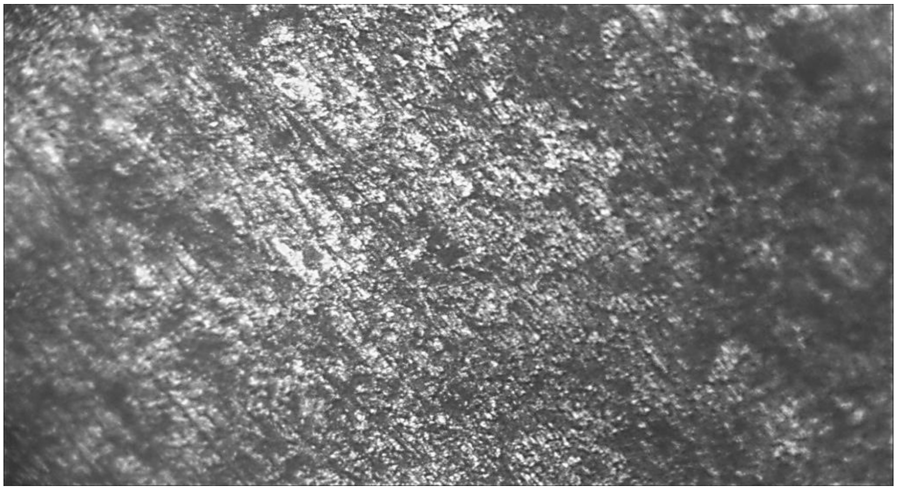

Plate 4.2b Micrograph of Tensile Test Specimen of WM (FZ) for Low Heat Input (100A) at 200X

Here the ferrite (white) grains increases as a result of the effect of welding consumables with relatively pearlite increase and sparsely distributed Fe_3C (black).

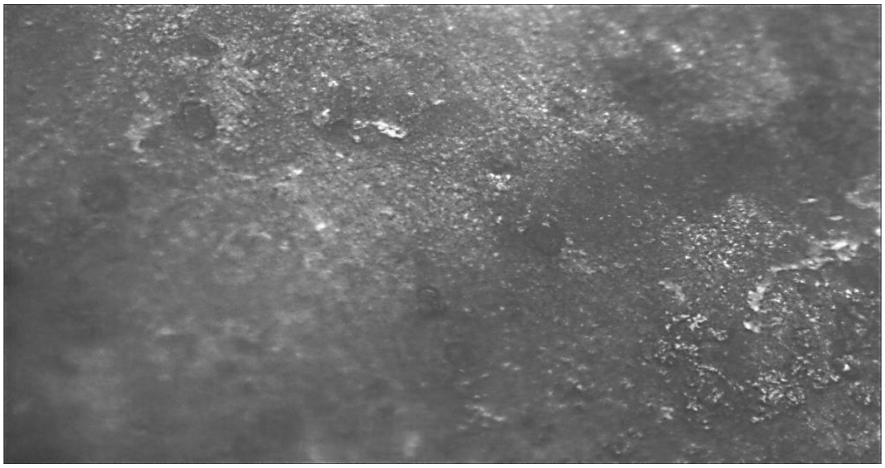

Plate 4.2c Micrograph of Tensile Test Specimen of BM for Low Heat Input (100A) at 200X

Here, there is an insignificant growth in the grain sizes due to low heat intensive application.

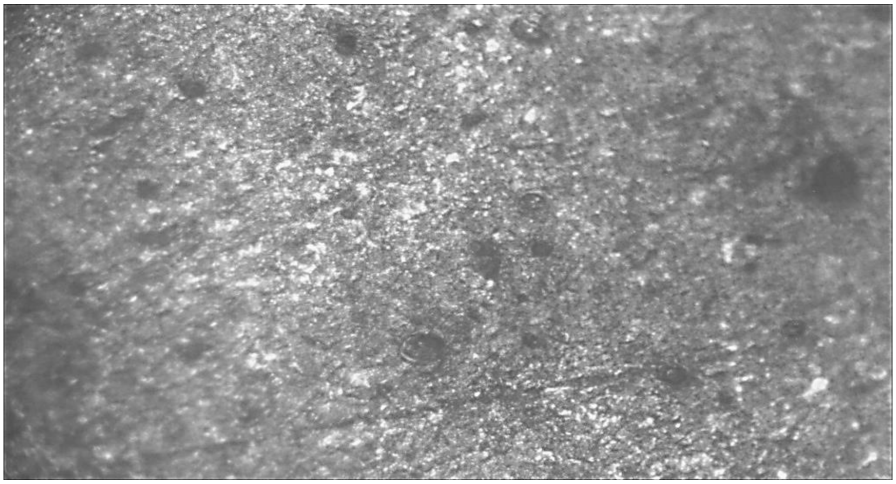

Plate 4.3a Micrograph of Tensile Test Specimen of HAZ for Medium Heat Input (112.5A) at 200X

Increase in ferrite (white) grains with evenly distributed pearlite and Fe_3C (black) grains.

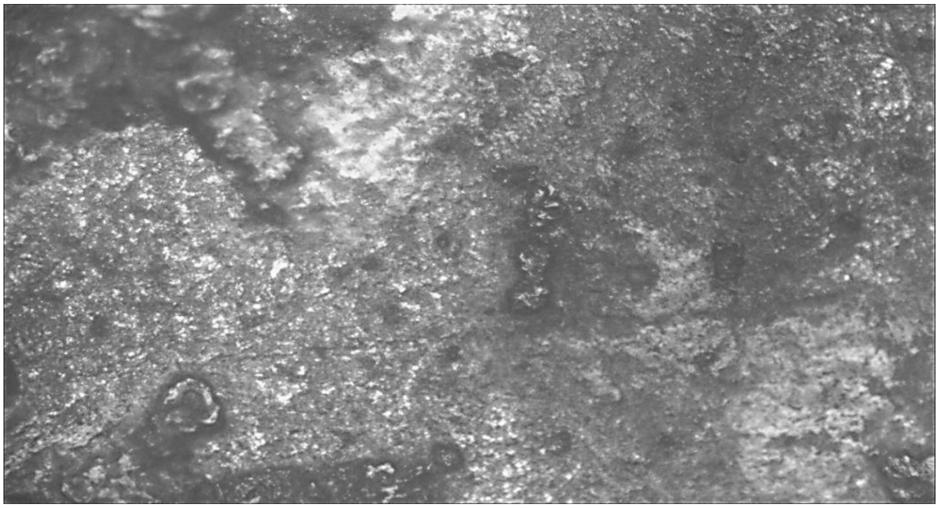

Plate 4.3b Micrograph of Tensile Test Specimen of WM (FZ) for Medium Heat Input (112.5A) at 200X

Coarse grain ferrite (white) with pearlite and Fe_3C (black); with some traces of inclusions due to combination of welding consumable and weld defects.

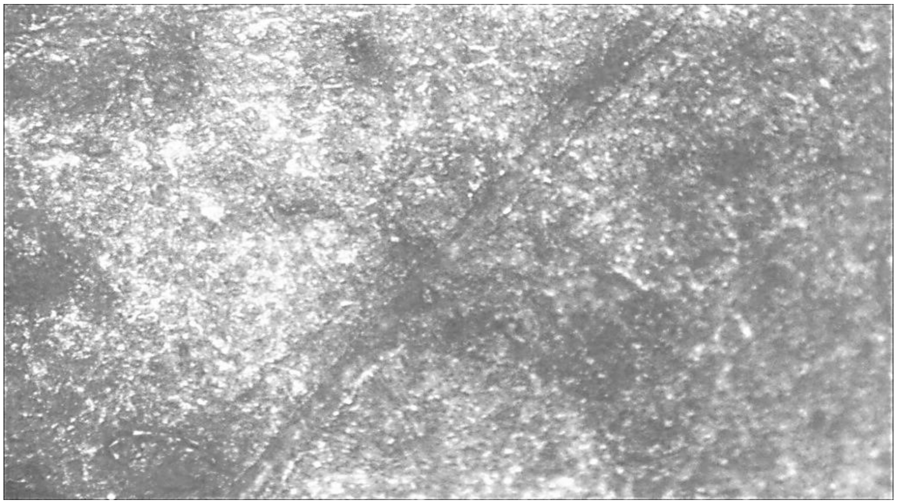

Plate 4.3c Micrograph of Tensile Test Specimen of BM for Medium Heat Input (112.5A) at 200X

Here, the ferrite (white) grain increases around the area closer to the HAZ and decreases as it moves away from the HAZ, while the pearlite grains are predominant with few grains of Fe_3C (black).

Plate 4.4a Micrograph of Tensile Test Specimen of HAZ for High Heat Input (125A) at 200X

Here, the ferrite (white) has highest coarse grain structure with pearlite and Fe_3C (black) grains present as well.

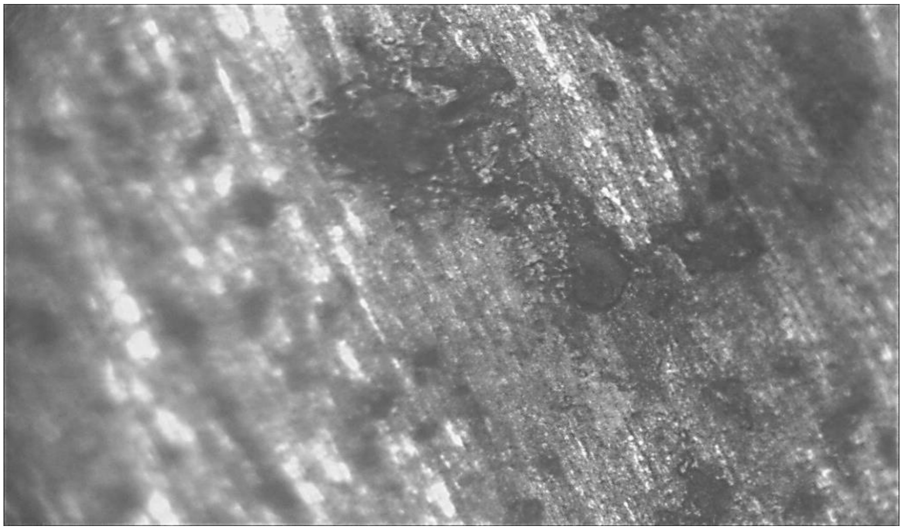

Plate 4.4b Micrograph of Tensile Test Specimen of WM (FZ) for High Heat Input (125A) at 200X

High coarse grain ferrite (white) with evenly distributed pearlite and Fe_3C (black) grains.

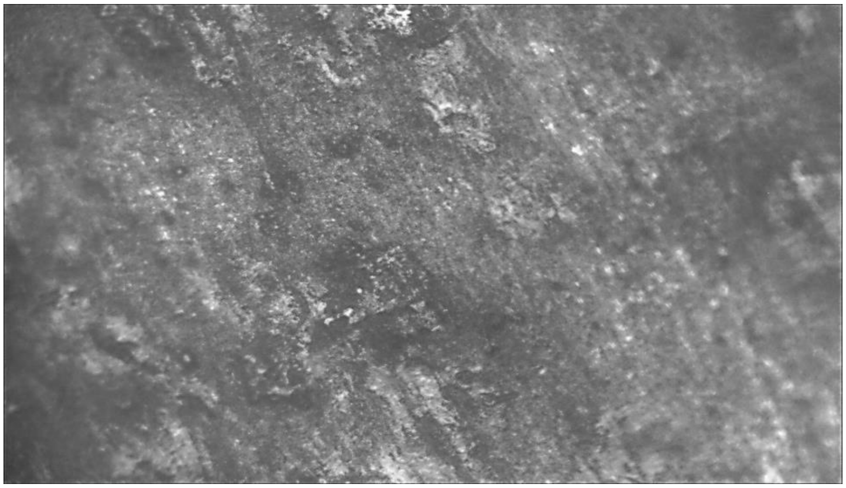

Plate 4.4c Micrograph of Tensile Test Specimen of BM for High Heat Input (125A) at 200X

The grains are evenly distributed; ferrite (white), pearlite and Fe_3C (black).

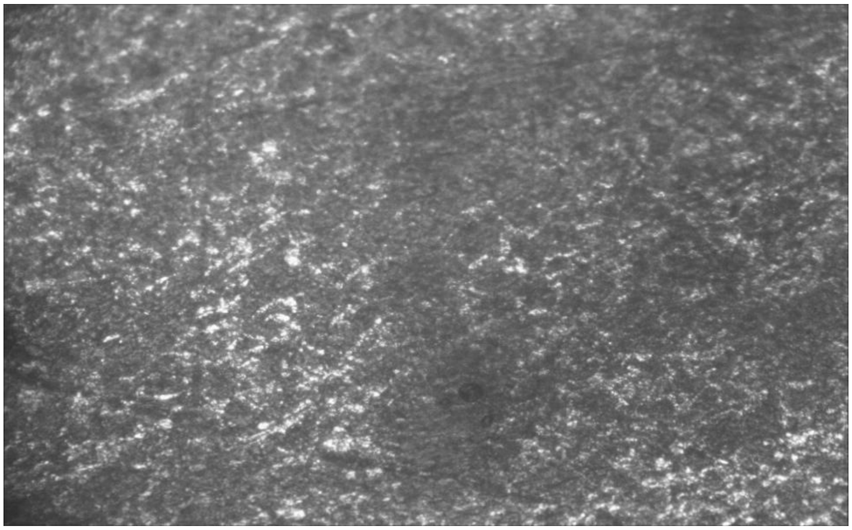

Plate 4.5a Micrograph of Hardness Test Samples of HAZ for Low Heat Input (100A) at 200X

Shows fine pearlite dispersed within the ferrite matrix.

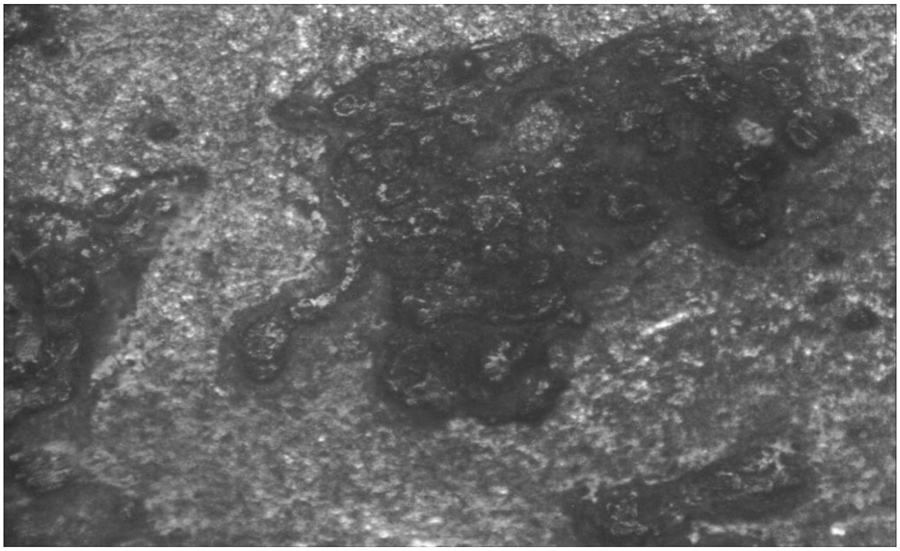

Plate 4.5b Micrograph of Hardness Test Specimen of WM (FZ) for Low Heat Input (100A) at 200X

The grains are evenly distributed, ferrite (white), pearlite and some colony of Fe_3C (black) grains.

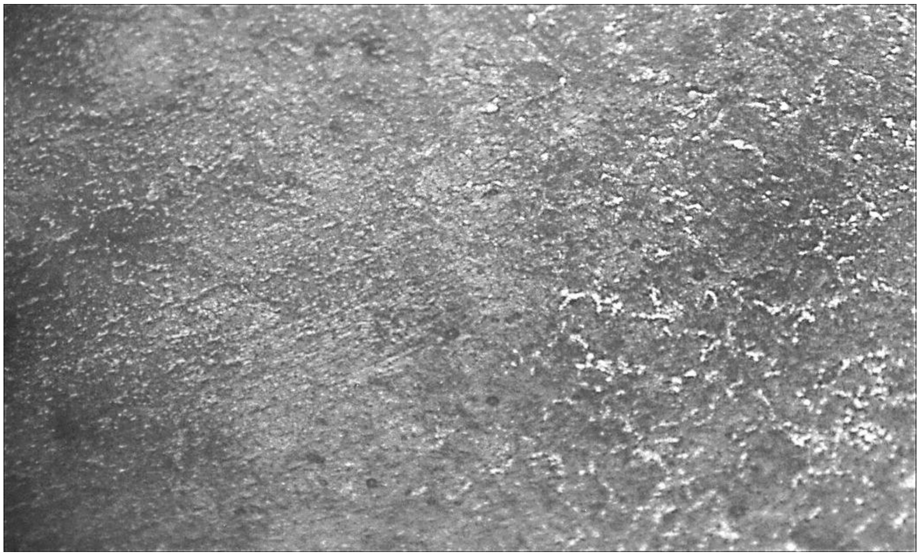

Plate 4.5c Micrograph of Hardness Test Specimen of BM for Low Heat Input (100A) at 200X

Evenly distribution of all the grains present; ferrite (white) pearlite (brown) and Fe_3C (black)

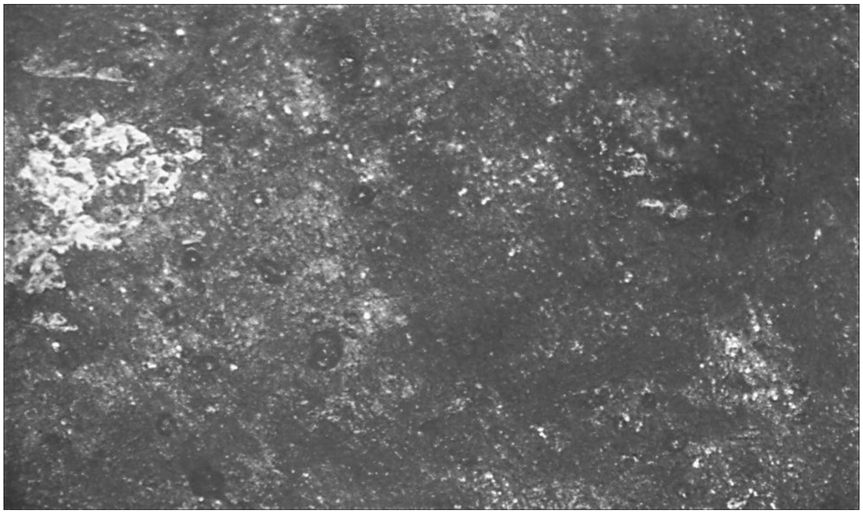

Plate 4.6a Micrograph of Hardness Test Specimen of HAZ for Medium Heat Input (112.5A) at 200X

Here, the ferrite (white) grain grows as result of heat input with evenly distributed pearlite grains and precipitation of Fe_3C (black).

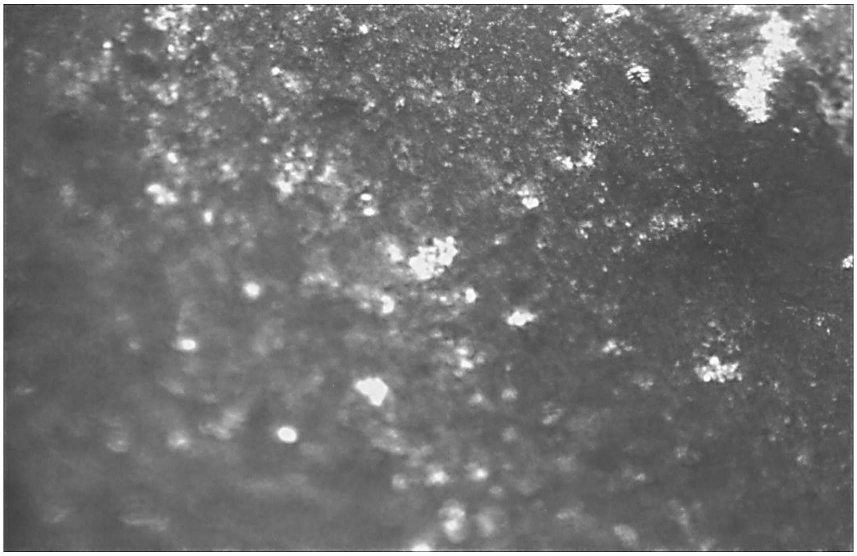

Plate 4.6b Micrograph of Hardness Test Specimen of WM (FZ) for Medium Heat Input (112.5A) at 200X

At this zone appears coarse grain ferrite (white), with fine grain pearlite and precipitate of Fe_3C (black).

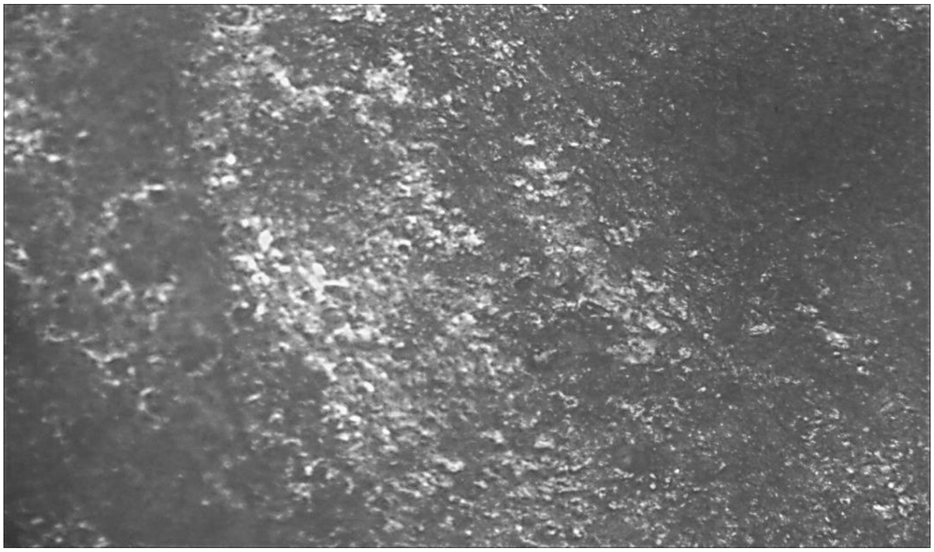

Plate 4.6c Micrograph of Hardness Test on BM for Medium Heat Input (112.5A) at 200X

This is the zone of evenly distributed ferrite (white), pearlite and Fe_3C (black).

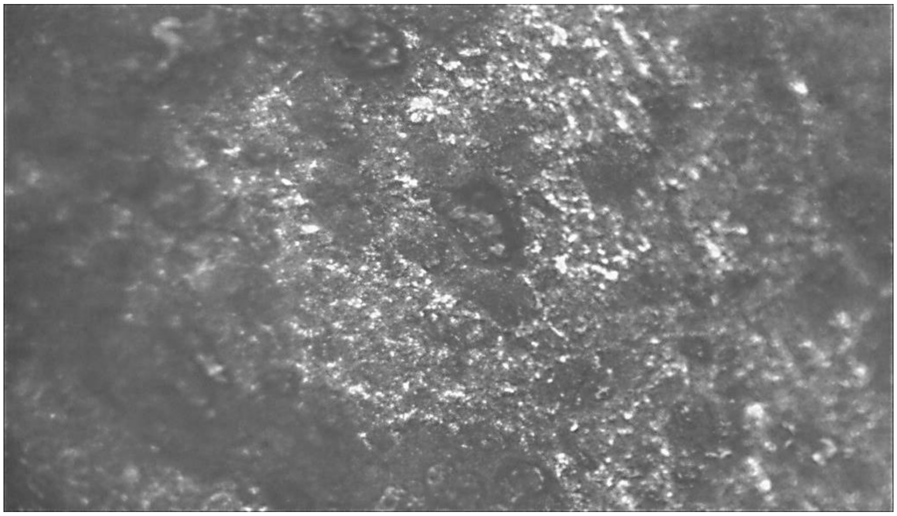

Plate 4.7a Micrograph of Hardness Test Specimen on HAZ for High Heat Input (125A) at 200X

Here, the ferrite (white) grains increases with evenly distribution of pearlite and precipitation of Fe_3C (black).

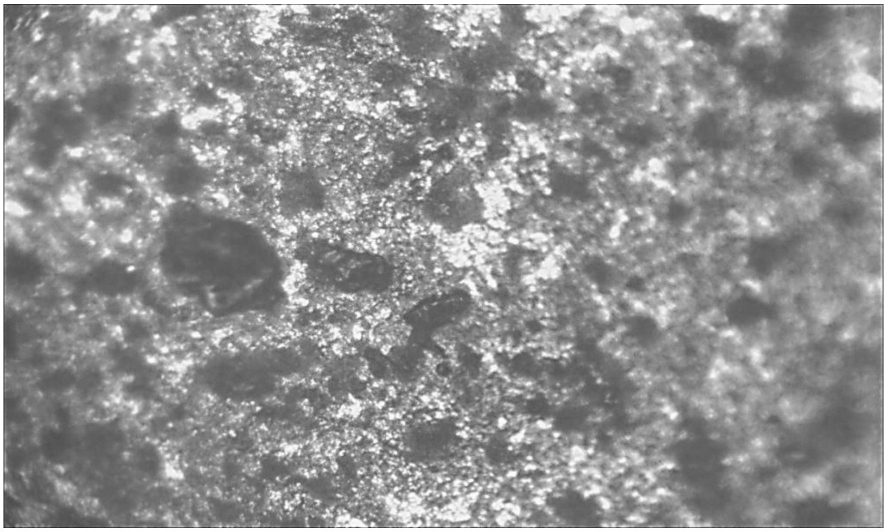

Plate 4.7b Micrograph of Hardness Test Specimen on WM (FZ) for High Heat Input (125A) at 200X

Here, the micrograph shows coarse grain ferrite and pearlite and some colony of Fe_3C.

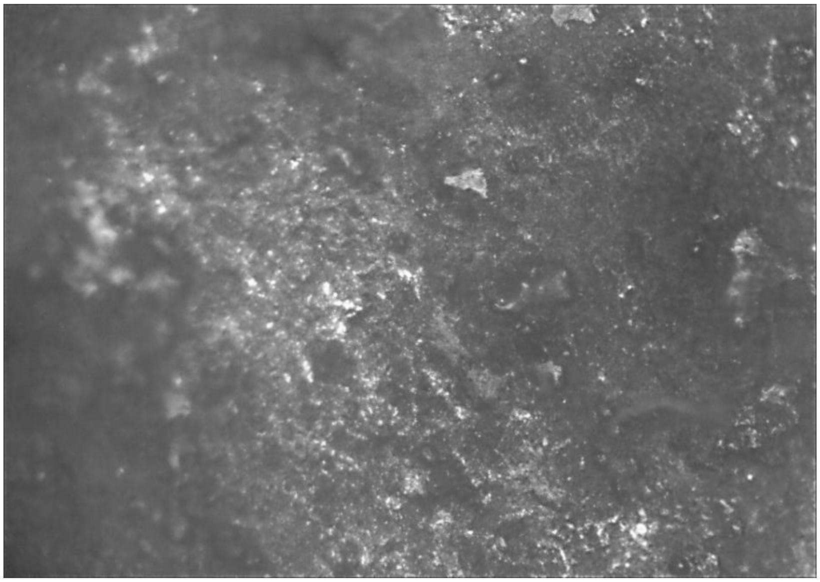

Plate 4.7c Micrograph of Hardness Test Specimen on BM for High Heat Input (125A) at 200X

The micrograph shows sparsely distributed fine ferrite, pearlite grains and precipitation of Fe_3C in ferrite matrix.

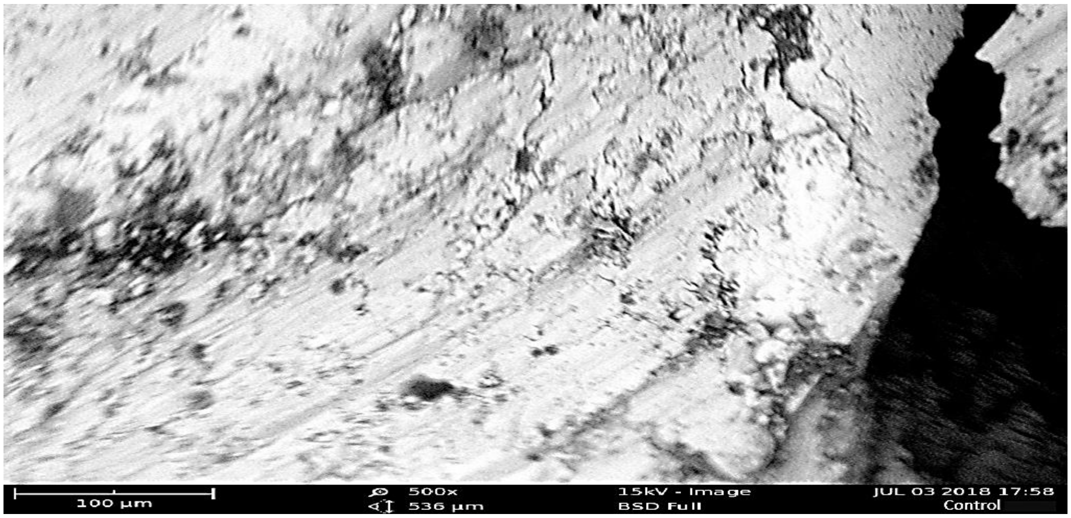

Plate 4.8 Fracture Surface of Control Specimen at 500X Magnification

A scanning electron micrograph of control specimen showing dimples of varying sizes and shapes observed in the fractured surface. It is observed that fractured surface of the control specimen contains a large population of small and shallow dimples which is indicative of its relatively high tensile strength and ductility.

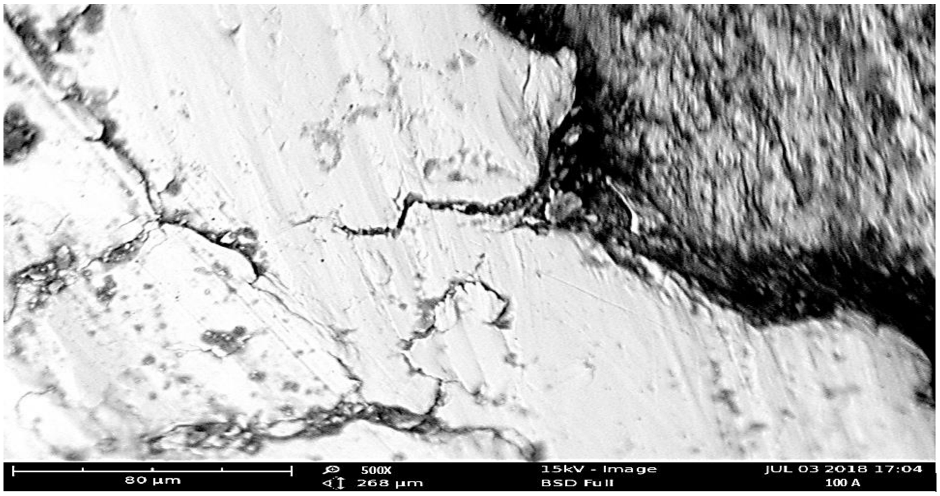

Plate 4.9 Fracture Surface of the Test Specimen of Low Heat Input at 500X Magnifications

Scanning electron micrograph of low heat inputs specimen appearing ductile under static loading and shows dull and irregular appearance structure produced by stretching of crystals given a number of tear ridges and dimples. It also shows a classic mechanism of ductile fracture known as microvoid coalescence. The rough fracture surface indicates that a large amount of energy was absorbed during fracture.

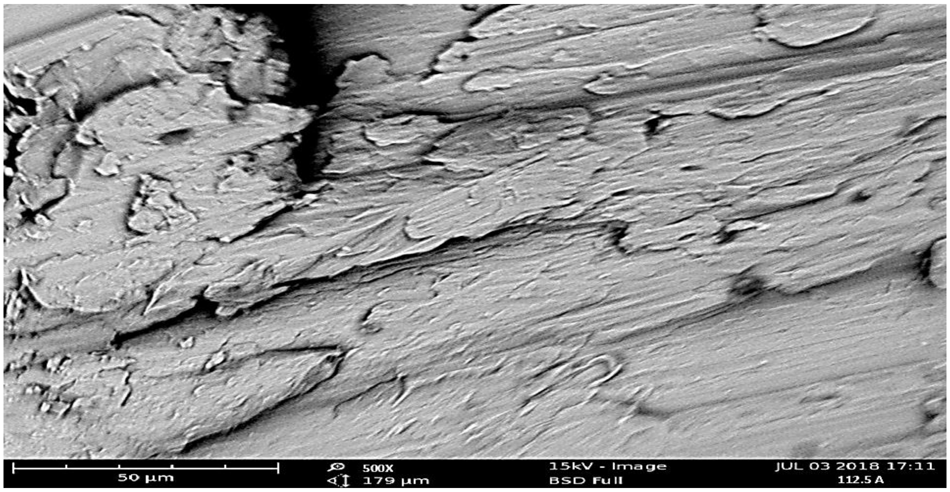

Plate 4.10 Fracture Surface of Test Specimen of Medium Heat Inputs at 500X Magnifications

Scanning electron micrograph of medium heat inputs specimen of mixed ductile/brittle fracture surface showing microvoids coalescence with some tear ridges and river pattern markings visible, which points to the origin of failure.

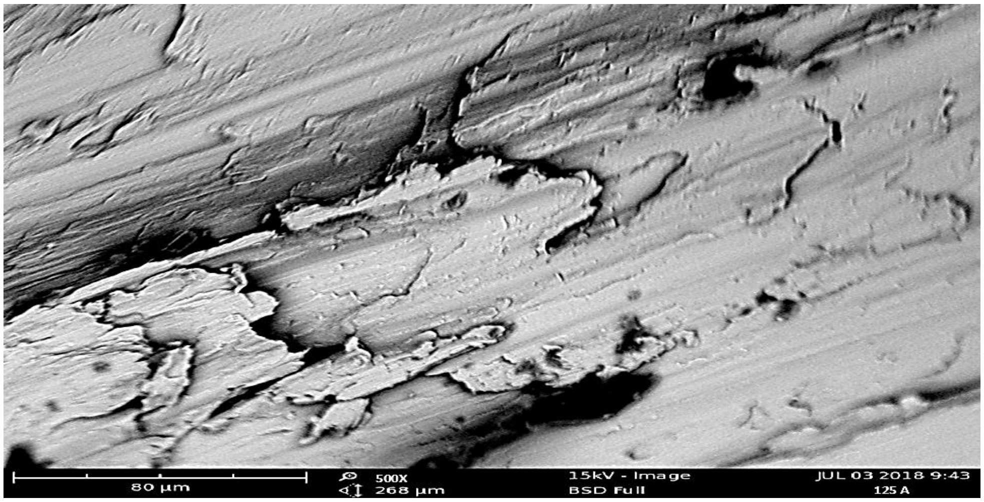

Plate 4.11 Fracture Surface of Test Specimen of High Heat Inputs at 500X Magnifications

Shows fully brittle crystalline fracture broken with high heat input, trans-granular form of fracture of quasi-cleavage along the crystal planes , inter-granular occuring along the grain boundaries and a river pattern of branching cracks. This indicates brittle fracture and that failure occurred with lower plastic deformation as compared with the control sample and lower heat inputs.

4.2 Discussion

Having investigated the work, the following observations were made.

4.2.1 Effect of Electric Arc Power Inputs on the Mechanical Properties of 0.4%C Steel

In Figure 4.1 depicts the hardness profile for the test samples at different welding parameters. It can be seen that there is a hardness variation across the weldment. The variation is due to welding thermal cycle; the un-molten material reaches a maximum temperature, which depends on the distance from the fusion boundary and hence different microstructure are formed after cooling. The result is in agreement with the findings (Abioye, 2017) which states that, variation across the weldment leads to property deterioration during service applications. From Figure 4.1, it is observed that as the indentor travels from the center of the weld/fusion zone towards the fusion boundary for different samples, the hardness properties decreases as the power inputs increases, this is supported by (Oluwasegun et al, 2016) who observed that increasing heat inputs results in decrease in hardness properties. The fusion zone has the hardness (145.5 HRC) at low heat input, decreases to (132.5 HRC) for medium heat input and (125.5 HRC) for high heat input. The heat affected zone has the highest hardness (179.5 HRC) for low heat inputs then decreases to (153.5 HRC) for medium heat inputs and (137.9 HRC) for high heat input. The base metal has approximately hardness value (113.5 HRC) across all the heat inputs. The area adjoining the base metal undergoes rapid cooling rate due to steeper thermal gradients and consequently has fine grained microstructure encountered in welding operation. This highest hardness is also attributed to the effectiveness of interstitial carbon atoms in hindering dislocation movement (as a solid-solution effect) and too relatively few slip systems along which dislocations moves as observed by (Apurv and Jatti, 2007). This renders the weldment susceptible to cracking. With increased current, the heat generated increases causing the grains to recrystallized and grow in size. Increased in grain size, reduces the hardness value (strength) of the weldment and the heat affected zone as observed by (Bodude and Momoh, 2015) and shown in Figure 4.2. The heat persisted for a period of time and is gradually conducted away into the base metal as a result of low power density (the rate of energy flow (power) per unit volume, area or mass) of the welding process as reported by (Callister, 2007). The amount of heat input from the heat source is given as stated in chapter of the literature review. This show that as the current increases more heat is produced into the weld causing expansion and contraction between the weldment and base metal. These increases the residual stresses in the weldment and heat affected zone which affects the engineering properties of the materials resulting in reduction of strength and hardness of weldment and the heat affected zone as shown from Plate 4.5-4.7 for hardness microstructure. This is in agreement with the findings of (Bodude and Momoh, 2015) who stated that the hardness strength of the weldment reduces with increase in heat input into the weld.

The transverse tensile strength of all the welded specimen made using different heat inputs conditions has been evaluated. In each condition, three specimens were tested and the tensile strength of the three specimens per unit heat inputs was obtained. The tensile results so obtained shows that maximum tensile strength of 179.5 Mpa is possessed by the specimen made using low heat input combination followed by 153.5 Mpa using medium heat input and 137.9 Mpa using high heat input combination. The tensile strength of the weldment was observed to be lower compared to as-received sample, this is as a result of thermal stresses stored in the weldment during the welding operation and it is in agreement with (Wan et al, 2015) who observed that the high tensile strength and good ductility is possessed by the joint at low heat input, which can be attributed to smaller dendrite sizes and lesser inter-dendritic spacing in the fusion zone. Relatively lower tensile strength and ductility is possessed by the joints with long dendrite sizes and large inter-dendritic spacing in the fusion zone of the joint welded using higher heat inputs. This is supported by (Bodude and Momoh, 2015) who noted that with increased current, the heat generated increased causing the grains to recrystallized and grow in size. Increase in grain size decreases the tensile strength whereas decrease in grain size increases the tensile strength. Figure 4.2 show that the tensile strengths of medium carbon steel used decreases with increase in welding parameters (welding current, voltage, and welding speed). It is shown that during low heat input condition, the grain size of the HAZ is small which varies when changes to higher heat input. During higher heat input, it was observed that carbide precipitates a lot along the grain boundaries leading to sensitized zone around grain boundaries which helps in grain coarsening of HAZ zone and significant grain coarsening was observed in the HAZ of all the joints and it was found that the extent of grain coarsening in the HAZ zone increased with increase in heat input. This is in agreement with (Abioye, 2017) who observed that this behavior was attributed to the fact that increased current meant an increase in heat input which could create room for defect formation, thus the observed reduced mechanical properties and they also established that service failure of arc welded joints is due to cracking in the HAZ and also that, the performance of the welded structure is usually limited by failure initiation within the HAZ of the base material, particularly within the coarse-grain region of HAZ adjacent to the weld metal as a result of increase in heat input.

The ability of a material to withstand an applied load is referred to as toughness. The transverse impact strength of all the welded specimen made using different heat inputs conditions has been evaluated. In these conditions, three specimens with control specimen were tested and the impact strength of the three specimens with the control specimen per unit heat inputs was obtained. It was observed that the impact toughness values are proportionally decreasing when heat inputs increases. This is in agreement with (Mohammed et al, 2013) who observed that this attributes is as a result of fine ferrite and pearlite matrixes distributions in low heat input when compared with coarse ferrite and pearlite matrixes distributions as heat input increases. From Figure 4.3, it was observed that the control specimen has the maximum impact toughness value of 8 Joules (J), Followed by the low heat input with impact toughness value of 6.5 Joules (J). At medium heat input and high heat input, the impact toughness values are 6.2Joules (J) and 6Joules (J) respectively. Therefore, low heat input has the best impact strength of 6.5 Joules (J) while the high heat input has the lowest impact strength of 6 Joules (J). These results showed that the increase in heat input coarsens the grain structure both in the weld metal and heat affected zone and is in agreement with (Asibeluo and Emifoniye, 2015) who noted that the notch toughness of the coarse grained HAZ decreases with an increase in energy input. They also found that stress relieving reduced the notch toughness of both the weld metal and HAZ as a result of embrittlement caused by carbide precipitation.

4.2.2 Effect of Electric Arc Power Inputs on the Microstructure of Welded 0.4%C Steel

The microstructures of the medium carbon steel were illustrated clearly in Plate 4.1-4.7, for the structures of as-received and as welded samples. The microstructures contain some colonies of pearlite which is represented by brown region; ferrite is represented by white region and cementite {iron carbide (Fe_3C)} represents the black region. The microstructure of as-received steel in Plate 4.1 contains fine ferrite and pearlite, while microstructure of as-welded samples varies across the weldment; and it was observed that a large amount of pearlite is present in the ferrite matrix. As depicted in Plate 4.2-4.7, as the current was increased, the pearlite become finely distributed within the coarse ferrite matrix with an increase in the proportion of the ferrite in pearlite, and with ranges of fine dispersion of iron carbide in a strained ferrite matrix in the weld and in the HAZ. The weld microstructure is controlled mainly by the cooling cycle. At lower energy input (i.e. with low level of current) the time for solidification is less. This rapid cooling promotes smaller grains that leads austenite to transform into martensite and form fine grain microstructure and as compared with higher energy input, the time required for solidification decreases and therefore cooling rate slows down which makes austenite to have enough time to transform to pearlite and yields coarse grain microstructure. This Coarse grain in the microstructure indicates lower hardness, tensile and impact strength. This is in agreement with (Abioye, 2017) who observed that this cooling rate which is a function of the heat input utilized determined the proportion of ferrite and pearlite formation in the microstructure of the weldments and that these in turn, influences the tensile, impact and hardness behavior of weldments. Conclusively, it can be stated low heat input produces fine microstructure and in turn improves the mechanical properties of the welded samples. However, increasing the heat input values causes' expansion towards the microstructure's grain sizes; which becomes coarse and decreases the mechanical properties which led to the loss of ductility at the welded joint, and resulted in brittleness of the material.

4.2.3 Effect of Electric Arc Power Inputs on the Fracture Surface of Welded 0.4%C Steel

The fracture surfaces of the welded medium carbon steel specimen are illustrated clearly in Plate 4.8- 4.11, for the structures of as-received and as welded samples. The fracture surfaces were evaluated by SEM. Plate 4.8 show a scanning electron micrograph of control specimen showing dimples of varying sizes and shapes observed in the fractured surface. It is observed that fractured surface of the control specimen contains a large population of small and shallow dimples which indicative of its relatively high tensile strength and ductility as is observed by (Wan et al, 2015). As seen in Plate 4.9 Scanning electron micrograph of low heat inputs specimen appearing ductile under static loading and shows dull, fibrous and irregular appearance structure produced by stretching of crystals given a number of tear ridges and dimples. It also shows a classic mechanism of ductile fracture known as microvoid coalescence. The rough fracture surface indicates that a large amount of energy was absorbed during fracture according to (Mohammed et al, 2013). Plate 4.10 show scanning electron micrograph of medium heat inputs specimen of mixed ductile/brittle fracture surface showing microvoids coalescence with some tear ridges and river pattern markings visible, which points to the origin of failure observed by (Wan et al, 2015). Plate 4.11 Show fully brittle crystalline fracture broken with high heat input, trans-granular form of fracture of quasi-cleavage along the crystal planes , inter-granular structure occuring along the grain boundaries and a river pattern of branching cracks. This indicates brittle fracture and that failure occurred with lower plastic deformation as compared with the control sample and lower heat inputs according to (Mohammed et al, 2013).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study carried out was to investigate the effects of electric power arc inputs on the microstructure and mechanical properties of 0.4%C steel. Having investigated the work, the following conclusions were made:

i. The control sample (un-welded sample) has the highest toughness value of 8 Joules (J) and is the most ductile. This is because of the fine microstructure of the sample when compared with the microstructures of the welded samples at various heat inputs.

ii. Increasing the welding current from 100A-120A increases the welding heat inputs and results in an increase in temperature of the weld and led to the decrease of tensile, hardness and toughness properties of the material as a result of increased cooling time and gave rise to the rapid growth of the grain.

iii. The higher the heat input, the lower the hardness 137.9 HRC and tensile value 388.69 (Mpa). Retention of heat in the coarse grain HAZ zones contributed to this low value.

iv. The high heat input possessed lower impact toughness value of 6 Joules (J) and this decrease in toughness shows less ductility of the weldments when compared with low heat 6.5 Joules (J), medium heat 6.2 Joules (J) and control sample8 Joules (J) respectively.

v. It is also shown that as the current increases, more heat is produced into the weld; causing expansion and contraction between the weldment and base metal. These increases the residual stresses in the weldment and heat affected zone which affects the engineering properties of the materials, resulting in reduction of strength 388.69 (Mpa) and hardness 137.9 HRC of weldment and the heat affected zone.

vi. The analysis of microstructures of the welded specimens confirmed the heat input directly affected the mechanical properties and microstructure of the weldment. In general, the higher heat inputs led to the slower cooling rate which resulted in coarse grains in both HAZ and weld metal while lower heat input led to fast cooling rate which resulted in fine microstructure.

vii. Finally, the scanning electron micrograph showed dimples of various sizes and shapes observed in the control sample which is an indicative of its relatively high tensile strength and good ductility. That of low heat input showed dull, fibrous and irregular appearance structure produced by stretching of crystals given a number of tear ridges and dimples, an indicative of ductile fracture called microvoid coalescence. The medium heat input showed a mixed ductile/brittle fracture surface of microvoid with some tear ridges and river pattern markings which points to the origin of failure. Then, the high heat input showed trans-granular form of fracture of quasi-cleavages along the crystal planes, inter-granular structures occurring along the grain boundaries and a river patter of branching cracks which is an indicative of brittle failure that occurred with lower plastic deformation as compared with the control sample and lower heat inputs.

5.2 Recommendation

From the findings of the study: An investigation of the effect of electric power arc inputs on the microstructure and the mechanical properties of 0.4%C steel. Low heat input (100A) is recommended as the best heat input for welding of 0.4%C steel, reason being that it gives the best balance of both mechanical and micro-structural properties for service condition application as against high heat inputs. However, post weld heat treatment should be carried out on the samples with higher heat input for appropriate application in service.

Having investigated the work, the following suggestions for further research works are made:

i. A further research should be conducted to investigate the effect electric are power inputs on the microstructure and mechanical properties in the steel studied.
ii. A research should be conducted to investigate the effect of preheat on the mechanical properties of weld in the steel studied.
iii. A research should be conducted to investigate the effect of post-weld heat treatment on the mechanical properties of weld in the steel studied.
iv. A research should also be conducted to investigate the effect of combination of both pre-heat and post weld heat treatment (PWHT) on the mechanical properties of welds in steel studied.

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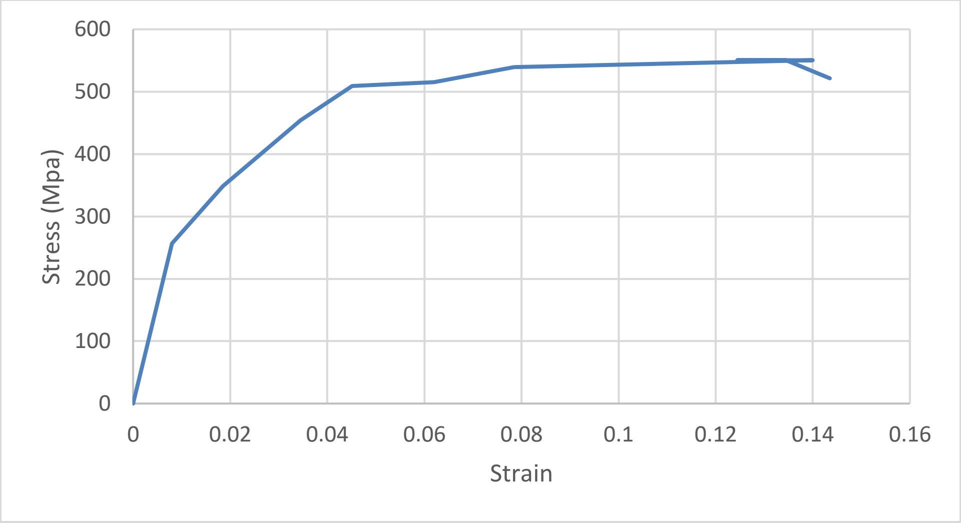
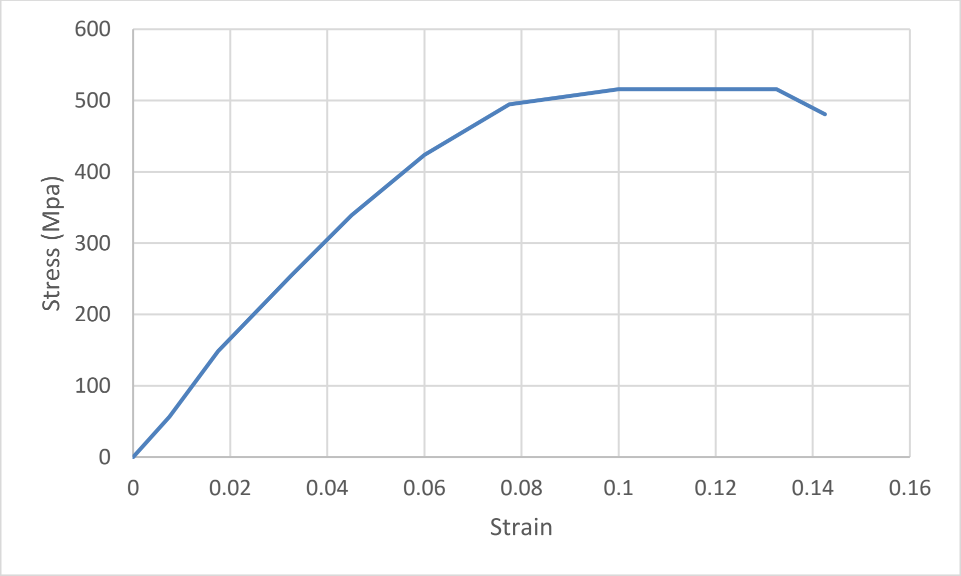
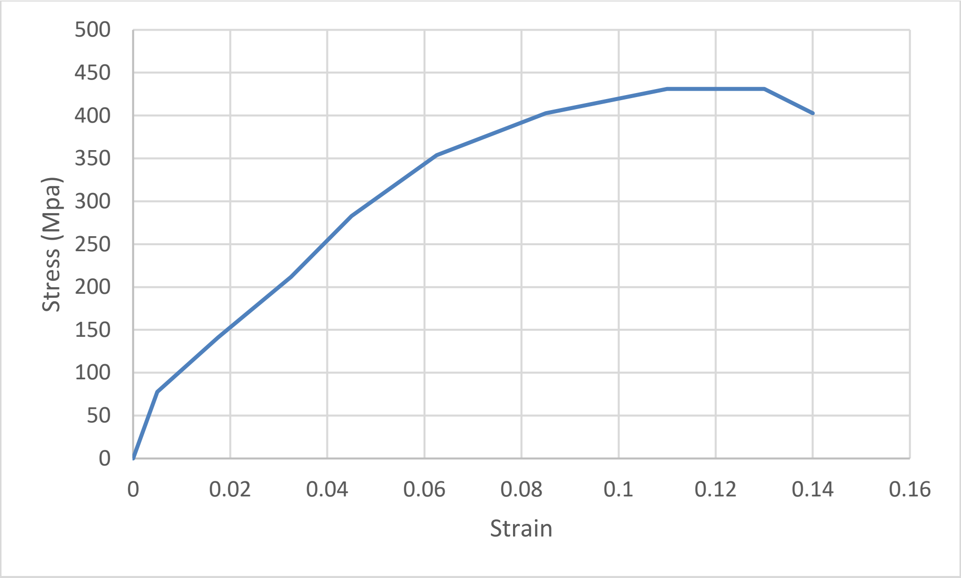
APPENDIX



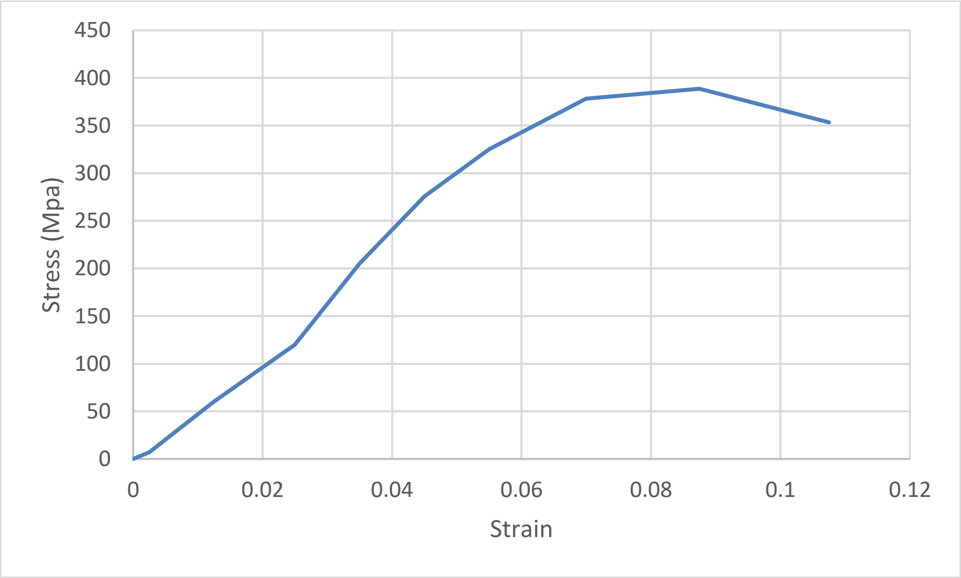
Stress – Strain Curve of the control sample. Showing a Yield Stress of 509.22 (MPa) and Tensile Strength of 550.40 (MPa)



Stress – Strain Curve of the low heat input sample. Showing a Yield Stress of 424.03 (MPa) and Tensile Strength of 515.90 (MPa)



Stress – Strain Curve of the medium heat input sample. Showing a Yield Stress of 353.83 (MPa) and Tensile Strength of 431.10 (MPa)



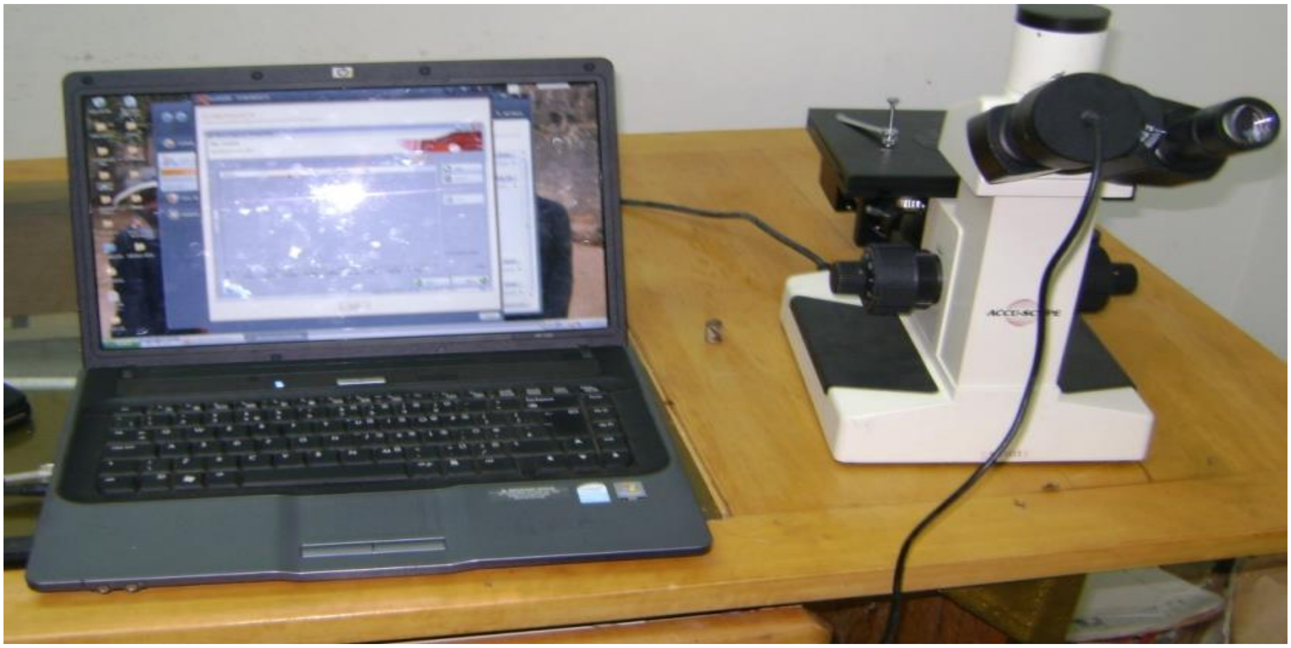
Stress – Strain Curve of the medium heat input sample. Showing a Yield Stress of 275.62 (MPa) and Tensile Strength of 378.09 (MPa)

VariosFabrieken Groningen Shielded Metal Arc Welding Machine. Source: UNN

Welding Workshop Setup. Source: UNN Metallurgical and Materials Engineering Workshop

Computerized Instron Electromagnetic Tensile testing Machine (Model 3369): Source: UNN Department of Metallurgical and Materials Engineering

Electrical Grinding/Polishing machine; Source: Department of Metallurgical and Materials Engineering, Enugu State University of Science and Technology



An Optical Microscope, Source: Department of Metallurgical and Materials Engineering; Enugu State University of Science and Technology.

SEM Machine –Model Phenom Prox. Source: Ahmadu Bellow University Zaria.

Charpy Impact Testing Machine; Source: University of Benin Faculty of Engineering Workshop.