EFFECTS OF ELECTRODE TYPE AND HEAT TREATMENT ON THE STRUCTURE AND MECHANICAL PROPERTIES OF MICRO-ALLOYED STEEL WELDMENT

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NNAMDI AZIKIWE UNIVERSITY, AWKA.

MARCH, 2020

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A DISSERTATION SUBMITTED TO THE DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING, FACULTY OF ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY (PhD) DEGREE.

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CERTIFICATION

I Adzor Sunday Abella a postgraduate student in the Department of Metallurgical and Materials Engineering do declared that the work embodied in this dissertation is original and has not been submitted in part or full for any other diploma or degree of this or any other university.

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ENGR. S. A. ADZOR **DATE**

APPROVAL PAGE

We, the undersigned hereby certify that the dissertation "Effects of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel weldment" presented by Adzor Sunday Abella (2014257005F) be accepted as fulfilling part requirements for the award of Doctor of Philosophy Degree in Metallurgical and Materials Engineering on this day.

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DEDICATION

I dedicate this dissertation to the saviour and redeemer of the world, Jesus Christ and my late Father, Mr. Michael Abella Adzor.

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ABSTRACT

The enhanced mechanical properties and advantageous characteristics of micro-alloyed steels are tremendously affected during welding with consequential effect on the safety and integrity of the entire welded structure in service. Therefore, to decrease the risk of premature failure of the welded component and improve its performance in service. The effects of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel weldment were investigated. The welds were producedwith E7016, E7018 and E7024 electrode at the preset welding current settings of 90, 94, 98, 102 and 106 ampere, employing shielded metal arc welding process. Post weld heat treatment (PWHT) hardening and tempering were also performed on the welded samples at varied heating temperature and soaking time.Thereafter, the as-welded and heat treated samples were machined to the required dimensions for hardness, impact and tensile tests to evaluate yield strength, tensile strength and percent elongation. The microstructures across the steel weldment were analyzed using optical microscope and scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). The results obtained showed that for each electrode type, the hardness, yield strength, tensile strength decreased with increase in welding current but impact strength and percent elongation increased correspondingly for the as-welded and heat treated samples. This phenomenal trend is indicative of microstructural grain coarsening due to the increasing slow cooling rate associated with increasing heat input and longer tempering soaking duration. Higher hardness values were obtained at the weld metal zones than the heat affected zones and base metal. The results also revealed that optimum hardness, yield strength and tensile strength were obtained from welds made with E7016 electrode. Whereas maximum impact strength and percent elongation were obtained from the welds made with E7024 electrode. The computed quality index values for each electrode welds indicated that weldment of optimal combination of longitudinal tensile strength and percent elongation required for structural applications can be obtained using E7018 electrode.The analysis of variance of the developed model for tensile strength, impact strength and percent elongation indicated that they are statistically significant at $p<0.0001$. The regression coefficient (R^2) values of the models are in the range of 94.74 - 99.83%, and adjusted coefficient ($R^2_{adj.}$) values are in the range 89.99 - 95.76%. These values indicate the goodness of developed models and a proof that they are valid. This work has shown that the most effective welding and heat treatment variables for achieving optimal combination of tensile strength and percent elongation suitable for structural applications are welding current setting of 90 ampere, tempering temperature of 450^0C and soaking time of 90 minutes.

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List of Abbreviation and Symbols

WM	Weld metal
HAZ	Heat affected zone
BM	Base metal
SMAW	Shielded metal arc welding
PWHT	Post weld heat treatment
A	Welding current
B	Soaking time
C	Temperature
QI	Quality index
^0C	Degree Celsius
K	Thermal efficiency
API	American Petroleum Institute
ASTM	American Society for Testing and Material
SEM	Scanning electron microscope
EDS	Electron dispersive spectrometer
TP	Test piece
BHN	Brinell hardness number
KN	Kilo Newton
ANOVA	Analysis of variance
R^2	Regression coefficient
$R^2_{adj.}$	Adjusted regression coefficient
CV	Coefficient of variation
<	Less than
>	Greater than
DF	Degree of freedom
P	Probability

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Welding is an important fabrication process that is widely used in industry to join metals by the application of heat and/or pressure, with the use of filler wire or covered electrode. There is hardly any engineering structure that does not have a welded component. Therefore, to ensure the safe performance of welded components in service, deliberate effort must be taken in selecting the proper welding consumables, as well as the correct welding parameter (welding current) that will be used to produce welds with satisfactory combination of properties suitable for specific applications. This is very necessary in prolonging the service life of engineering structure. Reports available in the public domain indicates that the premature failure of some welded components in service emanated from inappropriate choice of welding consumables and welding current (Thomas *et al.*, 2016, and Yusof and Jamaluddin 2014). The issues related to inappropriate choice of welding consumables and welding current are formation of undesirable metallurgical microstructures and welds that contain defects like porosity and slag inclusions, etc., which do impair the mechanical behaviour of the welded component in service. The term welding consumables refers to the covered electrodes or filler wires employed by welders to establish a welded joint. The selection of the most appropriate welding consumable is of prime importance to achieving quality most suitable in terms of fitness for service and cost. The selection usually involves study of metallurgy of the base metal and service conditions (Raj *et al.,* 2012). There are different types of electrode with varying alloying contents available commercially in the market for use by welders. However, the challenge frequently encountered by most welders is selecting the electrode with the right alloying contents that will produce welds with the desired metallurgical microstructures to provide optimal combination of mechanical properties suitable for stringent service applications.

Adopting the appropriate welding procedures will produce welds with mechanical properties that will meet the same requirements for strength, toughness and ductility as the parent material and at the same time free from defects. Therefore, with the increasing application of micro-alloyed steel for structural applications coupled with the demand for materials with improved properties that will meet the service requirement of critical infrastructure. Attempt is made to study the effects of electrode type and heat treatment on structure and the mechanical properties of micro-alloyed steel weldment.

1.2 Statement of problem

The major metallurgical problems encountered during the welding of micro-alloyed steelsare the tremendous change in the microstructure of the weld zones with its attendant effect on the structure and mechanical behaviour of the fabricated structure in service and the negative effect of residual stresses introduced into the steel weldment due to the non-uniform heating and cooling of the welded metal resulting to cracks and distortions in the HAZ and weld metal. Therefore, to avoid the formation of the undesirable microstructure with poor mechanical properties highly detrimental to the safety and integrity of the welded structure in service.Three different commercial electrodes (E7016, E7018 and E7024) with wide range of permissible alloying elements in their composition were carefully selected for the welding of the micro-alloyed steel, using shielded metal arc-welding process and thereafter applying post weld heat treatment (PWHT)in order to produce microstructure with the required mechanical properties for improved performance and also to reduce the risk of brittle failure in service as a result of the locked in welding residual stresses in the welded component. According to Entrekin (1983) PWHT process is one of the most common meansthrough which the properties of many weldment can be improved.Several reports available in the public domain have also supported this claim (Abdelmaoula *et al.*, 2015, Trudel *et al.*, 2013 and Hornsey 2006). PWHT process is therefore one of most effective and efficient means that is widely utilized in the fabrication industries to improve the deteriorated properties of welded structures and to reduce the likelihood of brittle fracture in the HAZ and the weld areas by reducing the level of tensile welding residual stresses before the welded components are put to use in stringent service applications. Entrekin (1983) further stated that the most common form of PWHT usually consists of heating the weldment to an elevated temperature below the lower critical transformation temperature and holding it long enough to relax the residual stresses embedded in the weldment. Hence, the need to study the effects of electrode composition and heat treatment parameters on the structure and mechanical properties of micro-alloyed steel weldment.

1.3 Aim and objectives of the study

1.3.1 Aim of the study

The aim of the study is to investigate the effects of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel weldment.

The study has the following objectives in view:

i. To study the effect of welding current on the mechanical properties of the micro-alloyed steel weldment.
ii. To establish the effect of the different electrode type on weld metal properties.
iii. To determine the effect of tempering temperature and soaking time on the structure and mechanical properties of the micro-alloyed steel weldment.
iv. To correlate the microstructure to the mechanical properties of the micro-alloyed steel weldment.
v. To use response surface method (RSM) to develop mathematical models for predicting tensile strength, impact strength and percent elongation of the micro-alloyed steel weldment.

vi. To adopt optimal (custom) design to optimize the welding and heat treatment variables to produced welds with optimal response values in the experimental domain.

1.4 Scope of the study

The work covers only the effects of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel weldment,employing shielded metal arc-welding process. The welding current of 90, 94, 98, 102 and 106 amperes were utilized to established the welds. The mechanical properties investigated were tensile strength, ductility, hardness, yield strength and impact strength. Structural examination was also carried out at the different zones of the steel weldment using metallurgical and scanning electron microscopes. The study was concluded with discussion of the results, conclusion, contributions to knowledge and recommendations.

1.5 Significance of the study

i. The study would determine the welding and heat treatment parameters to produce weld with optimal properties for different applications.

ii. The correlation between the structure and mechanical properties of the steel weldment would be established

iii. Based on the result of the mechanical test, the service conditions, suitable for each weldment would be established.

iv. The result of the test conducted would provide useful information regarding the quality of the welding process selected for the research.

v. The study would determine the optimum mechanical properties that can obtained from each electrode type.

vi. The overall outputs of the research work would provide an insight on the weldability of micro-alloyed steel.

vii. A mathematical relationship between the response (outputs) and process variables (inputs) would be developed.

viii. The optimum welding and heat treatment variables that would result to optimal response variables would be determined.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical development of welding

Welding is a term used to describe a wide range of processes for joining metals/alloys or plastics by fusion or coalescence of the interface. It involves bringing two surfaces together under condition of pressure or temperature which allows bonding to occur at the atomic level. Usually, this is accompanied by diffusion or mixing across the boundary, so that in the region of the weld an alloy is formed between the two pieces that have been joined. The accounts of the origin and development of welding in the world has been reported by several authors. Weld Guru (2016) in his own historical perspective stated that welding began in Egypt in 4000BC and the first metal to be welded was copper then followed by bronze, silver, gold and iron. International Agency for Research on Cancer Monographs (1990) posited that the welding of metals has its origins in pre-history at least 5000 years ago, when metal was welded by heating and hammering overlapping pieces. The same principles are employed this day in forge welding and other modern forms of solid state welding (Lancaster 1980, and Lindberg and Braton 1985). According to Howard (1998), the historic development of welding in the world could be traced back to the Bronze Age, where small circular boxes were made using pressure welding, were lap joined together. It is estimated that the boxes were made more than 2000 years ago. During the Iron age, the Egyptians and people in the eastern

Mediterranean area learned to weld pieces of iron together.During the Middle Ages, the art of blacksmithing was developed and many items of iron were produced which were welded by hammering. It was not until the 19th Century that welding, as it is known today was invented.In England, Edmund Davy (1836) discovered acetylene. The production of an arc between two carbon electrodes using a battery in 1800 is credited to Sir Humphrey Davy. In the mid-nineteenth century, the electric generator was invented and arc lighting became popular. During the late 1800's, gas welding and cutting was developed. Arc welding with the carbon arc and metal arc was developed and resistance welding became a practical joining process. Auguste De Meritens (1881), working in the Cabot Laboratory in France, used the heat of an arc to join lead plates for storage batteries. It was his pupil, a Russian, Nikolai N. Benardos, working in the French Laboratory, that was granted a patent for welding. He, with a fellow Russian, Stanislaus Olszewski, secured a British patent in 1885 and an American patent in 1887.This was the beginning of carbon arc welding. Bernardos efforts were restricted to carbon arc welding, although he was able to weld iron as well as lead. Carbon Arc Welding became popular during the late 1890's and early 1900's. In 1890, C. L. Coffin of Detroit was awarded the first U.S. patent for an arc welding process using a metal electrode. This was the first record of a metal melted from the electrode carried across the arc to deposit filler metal in the joint to make a weld. About the same time, N. G. Slavianoff, a Russian, presented the same idea of transferring metal across an arc, but to cast metal in a mould. Approximately in 1890, Strohmenger introduced a coated metal electrode in Great Britain.That was a thin coating of clay or lime, but it provided a more stable arc. Oscar Kjellberg of Sweden invented a covered or coated electrode during the period of 1907 to 1914. Stick electrodes were produced by dipping short lengths of bare iron wire in thick mixtures of carbonates and silicates and allowing the coating to dry.Meanwhile, resistance welding processes were developed including spot welding, seam welding, projection welding and flash butt welding. Elihu Thompson originated resistance welding. His patents were dated 1885-1900. In 1903, a German named Goldschmidt invented thermits welding that was first used to weld rail-road rails. Gas welding and cutting were perfected during this period as well. The production of oxygen and later the liquification of air, along with the introduction of a blow pipe or torch in 1887, helped the development of both welding and cutting. Before 1900, hydrogen and coal gas were used with oxygen. However, in about 1900 a torch suitable for use with low pressure acetylene was developed. World War I brought a tremendous demand for armament production and welding was put into service. Many companies sprang up in America and in Europe to manufacture welding machines and electrodes to meet these requirements. Immediately after the war in 1919, twenty members of the Wartime Welding Committee of the Emergency Fleet Corporation under the leadership of Comfort Avery Adams founded the American Welding Society as a non-profit organization dedicated to the advancement of welding and allied processes. The use of alternating current for welding was discovered in 1919 by C. J. Holslag. However, it did not become popular until the 1930's when the heavy-coated electrode found widespread use. In 1920, automatic welding was introduced. It utilized bare electrode wire operated on direct current and used arc voltage as the basis for regulating the feed rate. Automatic welding was invented by P. O. Nobel of the General Electric Company. It was used to build up worn motor shafts and worn crane wheels. It was also used by the automobile industry to produce rear axle housings. During the 1920's, various types of welding electrodes were developed. There was considerable controversy during the period about the advantage of the heavy-coated rods over the light-coated rods. The heavy-coated electrodes, which were made by extrusion, were developed by Langstroth and Wunder of the A. O. Smith Company and by 1927, used by the company. In 1927, Lincoln Electric Company produced extruded electrode rods that were sold to the public. By 1930, covered electrodes became widely used. The establishment of welding codes further increased the use of covered electrodes. The invention of covered electrodes saw the emergence of researches in shielding the arc and molten area from atmospheric gases. The atmosphere of oxygen and nitrogen in contact with the molten weld metal caused brittle and sometimes porous welds. Alexander and Langmuir (1920) worked in chambers using hydrogen as a welding atmosphere. They utilized two electrodes starting with carbon electrodes but later changed to tungsten electrodes. The hydrogen was changed to atomic hydrogen in the arc. It was then blown out of the arc forming an intensely hot flame of atomic hydrogen and thus liberating heat. This eventually became the atomic hydrogen welding process. Atomic hydrogen never became popular but was used during the 1930's and 1940's for special applications of welding and later on for welding of tool steels. Hobart and Devers, 1926, did similar work but used argon and helium gas which were supplied around the arc, thus, making them the forerunner of the gas metal arc welding process, though these processes were developed much later. Stud welding was developed in 1930 at the New York Navy yard, specifically for attaching wood decking over a metal surface. It was popular in the ship building and construction industries. Gas tungsten arc welding (GTAW) was invented by C. L. Coffin, who developed an idea of welding in a non-oxidizing gas atmosphere and which he patented in 1890. The concept was further improved in the late 1920's by H. M. Hobart who used helium gas for shielding and P. K. Devers, who used argon gas. This process was ideal for welding magnesium, aluminum and stainless steel. It was perfected in 1941, patented by Meredith and named Heliarc welding. It was later licensed to Linde Air Products, where the water-cooled torch was developed. The Gas shielded metal arc welding (GMAW) process was successfully developed at Battelle Memorial Institute in 1948, under the sponsorship of the Air Reduction Company. This development utilized the gas shielded arc similar to the gas tungsten arc, but replaced the tungsten electrode with a continuously fed electrode wire. One of the basic changes that popularised the process was the small diameter electrode wires and the constant-voltage power source. This principle had been patented earlier by H. E. Kennedy.The initial introduction of GMAW was for welding non-ferrous metals. The high deposition rate led users to try the process on steel. The cost of inert gas was relatively high and cost saving was not immediately achieved. In 1953, Lyubavskii and Novoshilov announced the use of welding with consumable electrodes in an atmosphere of carbon dioxide (CO_2) gas.The CO_2welding process immediately gained wide acceptance since it utilized equipment developed for inert gas metal arc welding hence,making it economical for welding steels. The CO_2 arc is a hot arc and the larger electrode wires required fairly high currents. The process became widely used with the introduction of smaller- diameter electrode wires and refined power supplies. This development was the short-circuit arc variation which was known as micro-wire, short-arc, and dip transfer welding, all of which appeared in late 1958 and early 1959. This variation allowed all position welding on thin materials and soon became the most popular of the gas metal arc welding processes. Another variation was the use of inert gas with small amounts of oxygen that provided the spray-type arc transfer. It became popular in the early 1960's. A recent variation uses a pulsating current to melt the filler wire and allows one small molten droplet to fall with each pulse.The pulses allow the average current to be lower, thus, decreasing the overall heat input and thereby decreasing the size of the weld pool and affected zone when welding thin work pieces. After the introduction of CO_2 welding, a variation utilizing a special electrode wire was developed. This wire, described as an inside-outside electrode, was tubular in cross-section with the fluxing agents on the inside. The process was called dual shield, which indicated that external shielding gas was utilized, as well as the gas produced by the flux in the core of the wire, for arc shielding. This process, invented by Bernard, was announced in 1954, but was patented in .1957, when the National Cylinder Gas Company re-introduced it. In 1959, an inside-outside electrode was produced which did not require external gas shielding. The absence of shielding gas gave the process popularity for non-critical work and it was named inner shield. In 1958, the soviets made public the electro-slag welding process at the Brussels World Fair in Belgium.Though, it had been in use in the Soviet Union since 1951, but was based on a study done in the United States by R. K. Hopkins, who was granted patents in 1940. The Hopkins Process was never used to a very great degree for joining. The process was perfected and equipment was developed at Paton Institute Laboratory in Kiev, Ukraine and also at the Welding Research Laboratory in Bratislava, Czechoslovakia. The first production use in the U.S. was at the Electro-motive Division of General Motors Corporation in Chicago, where it was called the Electro-moulding process. It was made public in December, 1959 for the fabrication of welded diesel engine blocks. The process and its variation, using a consumable guide tube, is used for welding thicker materials.

In 1961, the Arcos Corporation introduced another vertical welding method called electro gas. It utilized equipment developed for electro slag welding but employed a flux-cored electrode wire and an externally supplied gas shield. It is an open arc plasma that has a higher temperature than the tungsten arc. It is also used for metal spraying and cutting. The electron beam welding process, which uses a focused beam of electrons as a heat source in a vacuum chamber was developed in France. The first public disclosure of the process was made by J. A. Stohr of the French Atomic Energy Commission on November 23, 1957. In the United States, the automobile and aircraft engine industries are the major users of electron beam welding. Recent developments in welding include 1958 breakthrough of electron beam welding, making deep and narrow welding possible through the concentrated heat source. Following the invention of the Laser in 1960, Laser beam welding debuted several decades later and has proved to be especially useful in high speed automated welding. Both processes, however, continue to be quite expensive due to the high cost of the necessary equipment hence their limited application. Other developments in welding technology have involved refinements of the existing welding processes and the introduction of new, often more automated processes.

Welding power supplies, which are a little heavier than the welding transformers and rectifiers, are increasingly becoming more sophisticated

(Wilkinson, 1988). Since the late 1970s, development of transistorized solid state power sources has been dramatic, voltage and current profiles can be computer-programmed to give precise drop-by-drop delivery of weld metal to the weld pool. This has improved weld quality and productivity in MIG welding and related processes. The 1970s and 1980s have witnessed increasing use of electron beam and laser welding and in particular a marked increase in automated and robot welding. The automotive industry has for many years been highly automated, and few welds on motor vehicles are made by human welders. This type of automation is very inflexible and car production lines are usually built for a single product. Robot automation, in contrast, can be highly flexible and can be used for a variety of products. Computer-aided design and manufacture is now increasing, and this will gradually reduce the number of human welders employed in manufacturing industries in countries with advanced economies.

Welding is the most effective method of joining materials. Yet in many ways it is the most complex, especially from a metallurgical point of view. Virtually all types of metallurgical phenomena occur during the course of making a weld. Welding metallurgy is concerned with melting, solidification, gas-metal reactions, slag-metal reactions, surface phenomena and solid state reactions. These reactions occur very rapidly during welding in contrast to other metallurgical operations such as steel-making, casting and heat treatment. (America welding society 1976). A weld is a localized coalescence of metals or non-metals produced either by heating the materials to the welding temperature with or without the application of pressure or by the application of pressure alone and with or without the use of filler metal. Coalescence means “joining together”. Therefore, welding is the only method of developing monolithic structures (Pamar 2007).

Welding is a process critical to the present level of civilization and technical advancement, yet little is understood about it and most often things are taken for granted. Unless when applied to the building, machinery or automotive industries, it is often not realized how much dependent on the welding process modern technology is. Infact, once the objects around us are appreciated, it becomes hard to imagine the world without the welding process. When two structural members are joined by means of welds the connection is called a welded joint. A few decades ago, designers had the erroneous understanding that welded connections were less fatigue resistant and that good quality welded connection could not be made. The negative view had a great impact on the use of welding in structures. But the progress made in welding equipment and electrodes, the advancing art and science of designing for welding and the increasing trust and acceptance of welding have combined to make it a powerful implement for the expanding construction industry (Duggal 2006). The economics inherent in welding are helping to offset increase in the prices of material and cost of labour. In addition, the shortened production cycles made possible by welding, have helped effect to accelerate the pace of construction.

Welding will become increasingly important as greater depth of knowledge and experience that go with it is acquired. Today, most of the regulatory agencies and government departments accept welded joints. There are a number of reasons for using a welded design, but the few basic ones are as follows:

i. Welded designs offer the opportunity to achieve a more efficient use of materials.
ii. Weldingis the only process that produces a one-piece construction.
iii. The speed of fabrication and erection helps compress production schedules.
iv. Welding permits architects and structural engineers a complete freedom of design.
v. The use of outstanding design advancements such as open-web expanded beams, tapered beams, tubular column and trusses are a few examples of welded constructions.
vi. A properly welded joint is stronger than the material joined.
vii. Fused joints create a rigid structure in contrast to the non-rigid structures made using other types of joints.
viii. The compactness and greater rigidity of welded joints permits design assumptions to be realized more accurately.
ix. Welding saves weight and consequently cuts costs.
x. Connecting steel plates are reduced or eliminated since they often are not required.

xi. Welding offers the best method for achieving a rigid connection, resulting in reduced beam depth and weight.Thus, it noticeably lowers the overall height of buildings.

xii. The weight of the structure and consequently, the static loading is considerably reduced.This saves column steel and reduces foundation requirements. Saving in transportation, handling time and erection is proportional to the weight savings.

xiii. A welded structure is ideal for a situation which requires water and air tightness such as submarine hulls and storage tanks.

xiv. A welded joint has high joint efficiency. The joint efficiency is defined as the percentage of the fracture strength of a joint to the fracture strength of the base plate. The values of joint efficiency of welded joints are higher than riveted joints; it can be as high as 100%.

xv. Metal thickness is not a limit. It is very difficult to rivet plates that are more than 2inches thick. In welded structures there is virtually no limit to thickness thatmay be employed (Abdul 1990 and 1994 and Duggal 2006).

Despite the numerous advantages associated with the use of welded structures, there are some limitations with the application of welded structures:

1. Difficulty in arresting fracture: When crack starts to propagate in a welded structure, it is always very difficult to arrest it.

2. Possibility of defects: Welds are often plagued with various types of defects including porosity, cracks, slag inclusion, etc.

3. Sensitivity of materials: Some materials are more difficult to weld than others.

4. Lack of reliable non-destructive techniques: Although many non-destructive testing methods have been developed and are in use today, some are completely satisfactory in terms of cost and reliability for specific application only.

5. Residual stress and distortion: As a result of the non-uniform heating during welding, residual stresses and distortion are introduced in the weldment. This lead to cracks in the heat affected zones and welds areas (Abdul 1990 and 1994)

Welding is used as a fabrication process in every industry large or small. It is a principal means of fabricating and repairing metal products. The process is efficient, economical and dependable as a means of joining metals. This is the only process which has been tried in space. The process finds application in the automobile industry, and in the construction of buildings, bridges, ships, submarines, pressure vessels, offshore structures, storage tanks, oil, gas and water pipelines, girders, press frames, and water turbines.

i. In making extensions to the hospital buildings, where construction noise is required to be minimal, the value of welding is significant.

ii. Rapid progress in exploring space has been made possible by new methods of welding and the knowledge of welding in metallurgy. The aircraft industry cannot meet the enormous demands for aeroplanes, fighters and guided planes, space crafts, rockets and missiles without welding.

iii. The process is used in critical applications like the fabrication of fission chambers of nuclear power plants.

iv. A large contribution welding has made to the society, is the manufacture of household products like refrigerators, kitchen cabinets, dishwashers and other similar items.

v. It finds applications in the fabrication and the repairs of farm, mining and oil machinery, machine tools, jigs and fixtures, boilers, furnaces, railway coaches and wagons, anchor chains, earth moving machinery, ships, submarines, underwater constructions and repairs.

2.2 Selecting the appropriate welding process

Selecting the appropriate welding process is an important decision to be made because it is particularly necessary in determining cost, ease of accomplishment and the quality of the weld. There is no one welding process suitable for all welding situations.Therefore, it is necessary to weigh the advantage and disadvantages of each welding process before taking a decision (Brumbaugh 1973). Ideally a weld should achieve a complete continuity between the parts being joined such that the joint is indistinguishable from the metal in which the joint is made. Such an ideal situation is unachievable but welds giving satisfactory service can be made in several ways. In order to best determine the type of welding process most appropriate for the welding job at hand, the following information are necessary to the welder, (Brumbaugh 1973 and Gourd 1984).

i. A correct and precise identification of the metal.
ii. An understanding of the metallurgical aspects that apply to the metals being welded.
iii. The total cost of the welding operations.
iv. Type of joint,its location and welding position.
v. End use of the joint.
vi. Structural (mass) size.
vii. Desired performance.
viii. Experience and abilities of manpower.
ix. Joint accessibility.
x. Joint design.
xi. Accuracy of assembling required.
xii. Welding equipment available.
xiii. Work sequence.
xiv. Welder skill.

All fabricated components and structures are expected to have some estimated service life. However, that does not mean that once such component/structure is put to service, it will be discarded at the end of the estimated life or that it is not likely to fail before estimated time. To ensure safe working without having to deal with unexpected failure, it is customary to select from the numerous welding processes one that can produce welds with acceptable quality which will meet the service requirement in view. There are numerous types of welding processes available to choose from, for any welding job. Depending on the welding process, for instance, in fusion welding, where heat flow is involved before the joint can be established, varying microstructure may be obtained at the different zones of the steel weldment giving rise to varying mechanical properties. (Singh, 2007).

2.3 Classification of welding processes

All metals can be welded but not by the same process. To achieve this, a large number of welding and allied processes has been developed. Different criteria have been used to classify welding processes. Mostwelding processes are classified on the nature of the heat source only while others are classified on the basis of following technical criteria:

i. Welding with or without filler material
ii. Source of energy for welding
iii. Arc and non-arc welding
iv. Fusion and pressure welding

2.3.1 Classification of welding processes on the basis of technical factors

2.3.1.1 Welding with or without filler material

A weld established without the use of filler metal is called autogenous weld. Such welds are done when the thicknesses of the metals to be welded are lesser than 5mm. The composition of the autogenous weld metal corresponds to the base metal only. However, autogenous weld can be crack sensitive when solidification temperature range of the base metal to be welded is significantly high (750-1000^{0}C). The following are typical welding processes in which filler metal is generally not used to produce a weld joint.

i. Laser beam welding
ii. Electron beam welding
iii. Resistance welding
iv. Friction stir welding

However, in the welding of thicker plates/sheets using any of the above processes,

filler metal can be used as per needs according to thickness of plates. Filler metal is the additional material that is added to the weld deposit to fill the weld groove. The composition of the filler metal can be similar to that of base metal or different, accordingly weld joints are categorized as homogeneous or heterogeneous weld, respectively. Some of the welding processes are inherently designed to produce a weld joint by applying heat for melting base metal and filler metal. These processes are mostly used for welding of thick plates (usually > 5mm) with comparatively higher deposition rate.

i. Metal inert gas welding: (with filler)
ii. Submerged arc welding: (with filler)
iii. Flux cored arc welding: (with filler)
iv. Electro gas/slag welding: (with filler)

2.3.1.2 **Source of energy for welding**

Almost all weld joints are produced by applying energy in one or other form to develop atomic/metallic bond between metals being joined and the same is achieved either by melting the faying surfaces using heat or applying pressure either at room temperature or high temperature. Based on the type of energy being used for creating metallic bonds between the components to be welded, welding processes can be grouped as under:

i. Chemical energy: Gas welding, explosive welding, thermite welding.
ii. Mechanical energy: Friction welding, ultrasonic welding.
iii. Electrical energy: Arc welding, resistance welding.
iv. Radiation energy: Laser beam welding, electron beam welding.

Energy in various forms such as chemical, electrical, light, sound, mechanical energies etc. are used for developing weld joints. However, except chemical energy all other forms of energies are generated from electrical energy for welding. Hence, categorization of the welding processes based on the source of energy criterion also does not justify classification properly.

2.3.1.3 **Arc or non-arc welding**

Metallic bond between the plates to be welded can be developed either by using heat for complete melting of the faying surfaces then allowing it to solidify or by

applying pressure on the components to be joined for mechanical interlocking. All welding processes in which heat for melting the faying surfaces is provided after establishing an arc either between the base plate and an electrode or between electrode and nozzle are grouped under arc welding processes. Those set of welding processes in which metallic bond is produced using pressure or heat generated from sources other than arc namely chemical reactions or frictional effect etc., are grouped as non-arc based welding processes. Welding processes corresponding to each group are given below.

Arc based welding processes

i. Shielded Metal Arc Welding: Arc between base metal and coveredelectrode.

ii. Gas Tungsten Arc Welding: Arc between base metal and tungsten electrode.

iii. Plasma Arc Welding: Arc between base metal and tungsten electrode.

iv. Gas Metal Arc Welding: Arc between base metal and consumableelectrode.

v. Flux Cored Arc Welding: Arc between base metal and consumable electrode.

vi. Submerged Arc Welding: Arc between base metal and consumable electrode.

Non-arc based welding processes

i. Resistance welding processes: uses electric resistance heating

ii. Gas welding: uses heat from exothermic chemical reactions

iii. Thermit welding: uses heat from exothermic chemical reactions

iv. Ultrasonic welding: uses both pressure and frictional heat

v. Diffusion welding: uses electric resistance/induction heating to

vi. facilitate diffusion

vii. Explosive welding: involves pressure

Arc and non-arc welding processes classification leads to grouping of all the arc welding processes in one class and all other processes in non-arc welding processes. However, welding processes such as electro slag welding (ESW) and flash butt welding were found difficult to classify in either of the two classes as ESW process starts with arcing and subsequently on melting of sufficient amount flux, the arc extinguishes and heat for melting of base metal is generated by electrical resistance heating by flow of current through molten flux/metal. In flash butt welding, tiny arcs i.e. sparks are established during initial stage of the welding followed by pressing of components against each other. Therefore, such classification is also found not perfect.

2.3.1.4 Pressure or fusion welding

Welding processes in which heat is primarily applied for melting of the faying surfaces are called fusion welding processes while other processes in which pressure is primarily applied (with little or no application of heat for softening of metal up to plastic state) for developing metallic bonds are termed as solid state welding processes.

Pressure welding

i. Resistance welding processes (spot, seam, projection, flash

    a. butt, arc stud welding)

ii. Ultrasonic welding
iii. Diffusion welding
iv. Explosive welding

Fusion welding process

i. Gas Welding
ii. Shielded Metal Arc Welding
iii. Gas Metal Arc Welding
iv. Gas Tungsten Arc Welding
v. Submerged Arc Welding
vi. Electro Slag/Electro Gas Welding

Fusion welding and pressure welding is the most widely used classification as it covers all processes in all the categories irrespective of the heat source and welding with or without filler material. In fusion welding, molten metal solidifies freely while in pressure welding, molten metal if any is retained in confined space (as in case of resistance spot welding or arc stud welding) and solidifies under pressure or semisolid metal cools under pressure. This type of classification poses no problems and therefore it is considered as the best criterion.

2.4 Types of welding process

2.4.1 Shielded metal arc-welding

Shielded metal arc welding (SMAW), also known as manual metal arc welding (MMA or MMAW) or informally as stick welding, is a manual arc welding process that uses a consumable electrode covered with a flux to lay the weld. An electriccurrent, in the form of either alternating current or direct current from a welding powersupply, is used to form an electric arc between the electrode and the metals to be joined. The work piece and the electrode melts 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 shielding gas and providing a layer of slag, both of which protect the weld area from atmospheric contamination. Shielded metal arc welding is one of the world's first and most popular welding processes (American Welding Society, 2000). It dominates other welding processes in the maintenance and repair industry. It is used extensively in the construction of heavy steel structures and in industrial fabrication because of the versatility of the process, the simplicity of its equipment and operation, low cost and it suitability for outdoor applications.

2.4.1.1 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 dominant in the maintenance and repair industry, and is heavily used in the construction of steel structures and in industrial fabrication. In recent years, its use has declined as flux-cored arc welding has expanded in the construction industry and gas metal welding has become more popular in industrial environments. However, because of the low equipment cost and wide applicability, the process will likely remain popular among amateurs and small businesses where specialized welding processes are uneconomical and unnecessary. SMAW is often used to weld carbon steel, low and high alloy steel, stainless steel, cast iron, while less popular for non-ferrous materials. It can be used on nickel and copper and their alloys and in rare cases, on aluminium. The thickness of the material being welded is bounded on the low end primarily by the skill of the welder, but rarely does it drop below 1.5mm. No upper bound exists (Cary and Helzer 2005).

2.4.1.2 Electrode

The choice of electrode for SMAW depends on a number of factors, including the weld material, welding position and the desired weld properties. The electrode is coated in a metal mixture called flux, which gives off gases as it decomposes to prevent weld contamination, introduces de-oxidizers to purify the weld, causes weld protecting slag to form and improves the weld quality. (Jeffus and Larry 1999). Electrode can be divided into three groups – those designed to melt quickly are called “Fast-fill” electrodes, those designed to solidify quickly are called “fast-freeze” electrodes and intermediate electrodes go by the name “full-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. (Lincoln Electric 1994). The composition of the electrode core is generally similar and sometimes identical to the base material. Even though a number of feasible options exist, a slight difference in alloy composition can strongly impact on the properties of the resulting weld. This is especially true of alloy steels such as HSLA steels. Likewise, electrodes of compositions similar to those of the base materials are often used for welding non-ferrous materials like aluminium and copper, (Lincoln Electric, 1994). However, sometimes it is desirable to use electrodes with core materials significantly different from the base material. For example, stainless steel electrodes are sometimes used to weld two pieces of carbon steel and are often utilized to weld stainless steel work pieces with carbon steel work pieces. (Lincoln Electric 1994).

2.4.2 Gas tungsten arc welding

The gas tungsten arc welding (GTAW) process also known as tungsten inert gas (TIG) was one of the first semi-automatic welding developed after the manually operated shielded metal arc welding process (Degarmo 1995). It is a process that melts and join metals by heating them with an arc established between a non-consumable tungsten electrode and the metals (Kou, 2003). The most significant feature of GTAW is that the electrode used is not intended to be consumed during the welding operation. It is made of pure or alloyed tungsten which has the ability to withstand very high temperature, even those of the welding arc. When filler wire is required, it must be added externally, usually manually or by some mechanical wire feed system. With skilled operator, GTAW can produce welds that are scarcely visible. In addition, the process produces very clean welds. Since no flux is employed, no special cleaning or slag removal is required. All metals can be welded by this process, and the use of inert gas makes it attractive for the welding of reactive metals, such as aluminum, magnesium, and as well as the high temperature refractory metals (Degarmo 1995).

2.4.3 Gas metal arc welding

Gas metal arc welding (GMAW), formerly known as metal inert gas (MIG) welding was a logical outgrowth of gas tungsten arc welding (Degarmo 1995). GMAW process is characterized by a solid wire electrode which is fed continuously through a welding gun. An arc is created between the wire and the work piece to heat and melt the base and filler wire. Once molten, the wire becomes deposited in the weld point. An important feature of GMAW is that the shielding gas for the welding is provided by the protective gas atmosphere which is emitted also from the welding gun from an external source. Gases used include, argon and helium (inert gases) and some reactive gases such as nitrogen, oxygen and carbon dioxide (American Welding Society, 2000). GMAW used in welding virtually all type of metals but are primarily used in welding nonferrous metals (Degarmo 1995).

2.4.4 Flux-core arc welding

Flux-core arc welding (FCAW) utilizes a continuous tubular electrode wire filled with flux. The function of the flux is similar to those of the electrode covering in SMAW, including protecting the molten metal from the atmosphere (Kou 2003). The process may sometimes requires an additional source of gas supply to protect weld pool. This is only needed when the electrode used does not have an internal flux. The process is used primarily for ferrous metals (Kou 2003).

2.4.5 Submerged arc welding

It is a welding process that melts and join metals by heating them with an arc established between a consumable wire electrode and the metals, with the arc being shielded by a molten slag and granular flux. The process differs from the other the welding processes in that the arc is submerged and is not visible. The gas is supplied from a hopper which travels with the torch. No shielding gas is required because the molten metal is separated from the air by the molten slag and granular flux. Direct current electrode positive is most often used (Kou, 2003) Submerged arc process is most suitable for making flat butt or fillet welds in low carbon steel (< 0.3% carbon). However, with some preheat and post heat, medium carbon steel and alloyed, cast iron, stainless steel, copper alloy, nickel alloy, etc. can be welded (Degarmo 1995).

2.4.6 Plasma arc welding

The plasma arc welding process is an arc welding process that melts and join metals by heating them with a constricted arc established between a tungsten electrode and the metals. It is similar to GTAW, but an orifice gas as well as a shielding gas is used. The arc in PAW is constricted because of the converging action of the orifice gas nozzle, and the arc expands only slightly with increasing arc length (Fuerschbach and Knorovsky 1991). It is used for welding metals thickness up to 12mm by employing a technique known as keyhole welding. Keyhole welding is performed on a square butt joint with no root opening. The concentrated heat of the joint penetrate through the metal thickness to form a small keyhole. As the welding progresses, the keyhole moves along the joint melting the edges of the base metal which then flow together and solidify after the welding arc passes. This creates a high quality welds, with no elaborate joint preparation and fast travel speed compared to GTAW (American Welding Society 2000).

2.4.7 Stud welding

The stud welding process is used to weld studs or attachments to some metal surface. The process is considered to be an arc welding process because the heat for welding is generated by an arc between the stud and the base metal. The process is controlled by a mechanical gun which is attached to a power supply through a control panel. The welding is accomplished very easily and repetitively. The process is performed in four cycles which are timed and sequenced by the control box once the stud is positioned and the trigger is pulled to initiate the current flow, and the gun lifts the stud to maintain the arc, the arc quickly melts the stud end and a spot on the work piece beneath the stud (American Welding Society 2000).

2.4.8 Electro slag welding

This is a process that melts and join metals by heating them with a pool of molten slag held between the metals and continuously feeding a filler wire electrode into it. The weld pool is covered with molten slag and moves upward as welding progresses. A pair of water cooled copper shoes, one in the front of the work piece and one behind it, keeps the weld pool and the molten slag from breaking out. The molten slag protects the weld pool from air and refines it. However, the electro slag process is not an arc welding process because the arc initiated is only present during the initiation period after it is extinguishes, and the resistance heating generated by the electric current passing through the slag keeps it molten

(Kou 2003).**2.5 Conditions for obtaining satisfactory welds**

To obtain satisfactory welds it is desirable to have;

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 atomspheric contamination
iv. Control of weld metallurgy

2.5.1 Source of energy

Energy supplied is usually in the form of heat generated by a flame, an arc, the resistance to an electric current,radiant energy or by mechanical means (friction, ultrasonic vibrations or by explosion). In a limited number of processes, pressure is used to force weld region to plastic condition. In fusion welding the metal parts to be joined melt and fuse together inthe weld region.The word fusion is synonymous with melting but in welding fusion implies union.

2.5.2 Surface contaminants

Surface contaminiant may be organic films, absorbed gas and chemical compounds of the base metal (usually oxides). Heat used as a source of energy, effectively removes organic films and adsorbed gases and only oxide film remains to be cleaned. Fluxes are used to clean the oxide film and other contaminants to form slag which floats and solidifies above the weld bead protecting the weld from further oxidation.

2.5.3 Protecting metal from atmospheric contamination

To protect the molten weld pool and filler metal from atmospheric contaminants, especially oxygen and nitrogen present in the air, some shielding gases are used. These gases could be argon, helium or carbon-dioxide supplied externally. Carbon dioxide could also be be produced by the burning of the flux coating on the consumable electrode which supplies the molten filler metal to th weld pool.

2.5.4 Control of weld metallurgy

When the weld metal solidifies, the microstructures formed in the weld and the heat-affected-zone (HAZ) region determines the mechanical properties of the joint produced. Pre-heating and post welding heat-treatment can be used to control the cooling rates in the weld and HAZ regions and thus control the microstruccture and properties of the welds produced. Deoxidants and alloying elements are added as in foundry to control the weld-metal properties. The foregoing discussion clearly shows that the status of welding have now changed from skill to science. A scientific understanding of material and service requirement of the joints is necessary to produce successful welds which meet the challenge of hostile service requirement.

2.6 Welding quality and performance

Welding is one of the principal activity in modern fabrication, ship building and offshore industry. The performance of these industries regarding product quality, delivery schedule and productivity depends upon structural design, production planning, welding technology adopted and distortion control measures implemented during fabrication. The quality of welding depends on the following parameters:

i. Skill of welder
ii. Welding parameters
iii. Shielding medium
iv. Working environment
v. Work layout
vi. Plate edge preparation
vii. Fit-up and alignment
viii. Protection for wild winds during-on-site welding
ix. Dimensional accuracy
x. Correct processes and procedures
xi. Suitable distortion control procedures in place

2.7 Basic metallurgy of fusion welds

Weldment formed by fusion welding results in the formation of monolithic structure but such a joint varies in metallurgical structure from point to point with consequential varriation in mechanical properties.This according to parmar (2007), is because welding results in the development of a temperature gradient which varies from the highest temperature encountered in the centre of the weld pool to the ambient temperature along the transverse direction to the weld axis. The extent of the zone so affected depends mainly on the heat input per unit time, the welding velocity and the physical properties like the melting point,thermal diffusivity etc,of the work material. Basically a weldment can be divided into three distinct zones as shown inAppendix 1 (Fig. 2.1a) namely: the weld metalzone (WZ) forming the weld bead,the heat affected zone (HAZ),and the unaffected base metal zone (BMZ).Between the weld metal zone and the heat affected zone lies what is known as fusion zone as shown in Appendix 1 (Fig. 2.1b) which is the volume of the parent metal actually melted to form part of the weld metal zone or the weld bead.The weld metal zone constitute the weld bead and is a cast structure, the HAZ is in a way the heat treated portion of the weldment, while the unaffected base metal is the original work material plus a small zone which has been heated to about 650^0C and hence, has undergone a slight change in its grain size and thus mechanical properties.Depending on the material composition,welding speedand the amount of heat input, different microstrutures maybe expected from the different zones of a weldment formed by fusion welding.

2.7.1 Weld metal zone

The weld metal zone is formed by the solidification of the weld pool which itself is formed by the melting of a part of parent material plus the additional material that is contributed by the melting of the electrode,if used. The solidification of the molten metal in the weld pool starts as soon as it reaches the liquidus temperature for that material composition. It requires no undercooling as the partly metal grains provide the nuclei where from the growth of grains start into the solidifying weld pool, such a mode of solidification is refered to as epitaxial solidification(Parmar 2007).

2.7.2 Fusion boundary zone

Different terms are used to define the volume of parent metal actually melted to form the weld deposit. Tweeddale (1969) calls it fusion zone while Kenyon (1979) calls it fusion boundary. However, Parmar (2007) described it as the zone which lie between the weld deposit and the heat affected zone. For low carbon steel weld this zone corresponds toliquid plus delta ferrite zone on the iron-carbon equilibrium diagram. In most metals and alloys, the fusion boundary zone is quiet sharp and may be refered to as fusion line. At the fusion line, the composition changes from that of parent metal to that of, more or less uniform weld deposit.

2.7.3 Heat affected zone

A heat affected zone (HAZ) of a weld is that part of the welded joint which has been heated to a tenperature up to the solidus of the parent material resulting in varying degree of influence on microstruture as a consequence of heating and cooling cycle. When metals and alloys with out polymorphous transformation (eg Cu, Ni, Al etc) are welded, the microstruture in the HAZ remains unattered though grain growth or recrystallization may take place, while in the case of metal and alloys with polymorphous transformation, (eg. Steel), significant microstrutural changes take place in HAZ, that in turn influence the mechanical properties and consequently the service behaviour of the welded joint (Parmar 2007).

2.8 Welding power supply

A welding power supply is a deivce that provides an electric current to perform welding. Welding usually requires high current (over 80ampere) and it can need above 12,000 amps in spot welding. Low current can also be used; welding two razor blades together at 5 amps with gas tungsten arc welding is a good example. A welding power supply can be as simple as a car battery and as sophisticated as a modern machine based on silicon controlled rectifier technology with additional logic to assist in the welding process. Most welding machines can produce both ac and dc current .the chioce of ac or dc depends on the welding characteristics required, (Miller Electric 2003).

2.8.1 Direct current

A direct current welding circuit may be either straigth or reverse polarity. When the machnie is set on straigth polarity, the electrons flow from the electrode to the plate,concentrating most of the heat on the work. With reverse polarity, the fllow of eletrons is from the plate to the electrode, thus causing a greater concentration of heat on the electrode. As a result of the intense heat, the electrode tends to melt off. Therefore, direct current reverse polarity(DCRP) requires a larger diameter electrode than direct current straigth polarity (DCSP), (Kou 2003).

2.8.2 Alternating current

AC welding is actually a combination DCSP and DCRP; however, the electrical characteristics of the oxides on the metal often prevent the current from following smoothly in the reverse polarity half of the cycle. This partial or complete stoppage of current fllow (rectfication) causes arc to be unsuitable and some times go out. AC welding mechines were develop with high frequency current fllow uint to prevent this rectification. The high frequency current pierces the oxides film and forms a path for the welding current to follow(Kou, 2003).

2.9 Classification of welding machines

Welding machines are usually classified as constant current (CC) or constant voltage (CV); a constant current machine varies its output voltage to maintain a steady current while a constant voltage machine will fluctuate its output current to maintain a set voltage. Shielded metal arc welding uses a constant current source while gas metal arc welding and flux-cored arc welding uses constant voltage sources. The CV machine is required by gas metal arc welding and flux-cored arc welding because it is very difficult for the welder to control the arc length manually. If a welder attempted to use a CV machine to weld with shielded metal arc welding the small fluctuations in the arc distance would cause wide fluctuations in the machine's output. With a CC machine the welder can count on a fixed number of amps reaching the material to be welded regardless of the arc distance but too much distance will cause poor welding(Lincoln Electric, 1994).

2.10 Weldability of steel

The term weldability 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 judged from the standpoint of mechanical properties; the strength of the joint must be at least as great as that of the parent metal; 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 not limited by these factors alone; the fatigue properties of the joint should not be impaired by the metallurgical condition of the weld metal or HAZ; the metallurgical condition of the joint should not impair the behaviour of the structure during service as a result of localized corrosion, etc. (Baker 1967 in Wallace 1979).

The metal which can be welded to fit these criteria with no special precautions to prevent discontinuities or other difficulties is considered to have good weldability.

Weldability, encompasses the metallurgical compatibility of a metal/alloy with any specific welding process, the ability of the metal to be welded with mechanical soundness must meet soundness requirements and normal engineering standards. The serviceability factors concern the ability of the finished weldment to meet special requirements such as low temperature input high temperature stability or other designated qualities (Parmar 2007).

2.10.1 Weldability assessment

Before weldability can be assessed in relation to a process, three things must be decided (Tweeddale 1969).

i. Tolerance for Metallurgical Defects:

The metallurgical structures within a welded joint and in its immediate vicinity are likely to differ appreciable from the structure of the parent material, for example with fusion welds the weld deposit will be a cast structure tending to show all the defects likely to occur in that form of structure and the heat affected zone is likely to show enlarged grain size and other structural differences from the unaffected parent material. It is also likely that the composition of the deposit will differ from that of the parent material. Thus, it is essential that a decision should be made as to the amount of such defects and variation that can be accepted and yet still class the weld as completely satisfactory.

ii. Tolerance for Operational Defects:

Having determined the minimum metallurgical standards, it is still necessary to determine the operational standards. Even a completely automated welding process is liable to produce defects such as misalignment, imperfect bonding, poor welding fusion, poor weld shape, hence, as the skill that is required in a particular process becomes more individual, the more likely it is that defects of technique will occur. Therefore, a decision has to be taken concerning the technical standard that is required in making a particular kind of weld for a particular purpose.

iii. The type of testthat will be suitable inthe circumstances:

Various factors can affect the form of weldability test that is used, for example if only a few short welds are to be made in a particular material, cost alone will prevent the application of any comprehensive form of scientifically devised test, even if facilities are available.

i. Visual examination; Visual examination of a weldability test sample will include first of all checking of weld size, shape, appearance and freedom from performance defects. Secondly, the weld will be examined for signs of cracking or other defects such as porosity that can be considered to be due to deficiency in weldability.

ii. Metallurgical examination of simulative tests; If an accurate assessment is to be made of weldability it is essential that a metallurgical assessment should be included. This certainly entails studying one or more macro-sections of each weld sample and also a metallographic analysis of each weld sample. It is desirable to cut weld sample for macro-examination from several locations transverse to the weld. Each section is carefully polished and examined for weld defects before etching the surface to bring out the structural features.

iii. Mechanical test for weldability; Any assessment of weldability should include some estimate of mechanical efficiency of the test joint. At some stage, it is highly desirable to apply transverse tensile forces by taking the weld to the limit of its strength. How this force is applied will depend on the local circumstances and may vary from the most elementary breaking of a saw-notched weld by hammer bending it with the notch on the outside of the bend..

2.11 Welding defects

A weld defect is an imperfection in the weld which may eventually lead to failure of the weld joint under the service conditions for which it is designed

(Kenyon 1979). The imperfections may be detected by;visual inspection of the surface cutting of joint and preparing for macro-inspection

2.11.1 Under cut

It is groove or depression parallel and adjacent to the sides of the weld which results in thinning of the parent metal at the toe of the weld.

Causes

i. A too rapid rate of travel of blow pipe or electrode.
ii. Excess heat buildup.
iii. Incorrect angle of electrode or blow pipe.

2.11.2 Shape of profile

The profile should be uniform and slightly converse for butt welds and slightly concave or converse for fillet welds.

(a) Incompletely Filled Groove

Causes

i. A too rapid rate of travel with electrode or blow pipe
ii. Too small an electrode or rod

(b) Overfilled Groove

Causes

i. Welding current or blow pipe size too small

ii. A too slow rate of travel

iii. Electrode or rod too large

2.11.3 Overlap

This is excess weld metal at the toe of a weld covering the parent metal surface and fused to it.

Causes

i. Welding current too low and too fast the travel rate of electrode or blow pipe.

ii. Melting of filler rod before parent metal.

2.11.4 Penetration

Excessive – This is where excess weld metal is protruding through the root of the joint.

Causes

i. Too high welding current

ii. Concentration of heat

iii. Slow speed of travel of blow pipe or electrode

2.11.5 Slag inclussions

Causes

i. Current too low, electrode too large

ii. On fillet, incorrect angles, insufficient cleaning on multi runs

2.11.6 Lack of fusion (incomplete fusion)

This is the lack of union between the weld metal and parent metal.

Causes

i. Welding current too low
ii. Insufficient heat
iii. Too rapid travel with blow pipe or electrode
iv. Dirty surface
v. Melting of filler rod before plate

2.12 Testing for evaluation of welded joints

Welded joints in engineering structures or components are designed for service related capabilities or properties. To assured that they will fulfill their intended function, a test of some type is usually performed. The ideal testis of course, the observance of the structure in actual service, but actual service tests are expensiveand time consuming (Welding Hand book,1987). Therefore,standardised test and testing procedure has been developed by different international bodies like AWS, ASTM, API, ANSI, etc., that gives results which can be related to metal and structures that have performed satisfactorily in service. The various testing methods that are regularly use to evaluate the performance of welded joints are presented here.

2.12.1 Tensile strength and ductility test

These tests are frequently used to evaluate the breaking strength and ductility of a metal and to determine that the metal meets applicable specification requirements.Welded joints contain metallurgical and compositional differences that results from the welding process. It is important to know the effect of these changes on mechanical properties. The tensile strength and ductility of metal are generally obtained from a simple uniaxial tensile test in which a machined specimen is subjected to an increasing load while simultaneously observation of extention are made. The tensile strength is the maximum load in tension which a material will withstand prior to fracture. It is calculated by dividing the maximum load applied during the tensile test by the original cross sectional area of the sample.Ductility could be express in term of percent elongation or reduction in area. Elongation is defined as the permanent increase in length, expressed as a percentage of a specified gauge length marked in a tensile test bar, which is produced when the bar is tested to failure.

2.12.2 Relationship between tensile properties

Singh (2011) reported that the phases present,their proportion and morphology has great influence on the tensile properties of metals,this therefore, accounts for the different tensile properties of metals.Ductile Iron Society(2012),affirmed in their annual meeting that,the strong influence of graphite morphology and matrix structure on the different tensile properties of ductile iron produces significant correlations between these properties.In 1970 Siefer and Orths,in a statistical study of the mechanical properties of a large number of ductile iron samples,identified a relationship between tensile strength and elongation of the form:

Quality index (QI) = (tensile strength)^2 x (elongation%); (2.1)

A larger value of Q indicates a combination of higher strength and elongation and, therefore, higher material performance. Crews (1974) defined Q as the quality index (QI) for ductile iron. Both the QI and the underlying relationship between strength and elongation offer valuable insights into the quality of different ductile iron castings and the feasibility of obtaining various combinations of properties. High QI values have been shown to result from high modularity (high percentage of spherical or near-spherical graphite particles), absence of intercellular degenerate graphite, high nodule count, a low volume fraction of carbides, low phosphorus content (<O.03%) and freedom from internal porosity. High quality castings with these characteristics can be produced consistently by a competent, modern ductile iron foundry.It could therefore be inferred that, the quality of a steel weldment is a fuction of the resulting microstructural features obtained at the different regions of the weldment due to thermal cooling effects and the absence of defects such as porosity,slag inclusions, etc.,which could be obtained by a competent welder.

2.12.3 Relevance of yield-tensile ratio

The term Yield to Tensile Ratio (YTR) was introduced to Standards in the 1960's (British Steel Plc., 1986) and is appearing more frequently in materials specifications, Standards and codes. It is readily determined from certified standard tensile testing results, although it is a calculated parameter and not a direct measurement, and due to this it can be applied in integrity measurement situations. It was design to set a minimum level on how many multiples of the yield point that is necessary to be able to stress a metal beyond its yield without it failing for it to be considered a "ductile" material. The American Concrete Institute, (ACI) 318M-14 and the Standard National Indonesia (SNI) 2847:2013 building codes emphasizes that the ratio of the tensile strength and yield strength for rebar steels should not be less than 1.25. This requirement is based on the assumption that the capacity of a structural member to develop inelastic rotation capacity is a function of the length of the yield region.The yield-tensile ratio has been a standard requirement in many global standards for many years now, and has served its purpose well in traditionally made lower strength level steels. However, it may not be the optimum parameter required to define the behaviour of today's steels in the inelastic zone of the tensile load-elongation curve (Wright and Glodowski 2000). As a result of this, Wright and Glodowski (2000) suggested that a more sophisticated material property measurement may be required. Historically, a low YTR has been considered to provide a "high" capacity for plastic deformation, and so a safe margin against fracture. But in reality, the YTR is an indication of the level of stress the steel will sustain beyond its yield point to reach UTS, and it is represented as a factor of the original yield stress. The strain component is not taken into consideration.

2.13 Hardness testing

Hardness testing may be used in weld evaluations, either alone or to complement information gained through the tensile or bend tests previously described. Routine testing methods for the hardness testing of metals are well established. These include, the Brinell, Vicker and Rockwell tests. The first two use the area of indentation under load as the measure of hardness and the Rockwell test relates hardness to the depth of indentation under load. Hardness measurement can provide information about the metallurgical changes caused by welding. In constructional steels, for example, rapid cooling from heat affected zone may cause the formation of martensite of much higher hardness than the base metal. Welding of cold worked or age-hardened materials may result in significantly lower heat affected zone hardness due to recovery and re-crystallization or over-ageing. Hardness values in a weld joint are usually sensitive to such conditions of welding as the process used, heat input, pre-heat or inter-pass temperature, electrode composition and plate thickness. Hardness testing of welds is performed on ground, polished and etched cross sections of the joint area. Indentations are made in the specific areas of interest, including the weld centre line, face or root regions of the deposit, the heat-affected zone and the base metals, frequently transverse covering; all of these areas are made with indentation at regular intervals along transverse line. Which hardness test to be used depends primarily on the hardness or strength of the material, the size of the welded joint and the type of information desired. The Brinell test produces a large indentation typically 2 to 2.6mm in diameter and is thus suited only for large welds as in heavy plates (American Welding Society 1976).

2.14 Fatigue test

When a structure or component is subjected to repeated cycles of stress or strain, it causes its structure to break down, ultimately leading to fracture. This behavior is called fatigue, and it is usually responsible for a large percentage of failures at the welded joint, connecting rods, crankshaft and other parts subjected to cyclic loading. In all the cases, fracture will occur at a stress less than the material’s yield stress (Hibbeler 2008). Since fatigue failure occurs at a stress lower than the material yield strength fatigue test is often necessary because it specifies the stress below which no evidence of failure can be detected after applying a load for a specified number of cycles. This limiting stress is often called the endurance limit or fatigue limit. Typical values of endurance limits for various engineering materials are usually reported in hand books. Once a particular value is obtained, it is often assumed that for any stress below this value the fatigue life is infinite and therefore the number of cycles is no longer given consideration (Hibbeler 2008).

2.15 Impact testing

Impact testing is very essential in order to study the behaviour of materials under dynamic loading. In an impact test, a specimen machined or surface ground and notched, is struck and broken by a single blow in a specially designed testing machine. The quantity measured is the energy absorbed in breaking the specimen by a single blow. The ideal impact test is one in which all the energy of blow is transmitted to the test specimen. The test gives an indication of the relative toughness of the material. The test is usually conducted on a Charpy or Izod testing machine (Khanna 2008).

2.16 Micro-alloyed steel

Micro-alloyed steels also known as high strength low alloy steels are increasingly receiving greater attention for structural applications. The continuing increase in its demands is as a result of the enhanced mechanical properties and greater resistance to atmospheric corrosion which it offers when compared to the conventional carbon steels. It has been found that the improved mechanical properties and good resistance to atmospheric corrosion is due to the addition of small quantity of micro alloying elements such as niobium, titanium, vanadium, chromium, boron, etc. (Hakansson 2002).The strengthening of micro alloyed steels is achieved by grain refinement, controlled rolling, precipitation of carbides, carbonitrides and not by producing martensite and its subsequent tempering to improve toughness (Albert in Raj 2012). Micro-alloyed steels are widely used in the fabrication of structures where load bearing and weight saving are critical. The areas where these considerations are of prime importance are in the construction of oil gas pipeline, bridges, heavy-duty high ways and off-road vehicles, farm machinery, storage tanks and lawn mowers, etc. (American Society for Materials 2001, Hakansson 2002, Maciej and Danuta 2015, and Uranga 2019).Micro-alloyed steels can be welded by all conventional welding processes due to their low carbon equivalent values. Safe welding procedures should result in welds with mechanical properties meeting the same requirements for strength and toughness as the parent material and at the same time free from defects. Although, in true sense, welded joints having the same matching properties with the parent metal can rarely be achieved because of the thermal gradient encountered by the welded metal during welding leading to uneven heating and cooling cycles. This differential in heating and cooling cycles has significant effects on the final transformation products formed at the different zones of the steel weldment.

2.16.1 Classification of micro-alloyedsteel

Micro-alloyed steel include many standard and proprietary grades designed to provide specific desirable combinations of properties such as strength, toughness, formability, weldability, and atmospheric corrosion resistance. These steels are not considered alloy steels, even though their desired properties are achieved by the use of small alloy additions. Instead, micro-alloyed steels are classified as a separate steel category, which is similar to as-rolled mild-carbon steel with enhanced mechanical properties obtained by the addition of small amounts of alloys and, perhaps, special processing techniques such as controlled rolling and accelerated cooling methods. This separate product recognition of micro-alloyed steels is reflected by the fact that micro-alloyed steels are generally priced from the base price for carbon steels, not from the baseprice for alloy steels. Moreover, micro-alloyed steels are often sold on the basis of minimum mechanical properties, with the specific alloy content left to the discretion of the steel producer (ASM International 2001). Micro-alloyed steels can be divided into six categories:

2.16.1.1Weathering steels

They contain small amounts of alloying elements such as copper and phosphorus for improved atmospheric corrosion resistance and solid-solution strengthening

2.16.1.2Microalloyed ferrite-pearlite steels

They contain very small (generally, less than 0.10%) additions of strong carbide or carbonitride forming elements such as niobium, vanadium, and/or titanium for precipitation strengthening, grain refinement, and possibly transformation temperature control.

2.16.1.3As-rolled pearlitic steels

They include carbon-manganese steels but which may also have small additions of other alloying elements to enhance strength, toughness, formability, and weldability.

2.16.1.4Acicular ferrite (low-carbon bainite) steels

These are low-carbon (less than 0.05% C) steels with an excellent combination of high yield strengths, (as high as 690 MPa, or 100 ksi) weldability, formability,

and good toughness.

2.16.1.5Dual-phase steels

These steels have a microstructure of martensite dispersed in a ferritic matrix and provide a good combination of ductility and high tensile strength.

2.16.1.6Inclusion-shape-controlled steels

These steels have improved ductility and through-thickness toughness by the small additions of calcium, zirconium, and titanium, or perhaps rare earth elements so that the shape of the sulphide inclusions is changed from elongated stringers to small, dispersed almost spherical globules (ASM International, 2001).

2.17 Heat treatment

Heat treatment is a process utilized to change certain characteristics of metals and alloys in order to make them more suitable for a specific application. In general, heat treatment is the term use to describe any process employed to change the physical properties of steel by either heating or cooling. When properly performed, heat treating can greatly influence mechanical properties such as strength, hardness, ductility, toughness, and wear resistance (Zakharov, 1998). There are two main methods which are generally adopted for heat treating welded steels. They are, pre-heating and post heating. However, post weld heat treatment has been widely employed in welding operation because it is the most effective and efficient method in improving the mechanical properties and relieving residual stresses in welded component (Srivastava *et al.,* 2010 and Olabi 1994).

2.17.1 Post weld heat treatments and it effectiveness

The successful welding of steel of high thermal conductivity and/or thick sections and hardenable steel requires a proper controlled of the cooling rate to avoid the formation of undesirable structure. Also, where more than one multi pass weld runs are require in filling the groove of a joint, the continued overlapping heat of the welding will cause a tremendous change in the structure of the weld metal thus, affecting the mechanical properties. The two most widely used methods to control the effect of rapid cooling rate in the weld metal and HAZ, and improving the mechanical properties of a weldment are: preheat and post weld heat treatment. Preheat does control the cooling rate but there is always a chance for the residual stresses to develop and approach the dangerous level affecting the service life of a component (Parmar, 2007).The application of post weld heat treatment (PWHT) below the critical temperature (723 °C for AISI-1020 and 773 °C for AISI-410) produces softening of the base metal and can also have an influence more or less pronounced on the resistance to the brittle failure. However, the effects are very different according to the grades and qualities, on the one hand, and according to the welding conditions on the other hand. Olabi (1994) and Parmar (2007) posited that PWHT is usually applied with the aim to achieve the following improvements:

i. Stress relief.
ii. Minimizing the susceptibility to crack formation particularly under the conditions which call for high notch toughness.
iii. To improve the dimensional stability.
iv. To decrease the heat affected zone (HAZ) hardness by decomposition of martensite and other supersaturated structures.
v. To increase the resistance to corrosion.
vi. To remove cold cracking.
vii. Improved ductility of the material
viii. Tempered metal
x. Improved metallurgical structure

It is therefore evident that to achieve the desired quality of weld in a welded metal that are sensitive to hydrogen induced cracking and improvement in weld metal properties, PWHT is required. The ideal PWHT depends on the material composition, size and shape of the component, and the service conditions in which it is to be used (Olabi 1994). Therefore, it is necessary to select the heat treatment procedure which will develop the desired structure and properties in the material, while at the same time providing the maximum stress relief. Some of the PWHT processes used extensively in the fabrication industry include the following:

i. Annealing
ii. Normalizing
iii. Tempering
iv. Hardening

2.17.2 Annealing

The term annealing is used to describe a number of thermal treatments which are applied to metals/alloys. They are usually employed to reduce strength or hardness, remove residual stresses, improve toughness, restore ductility, refine grain size, reduce segregation or alter the electrical or magnetic properties of materials. Selecting the ideal annealing process suitable for a given material depends on the material characteristics and the objectives of the treatment (Degarmo *et al.,* 1995).

2.17.3 Normalizing

Normalizing is a heat treatment given to steels to refine their grain structure and improve its mechanical properties. The strength and hardness obtained after normalizing are usually higher than those obtained after annealing. The process consists of heating the metal/alloy into the austenistic temperature range to obtain a homogeneous single phase and allowing it to cool freely in air (Raghavan 1989 and Singh 2011).

2.17.4 Tempering

Tempering is defined as the process of reheating steels to a temperature below its lower transformation temperature and cooling it at any rate to increase the ductility and toughness of the steel. Several reports have revealed that after steel is quenched, it may be hard and brittle. Also, there are internal stresses which may introduce as a result of welding and casting. If steel is immediately reheated after quenching and welding, internal stresses will be relaxed and the material will be become less hard. The benefits of stress relief and the elimination of brittleness generally off-set problems caused by the slight loss of hardness and strength. Internal stress relief gives steel several desirable qualities; the material becomes more ductile, it gains more toughness and greater impact resistance (Warner and Brandt 2005).

2.17.5 Hardening

Hardening of steel is achieve by heating the steel to a proper austenitic temperature, soaking at this temperature to obtained a fine- grained and homogeneous austenite, and then cooling the steel at a rate faster than its critical cooling rate to obtain a harden martensitic structure. Obviously, the hardness of the martensite depends on the carbon content of the steel. The higher the carbon content, the higher the hardness of the martensite formed. The principal objectives of hardening include: to induce hardness in cutting tools to increase its cutting ability, to increase the wear resistance of many machine parts, like gears, cams, etc., (Singh 2011)

2.18 Design of experiment

Design of experiments (DOE) is defined as a branch of applied statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters (American Society for Quality, 2019). DOE is a powerful data collection and analysis tool that can be used in a variety of experimental situations.It allows for multiple input factors to be manipulated, determining their effect on a desired output (response). By manipulating multiple inputs at the same time, DOE can identify important interactions that may be missed when experimenting with one factor at a time. (American Society for Quality 2019). A strategically planned and executed experiment may provide a great deal of information about the effect on a response variable due to one or more factors

2.18.1 Response surface methodology

Response surface method (RSM) is a collection of statistical and mathematical techniques used in developing, improving, and optimizing processes (Myers 2002). It therefore, serve as a tool for the development of adequate functional relationship between response variables and associated control variables.

However, such a relationship is usually unknown but can be approximated by a low degree polynomial model. Carley *et al.,* (2004) who posited that RSM is generally use in situation where several variable inputs have potential influence on the performance measure of any process. The performance measure or quality characteristics is called response. The input variables are sometimes called independent variables, and are subject to control.

The field of response surface methodology consists of experimental strategy for exploring the space of the process or independent variables, empirical statistical modeling to develop an appropriate approximating relationship between the yield and the process variables, and optimization methods for finding the values of the process variables that produce desirable values of response.

2.18.2 Response surface method and Robust design

RSM is a critical technology in developing new processes and optimizing their performance. The objectives of quality improvement, including reduction of variability and improved process and product performance, can often be accomplished directly using RSM (Carley *et al.,* 2004). It is well established that variation in the key performance characteristics can result in poor process and product quality. Taguchi (1986 and 1987) reported that it was during the 1980s that considerable attention was given to process quality, and methodology was developed for using experimental design, for the following reasons:

i For design or developing products and processes so that they are robust to component variation.

ii For minimizing variability in the output response of a product or a process and target value.

iii For designing products and processes so that they are robust to environmental conditions.

By robust, imply that the product or process performs consistently on target and is relatively insensitive to factors that are difficult to control.

Taguchi was the first to use the term robust parameter design (RPD) describe his approach to this important problem. The RPD methodology essentially seek to reduce process or product variation by choosing levels of controllable factors (or parameters) that make the system insensitive (or robust) to changes in a set of uncontrollable factors that represent most of the sources of variability. Taguchi called these uncontrollable factors as noise factors. RSM assume that these noise factors are uncontrollable in the field, but can be controlled during process development for purposes of a designed experiment.

Controllable attention has been focused on the methodology advocated by Taguchi, and a number of flaws in his approach have been discovered. However, the framework of response surface methodology allows easily incorporate many useful concept in his philosophy (Myers *et al.*, 2002).

2.18.3 Sequential nature of response surface method

There are sequential experimental steps that are usually perform in RSM, they are:

i At first some ideals are generated concerning which factors or variables are likely to be important in response surface study. It is usually called screening experiment. The objective of factor screening is to reduce the list of candidates variables to a relatively few so that subsequent experiments will be more efficient and requires few runs or tests. The purpose of this phase is the identification of important variables.

ii In the second step, the experimenter`s objective is to determine if the current settings or levels of the independent variables are not consistent with optimum performance then the experimenter must determine a set of adjustments to the process variables that will move the process towards the optimum. This phase of RSM makes considerable use of the first-order model and an optimization technique called the method of steepest ascent.

iii The third step begins when the process is near the optimum. At this point the experimenter usually wants a model that will approximate the true response function within a relatively small region around the optimum. The true response surface usually exhibits curvature near the optimum, in this case a second-order model (or perhaps some higher-order polynomial) should be used. Once an appropriate approximating model has been obtained, the model may be analyzed to determine the optimum conditions for the process. The sequential experimental process is usually performed within some region of the independent variable space called the operability region or region of interest.

2.19 Building empirical models

2.19.1 Linear regression model

In the practical application of RSM, it is necessary to develop an approximating model for the true response surface. The underlying true response surface is typically driven by some unknown physical mechanism. The approximating model is based on observed data from the process or system and is an empirical model. Multiple regression is a collection of statistical techniques useful for building the type of empirical model required in RSM. The first-order linear regression model with two independent variables is of the form:

$$\mathbf{y = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \epsilon} \qquad \textbf{(2.2)}$$

The independent variables are often called predictor variables or regressors. The term linear is used because equation 2.2 is a linear function of the unknown parameters; β_0, β_1 and β_2. Models that have complex appearance than equation (2.2) are often analyzed by multiple linear regression techniques.

Regardless of the type of design that is been employed, Calado and Montgomery (2003) suggested that, the following considerations should be taken into account prior to the collection of experimental data:

i. Definition of the variables, which can be qualitative (additive type, presence of magnetic agitation, presence of light, etc.) and quantitative (ingredient concentrations, temperature, pressure, etc.).
ii. Definition of the relevant levels of each independent variable. This can be done by performing an initial experiment.
iii. Analysis of the results and of the need for relevant changes in the initial design.

2.19.2 Model adequacy checking

Granato and Calado (2014) advocated that, once a mathematical model has been selected, it is important to determine its significance by means of a variance analysis (ANOVA). To achieve that, the standard deviations of the main and the interactions effects of the selected factors should be calculated. If the standard deviations present a lower value than the mean values, it is possible to assume that the mathematical model is significant. If this does not happen, the experimental data should be evaluated in order to not presume that the effect is not significant.

In the evaluation of experimental designs, a mathematical model is provided to relate the response variable with the factor effects (Granato and Calado 2014). In this regard, several techniques have been proposed to estimate model goodness-of-fit. Granato and Calado (2014) proposed that model should be assessed on the following criteria: standard deviation of the estimated parameters and model; statistical significance of the estimated parameters; regression coefficient; value of the objective function; significance of the regression (ANOVA); analysis of the residuals. Thus, models are considered good fit to the experimental data when:

i. the standard deviation of the parameter presents a lower value than the correspondent effect, indicating that the standard deviation of the proposed mathematical model is low;
ii. the parameters of a model need to be significant, otherwise they will not contribute to the model;
iii. it is a myth to consider that if the model presents a regression coefficient (R^2) above 90%, then it is considered excellent. This is only one criterion to evaluate the model goodness-of-fit.

If a regression coefficient is low (<70%), the mathematical model is not good and on the other hand, if its value is high (>90%), it means that other statistical criteria may be used. It is noteworthy emphasizing that depending on the type of analysis, a regression coefficient may be considered good above 70%, such as what happens in sensory evaluation data;

i. the value of the objective function should be low
ii. the proposed mathematical model must be statistically significant;
iii. the analysis of the residuals consists in verifying if the residuals (experimental value for a response variable minus predicted value by the mathematical model) have a normal distribution and if the variance is constant. This is a necessary condition for the application of some post hoc tests, such as t and F. To test the validity of a normal distribution, quantitative tests need to be employed, such as Kolmogorov–Smirnov, Liliefors and Shapiro–Wilks. To test the variance constancy, Levene’s test is usually used.

2.20 Review of related works

Available research works by seasoned researchers have revealed that much works has been done on different welding processes to determine their effects on the microstructure and mechanical properties of different steel weldment. However, very little exist in the public domain on the effect of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel weldment using shielded metal arc-welding process. Pravin (2019) reported that due the uneven weld joint behavior impact strength increased up to the frequency of 150Hz and decreased at the frequency of 300Hz. The auxiliary stiring of weld pool during welding produced steeper thermal gradient which result in fine grain structures. Karabulut *et al.,* (2016) in their study of the effect of different welding current values on the microstructure and mechanical properties of micro-alloyed steels joined by submerged arc welding method observed that an increase in the welding current caused an increased in heat input which encourages the formation of widmanstatten ferrite in the weld metal thereby increasing the hardness, yield strength and tensile properties of the welded samples.

Nutalapati *et al.,* (2016) revealed that the welding of 90 ampere produced maximum tensile strength for single V joint design as compared to double V and single butt joint. Owolabi *et al.,* (2016) reported that increase in welding current increased hardness of low carbon steel and mild steel with a peak of 44.4HB and 43.4HB at the welding current of 116ampere and 115ampere respectively. They revealed that tensile strength for mild steel and low carbon steel decreased with increase in welding current and a peak value of 506.36Mpa and 654.73Mpa was obtained at 116ampere for mild steel and low carbon steel. This was attributed to the formation of martensite and bainite. The impact strength and yield strength also decreased with welding current increase. Singh *et al.,* (2016) studied the effect of flux composition on the percentage elongation and tensile strength of welds in submerged arc-welding and revealed that increase in CaFe increased tensile strength but decreased percent elongation. Abd elmaoula *et al.*, (2015) investigated the effect of Post weld Heat Treatment and Filler metals on Microstructures and Mechanical Properties of GTAW and SMAW Weldments between P11 and P91 Steels and concluded that tensile strength decreased with increase in temperature and soaking time. They also revealed that the post weld heat treatment parameters of 750^0C 1hr and 750^0C 0.5hr produced maximum tensile strength and minimum hardness in welds made with E9018B3/ER90SB and E9015B9/ER90SB9 filler metals respectively. Asibeluo and Emifoniye (2015) revealed that increase in welding current result in decrease in toughness and hardness. This was attributed to increase in cooling rate which caused grain growth. Dhobale and Mishra (2015) reported that increase in heat input affects the micro-constituents of base metal and heat affected zone. Tensile strength decreased with increase in heat input. Hardness of weld pool increased whereas hardness of heat affected zone decreased with increase in heat input. This was attributed to grain coarsening. The Okonji *et al.,* (2015) studied the effect of welding current and filler metal types on the macrostructure and tensile strength of GTAW welded stainless steel joints and found out that the welded joints produced with all the filler metals had higher tensile strength than the base metal in all the welding currents considered. This was attributed to the high carbon and chromium contents of the filler metals as well as the uniform distribution of the grains. Kaiser and Shorowordi (2014) studied the influence of welding current on the mechanical and physical properties of chromium-molybdenum steel and observed that there was a variation in the mechanical properties across the weldment in all the welding current used. This was attributed to the structural changes that occurred as a result of the heat input obtained from the different welding current used. It was found that the weld metal region exhibited maximum hardness than the HAZ and base metal region in all the welding current used. The yield strength and tensile strength was also highest at the weld metal region, at the current setting of 150 ampere. The impact energy was lowest at weld metal region than the HAZ and base metal in all the current settings. Talabi *et al.*, (2014) discussed the effect of welding variables on the mechanical properties of welded 10mm thick low carbon steel plate, welded using the Shielded Metal Arc Welding (SMAW) method. Welding current, arc voltage, welding speed and electrode diameter were the investigated welding parameters. The welded samples were cut and machined to standard configurations for tensile, impact toughness, and hardness tests. The results showed that the selected welding parameters had significant effects on the mechanical properties of the welded samples. Increases in the arc voltage and welding current resulted in increased hardness and decrease in yield strength, tensile strength and impact toughness. Increasing the welding speed from 40- 66.67mm/min caused an increase in the hardness characteristic of the welded samples. Initial decrease in tensile and yield strengths were observed which thereafter increased as the welding speed increased. An electrode diameter of 2.5mm provided the best combination of mechanical properties when compared to the as received samples. This behavior was attributed to the fact that increased current and voltage meant increased heat input which could create room for defect formation, thus the observed reduced mechanical properties. Ekici and Ozsarac (2013), while studying the mechanical properties of micro-alloyed steels joined by gas metal active welding and electric arc-welding methods using different gas protection composition observed that weld joint established with gas metal active welding method using ER100SG filler wire with a gas protection composition of 15% CO_2 + 85% Ar produced weld joint with optimum hardness and ductility values than that obtained with electric arc-welding method. Ghassemy *et al.,* (2013) investigated the effect of E8010-P1 electrode on the weld metal properties and observed that the presence of Mn, Mo, and Ni in the weld metal exerted significant influences on the morphology of ferrite in the weld metal zone. They also observed that large amount of Mn (around 1%) in the weld metal led to the formation of fine acicular ferrite in the weld metal while the presence of Mo (around 0.4%) in the weld metal prevent the formation of continuous grain boundary ferrite in the weld metal which is responsible for higher strength and ductility obtained. Mohammed *et al.,* (2013) investigated the mechanical and metallurgical properties of medium carbon steel using shielded metal arc welding process with reference to the weld metal, heat affected zone and parent metal. From the results, shielded metal arc welding of medium carbon steel increased the strength of the welded joint in particular the heat affected zone, as revealed by lower impact strength, higher tensile strength an d hardness values as compared with the parent and weld metal which is attributed to the fine ferrite matrix and fine pearlite distribution as compared to the weld and parent metal. However, there was a loss of ductility at the welded joint resulting to brittleness of the material. Okediran *et al.,* (2013) studied the effect of oerikon, santana, powder master and magnum electrodes on the mechanical properties of weldment and concluded that weldment produced using oerikon and powder master electrodes gave the maximum tensile strength of 508.25N/mm^2 and impact energy of 152.76J for Homus steel while powder master electrode produced weldments maximum tensile strength of 482.96N/mm^2 and impact energy of 137.033J for Universal steel. The results showed that a single electrode cannot produce weldment with maximum properties for the steel materials studied. Singh *et al.,* (2012) reported that amperage increase decreased depth of penetration, arc voltage of the increase decreased depth of penetration and travel speed is increase decreased depth of penetration. Adedayo *et al.,* (2011) investigated the effect of multipass runs on the mechanical properties of a arc - welded mild steel plate and observed higher toughness values for weld made under multipass runs than for single pass and unwelded metal, while the hardness values of welds made under multipass was lower than that made under single pass but was higher for the unwelded metal. Tensile strength values for weld made under multipass runs were lower than that of the unwelded metal.Thus, he concluded that the overlapping heat inputs resulting from the multipasses had significant effects on the mechanical properties of weldment. Adedayo *et al.,* (2011) while studying tempering heat treatment effects on steel welds revealed that hardness increased with increase in carbon content but toughness decreased. Kumar and Shahi (2011) investigated the effect of vibration on cooling characterization of weld pool. The cooling curve showed that the application of vibration increases the thermal gradient during the welding operation. Comparatively faster cooling was found during the vibratory welding condition. Adedayo,*et al*., (2010) studied the effects of initial elevated metal temperature on the mechanical properties of a arc-welded mild steel plate and found that, hardness, tensile strength and toughness properties of arc-welded steel plate were higher in the heat affected zone and lower on the base metal in all the welding conditions. Impact of initial metal preheat on mechanical properties diminishes with increasing temperature in the heat affectedzone. Microstructures of presented specimens differ from the no preheat specimen, showing traces of precipitated bainite. Oluwole and Omotoyinbo (2010) while investing the effect of welding current and voltage on the mechanical properties of wrought aluminium alloy concluded that at constant voltage and welding current of 100A and 75A tensile strength and hardness values increase but impact strength decrease. They also established that the maximum tensile strength and hardness was produced at the welding current of 100A and 75A respectively. Boumerzoug *et al.,* (2010) in their study of the effect of welding on the microstructure and mechanical properties of an industrial low carbon observed that the weld metal and HAZ regions recorded the highest hardness values compared to the base metal region. The variation in hardness across the weld was attributed to residual stresses introduced after the welding, grain size, phase composition and metallic inclusions. Pouranvari, (2010) while investigating the welding of grey cast iron by shielded metal arc welding process using nickel based filler metal concluded that welding of grey cast iron with nickel based filler metal and applying PWHT can serve as a solution for cast iron welding problems. Ren *et al.,* (2010) investigated the effects of welding wire composition and welding process on the weld metal toughness of submerged arc welded pipeline steel revealed that optimal contents of Mn, Mo, Ti-B, Cu and Ni alloying elements in welding wires improved the low temperature toughness of weld metal due to the formation of proeutectoid ferrite and bainite which suppressed acicular ferrite increase. Tewari *et al.,* (2010) revealed that optimum weldability for mild steel can be achieved with welding current of 105amp, arc voltage of 24volt, welding of 110.39mm/min and heat input of 1369.68J/mm using E6013 with a diameter of 2.5mm. Nnuka *et al*., (2008) studied the effect of electrode types on the mechanical properties and structure of welded steel joints using shielded metal-arc welding process and showed that maximum tensile strength was obtained for low carbon and medium carbon steels when stainless steel electrode was used and that gauge 10 electrode was not suitable for low carbon steel joints while gauge 12 electrode was best suited for medium carbon steel joints when hardness and impact strength are the most desirable properties. Nwoye, (2008) worked on the comparative studies of the cooling ability of hydrocarbon based media and their effects on hardness of the heat affected zone (HAƵ) in weldments. His research focused on the hardness that could be produced using hydrocarbon based media relative to that from water and air employing shielded metal arc welding process on aluminum, cast iron and mild steel of known composition. The study showed that the heat affected zone of specimens quenched in water gave the highest hardness value, while those quenched in air gave the lowest. A comparison of the three hydrocarbon based media used, Palm oil gave the lowest hardness for the heat affected zone, while kerosene and groundnut oil maintained equal hardness for all the materials used (aluminium, cast iron and mild steel). The variation in hardness value produced at the heat affected zone by any given welding process is based on the cooling rate experienced by the heat affected zone (Lancaster 1987).Oluwole *et al*., (2008) studied the effect of welding current and voltage on the mechanical properties of welded joint of as-cast 6063 aluminium alloy using metal inert gas welding process. Abson *et al.,* (2006) reviewed post weld heat treatment exemption codes explained that PWHT applied to steel assemblies primarily to reduce the likelihood of brittle fracture by reducing the level of tensile welding residual stresses and by tempering hard, potentially brittle, microstructural regions. He stated also that some fabrication codes stipulate that the PWHT should be exempted in structures where the materials thickness is very small. Narongchai *et al.,* (2006) investigated the optimal factors of Flux Cored Arc Welding Process for steel ST37 applying composite Design method.The effects of current,voltage,stick out and angle on tensile of weldment were investigated by response surface methodology.The statistical analysis indicated that the model was adequate,possessing no significant lack of fit and with very satisfactory of the R^2 (0.985).The studies showed that the most appropraite value of the factors from the models is 300ampere of current,30volts of voltage,45millimeter of stick out,and 60degree of angle which gave the tensile strength of weldment equal to 7410Kgf. Ghosh *et al.,* (2004) while investigating the influence of pre and post weld heating on the weldability of modified 9Cr-1MoV-Nb steel plates under SMAW and GTAW welding processes concluded that the increase of preheating and PWHT coarsened the microstructures of weld and HAZ and significantly influenced the properties of the welded joints. Wiley (2004) studied welding of tool steels, concluded that under no circumstances should a tool be welded at room temperature. Tool steels in the hardened condition always should be reheated for welding to a temperature not to exceed the tempering temperature and should be maintained as closely as possible at this temperature during welding operation. Annealed tool steel should be placed in a furnace immediately after welding and re-annealed. Abella (2002) studied the effect of weld penetration on mild steel plate using shielded metal-arc welding process and showed that the highest hardness value was obtained at the heat affected zone for the current value of 100amps and 300amps while the hardness value for other heat affected zones remain constant. This was attributed to the temperature gradient established in the steel weldment. Nenad *et al.*, (1999) conducted a comparative study on the hardness characteristics, mechanical properties, microstructures and fracture mechanisms of the thermite welded rail steel joints before and after heat treatment concluded that the heat treatment of the welded joints improves the mechanical properties (tensile strength and ductility), and changes the fracture mechanism from brittle to ductile. The improved strength and ductility were attributed to the finer ferrite-pearlite microstructure and the different fracture mechanism. Olabi and Hashmi (1995) and Hashmi and Olabi (1993) in their separate studies on the effect of post weld heat treatment on the mechanical properties and residual stresses of welded structural steel and martensitic stainless steel respectively, concluded that post weld treatment improves the toughness by 15%, without making any significant difference to the tensile strength and hardness but has significantly reduces the residual stresses by 70%. Thomas, *et al.*, (1993) while studying the effect of pre and post weld heat treatments on the mechanical properties of electron beam welded Ti-6A-4V alloy concluded that the as-welded specimens exhibited about 80% of the tensile ductility and about 90-95% of the impact/fracture toughness of the base metal. The low temperature stress relieving carried out subsequent to the welding operation improves the tensile properties but decreases the toughness at the fusion zone. Krishnan and Rao (1990) studied the effect of PWHT on microstructural changes and ferrite content in austenitic weld metals. They applied three different heat temperatures 600, 800 and 1000 °C and three different duration time 1, 10 and 100 hours. They used two different welding processes TIG and SAW. The results showed that the PWHTs and the heat input affected the shape of the ferrite network, and the network transformed to globules in some of the PWHT conditions. Burget and Blauel (1988) investigated the mechanical strength and fracture mechanics of (crack tip opening displacement) welded joints. He used submerged arc welding, the base metal was modified steel (TT St E36), the initial plate thickness was 60 mm and a wire electrode of type S3 was used. The welds were examined in the as-welded state and after stress relief annealing (570°C for 2.5 hrs.). The investigation involved comparison between the tensile strength, yield strength, hardness, and impact energy for the plates and pipes before and after heat treatment. The paper also has discussed the characteristic of the heat affected zone in the welded component. The results showed that in all cases, comparably lower fracture toughness characteristic values were obtained for the heat affected zone. Gauzzi and Missori (1988) investigated the microstructural transformations in austenitic ferritic joints. They carried out hardness test across the welding specimen in the as-welded condition and in the as-welded-tempered condition. Different types of pre-heating and PWHT was made for different types of filler metal. Salkin (1988) reviewed the ideas and codes on stress relief heat treatments of welded components. The major points in his study are that the residual stresses are located in the welded joint and in its direct vicinity. Generally, reach a level close to the yield strength of the metal with or without constraint having occurred during welding. The stress relief heat treatment generally, produces a softening of the base metal and can also have an influence on brittle fracture resistance. The stress relief heat treatment has a negligible effect on the coarse grain structure and the residual stress heat treatment allows an increase of the endurance limit ranging from 10 - 15%. He also studied the effect of welding process which might have a high energy input. There was no evidence about any improvement as a result of the high energy input. Farrar (1987) investigated the nature and kinetics of the phase transformation of metastable of delta-ferrite in two duplex stainless steel of the deposit weld metal. A microstructure examination was carried out for the weld metals in as welded condition and after the application of two different schemes of PWHTs, at 700°C for 15 hours and at 850°C for 8 hours. Vinokurov (1987) discussed the mechanical aspect of stress relieving by heat treatment and non-heat treatment and found out that heat treatment is the most effective method for relieving residual stresses in the welded components. He explained that post weld heat treatment has two aspects, first, relieving the negative stresses effect and second, improving the mechanical properties. Evans (1986a) investigated the effect of stress relieving on the microstructure and properties of C-Mn as welded metal deposits using different contents of C and Mn. Sixteen different metal deposits were used, all specimens were stress relieved at 580°C for 2 hrs. To evaluate the effect of stress relief heat treatment the investigator examined the metallographic and mechanical properties (hardness, tensile strength, impact). The results showed that this heat treatment has improved the notch impact and reduced the hardness and the tensile strength. Gill and Gnanamoorthy (1986) investigated the effect of alloy composition on the transformation kinetics of delta ferrite in AISI 316 stainless steel weld metal and found out that the transformation kinetics of delta-ferrite depend mainly on the carbon content of the weld metal. Mashinson, *et al*,. (1986) carried out an investigation to study the impact toughness of high frequency of pipes welded joints of St-52 produced by controlled rolling and welding by high frequency welding. Heat treatment at 820-840 °C was carried out, a partial recrystallization and equalization in the HAZ was obtained by the application of the heat treatment. The metal was completely recrystallized by heat treating at 930-950 °C. In both conditions, it was observed that it was possible to ensure stable impact toughness values of 20 J/cm^2. Toshioka (1986) reviewed the heat treatment deformation, residual stress and their effects which would be a result of some types of heat treatments. Vitek *et al.*, (1986) studied the microstructure of Fe-3Cr-1.5Mo-0.1V of thick section welded plates (102 mm thick). Electron beam welding was used to carry out the welding. An optical and electron microscope was used to observe the structures. The structure varied between bainite and ferrite and after PWHT the microstructure was mostly tempered bainite. Zubchenko, *et al.,* (1986) investigated the effect of temperature and time conditions on hardening welded joints in 15Kh2MFA and 15Kh2NMFA steels and of their relaxation resistance. They also investigated the effect of temperature and heating time on the relaxation process of residual stresses in heat treatment. Different reheating temperatures were used, and the investigator considered the relation between the chemical composition and duration. Anon (1985) the results of investigation on post weld treatments of steel pressure vessels were reported. The author described the conditions of applied heat treatment according to different regulations (Dutch, French, U.S, and Japan). He also listed other types of treatments which are possible to affect stress relief in pressure vessels. Akhtar (1985) studied the effect of different welding parameters which could lead to optimize the structural integrity of weldments made from 13/2 and 13/4 martensitic stainless steel base metals with austenitic 15/25 and a 50 per cent cobalt containing weld metals. He investigated the effect of weld metals and other different welding variables such as, pre-heat, PWHT and heat input on the mechanical properties. The mechanical tests carried out were hardness, tensile strength, impact energy and corrosion fatigue. Bmankirski (1985) investigated the mechanical properties of welded joint on 20K sheet plate (GOST 5520-69) 40 mm thick. He compared these properties under three conditions, (1) initial condition, (2) tempering [heating temperature 625 +10°C, holding time 2 hours, cooling in air], and (3) after vibration treatment [which was carried out at the resonance frequency of 24-32 Hz for a time of 20-25 min]. Welding was carried out by manual arc-welding process. The result detected that tempering reduced yield strength and hardness but increased impact toughness. Vibration loading resulted in slight increase of strength and reduced ductility. Hrivnak (1985) studied the effect of different type of stress relieving heat treatment for C-Mn steels. His paper includes a comparison between the hardness variation for as welded and heat treated conditions and a comparison for the notch toughness of different heat treatment conditions. The results showed that the most improved microstructure and mechanical properties was obtained by applying heat treatment with soaking temperatures of 550 to 700°C. Adoyan, *et al.*, (1984) used a new form of specimen to assess the effect of welding technology and all types of external loading on the distortion of the structure. They used a disc shaped specimen which was made of St3 steel for a range of heat treatment temperatures between 250 °C to 600°C for 3 hrs. The efficiency of stabilization of dimensions by low temperature heat treatment (250°C) in distortion caused by the relaxation of the residual stresses was almost identical with that achieved in high temperature tempering (600°C). Evans (1983) and (1986a, b and c) studied the effects of carbon, silicon, sulphur and phosphorus on the microstructure and properties of C-Mn steels. Different types of testing was carried out to evaluate the effects of C, Si, P, S, on hardness, tensile strength, impact and metallographic structure by changing the content of the elements C (0.05 - 0.15%), Si (0.20 - 0.90%), S

(0.007 - 0.046%), and P (0.007 - 0.040%). Heat treatments were applied and mechanical tests were carried out on specimens before and after heat treatment. The tests results showed that the hardness and tensile strength increases as the percentage of carbon was increased while the impact energy decrease. Also, the hardness and tensile strength increases as the percentage of phosphorous and silicon was increased, while there was no remarkable change on the impact strength. The increase in the percentage of sulphur resulted in decreased of hardness, tensile strength and impact energy. Evans, (1982a) studied the effect of heat input on the microstructure and properties of shielded metal arc welding. The metallographic studies revealed that the structure of as deposited weld metal changed as heat input was increased. It was found that the increase in the bead size was accompanied by a decrease in the amount of acicular ferrite and coarsening of the microstructure. The tensile properties were reduced by increasing the heat input, and an optimum impact properties were achieved at approximately 2 KJ/m. Evans (1982b, c and d) studied the effect of different factors on the microstructure and mechanical properties (interpass temperature, electrode diameter and welding position). Fidler (1982) investigated the influence of heat treatment on the residual stresses of AISI 316 welded components. He applied different types of heat treatments, four different soaking temperatures 650, 750, 850 and 1050 °C and three different duration time 1, 10 and 100 hours. The results showed that there was a sufficient reduction in the residual stresses after applying PWHT for 1 hour at 650 °C.

Takemoto, *et al.*, (1982) studied the effect of post weld cooling method (PWC) and PWHT on stress corrosion crack (SCC) of butt welded pipes of AISI 304. Stress relaxation method was employed to estimate the residual stresses in the welded pipes. Comparisons were made between as welded conditions and after PWHT and PWC to assess the value of stresses which will cause the SCC. These comparisons also included the effect of the pipe diameters and thicknesses. The results showed that there is a good improvement in the welded component after the application of PWC treatment. Zhou (1981) did an investigation which aimed to improve the mechanical properties of 2Crl3 steel welded joints and to avoid the distortion and welding crack. The mechanical properties tests were applied on six different types of deposited metal and different types of preheating temperatures were used. The results showed that the impact toughness of the welded joints decreases with the increase of the preheating temperature. Bosansky *et al.,* (1977) investigated the effect of niobium (Nb) and molybdenum (Mo) on weld toughness as a function of stress relieving heat treatment. Different percentage of niobium with and without molybdenum with different conditions of stress relief heat treatment (different temperature and cooling time) were looked at, and good result was obtained for heat treatment at 580°C for 1 hr. Hardness measurements and electron microscopy were used to define the difference between the heat treatment conditions used. Ito et *al.* (1970) study the effect of chemical composition, cooling rate during welding, pre and post weld heat treatment on the toughness of the welded joint.

2.20.1 Summary of literature review and knowledge gap

The various studies carried out by the different seasoned authors clearly showed that a large number of research works have been carried out to study the effects of welding parameters on welded components. Most of the studies were carried out to evaluate the effects of residual stresses on the welded steel parts. Other studies were focused on the application of the different types of treatments (mechanical and thermal) to reduce the residual stresses in the welded components. Some studies were also carried out to investigate the effect of post weld heat treatment (PWHT) on the reduction of the residual stress. However, not much has been done on the use of mild steel electrode type in the welding of micro-alloyed steels employing shielded metal arc-welding process to determine their impact on weld metal properties. Considering the importance of electrodes in accomplishing a welded joints; a slight difference in alloy composition of electrode can strongly impact on the properties of the resulting weld. Therefore, the present study is intended to investigate the effects of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel weldmentwith the view of establishing the electrode type with the alloying element contents and heat treatment parameters to produce the desired weld metal microstructures and mechanical properties suitable for different applications. The based approach consists of correlation of the microstructure with the mechanical properties of the micro-alloyed steel weldment and evaluation of the mechanical properties(tensile strength, impact strength, yield strength, hardness and ductility) of the steel weldment and parent metal because of their significance on service behaviour.

CHAPTER THREE

MATERIALSANDMETHODS

3.1Materials and Equipment

The materials and equipment used in the research study were: Micro-alloyed steel plate (5mm thickness), shielded metal-arc welding machine, electrodes, electrode drying oven, stop watch, digital multimeter, metallurgical cut-off wheel, grinding and polishing machine, emery papers, etchant, optical microscope, scanning electrode microscope, tensometer, impact testing machine, hardness tester and water. The commercial grade of the micro-alloyed steel for this research work was supplied by Donasula Brother's Limited Warri, Delta State. Whereas the electrodes; E7016, E7018 and E7024 were obtained from the welding materials and allied products section of the Bridge Head Market, Onitsha, Anambra State. The chemical composition of the E7016, E7018, E7024 electrode core wires and the micro-alloyed steel were analyzed at Engineering Materials Development Institute, Akure, Ondo State using EDX3600B energy dispersive x-ray fluorescence spectrometer and the results presented in Table 3.2. The photograph of the shielded metal arc-welding unit and muffle furnace are shown in Appendices 2 and 3 respectively.

3.2 Experimental procedure

3.2.1 Welding operations

The welding operation was carried out in the welding workshop of the Metallurgical Training Institute, Onitsha, employing a shielded metal-arc welding machine (Model: Safex M340). The SMAW process was adopted because it is reported to be suitable for welding ferrous and non-ferrous metal, versatile, portable and low cost. A total of two hundred and twenty five specimens with dimension, 300x60x5mm were used for the research study. The welding and post weld heat treatment (PWHT) operations were categorized into three stages namely: As-welded condition, as-welded and quenched condition, and as-welded and tempered condition. Prior to the welding, the open circuit voltage of the welding unit (the voltage across the terminals when the welding unit was not loaded), the arc voltage (voltage across the welding terminals when the welding unit was loaded) and the electrode travel speed were measured with a digital multimeter and stop watch respectively. The measured values were 60volt, 29volt and 2.4mm/s for the open circuit voltage, arc-voltage and electrode travel speed, respectively. These parameters were used to compute the heat input as shown in Table 3.1, for the different welding current using equation (3.1) Institute of Perguruan Raja Melewar (2007).

3.2.1.1 Welding operation 1: As-welded condition

Forty five pieces of the micro-alloyed steel plate were used at this stage. Using bead-on-plate welding technique, weld beads were deposited longitudinally on a straight line marked with chalk at the centre of each plate with dimensions (300x60x5mm) using E7016, E7018 and E7024 electrode types with preset welding current of 90, 94, 98, 102 and 106 amperes respectively.

3.2.1.2 Welding operation 11: As-welded and quenched condition

Similarly, using E7016, E7018 and E7024 electrode types with preset welding current of 90, 94, 98, 102 and 106 amperes respectively, weld beads were also deposited on each plate. After the welding, the welded specimens were allowed to cooled to room temperature before being inserted into the heating chamber of a muffle furnace and then heated to a preset austenitic temperature of 910^0C, soaked for 30 minutes to allow for uniformity of temperature across the welded steel plate and for the transformation of the room temperature phases of the steel to a single austenite phase. After which the specimens were removed in turn and quenched in a tap water in a bucket.

3.2.1.3 Welding operation 111: As-welded and tempered condition

Using the same electrode types and welding current settings as in welding operation 1 and 2, weld beads were also deposited longitudinally on a straight line of each plate. After the welding operation, the welded samples, numbering 135 were subjected to different tempering temperature and varied soaking time. The tempering operation was divided into three groups based on the tempering temperature used. Each group consists of test samples welded with E7016, E7018 and E7024 electrode types at the preset welding current of 90, 94, 98, 102 and 106 amperes respectively. Firstly, specimens welded using E7016 electrode at the welding current of 90, 94, 98, 102 and 106 amperes were placed inside the heating chamber of the muffle furnace which was preset to 250^0C and soaked for 60, 90 and 120 minutes respectively. The process was repeated for the other two groups using tempering temperature of 350^0C and 450^0C, respectively for the second and third group. After the welding and heat treatment process, a total of one hundred and sixty six (166) samples were cut out from the as-welded samples, as-welded and quenched samples, as-welded and tempered samples and base metal, and machined to the required dimensions for each test (hardness, impact and tensile strength) and marked for identification. For each test, three samples were prepared in order to authenticate the result. Samples for metallographic analysis were also cut out from the un-welded (base metal), weld metal zones and heat affected zones of the welded and heat treated welded metals.

Table 3.1: Calculated heat input per unit length for the different current used

Welding current (ampere)	Heat input (Kj/mm)

90	0.87
94	0.91
98	0.95
102	0.99
106	1.02

$$\text{Heat input} = \frac{\text{welding current x arc voltage x K}}{\text{Welding speed x 1000}} \tag{3.1}$$

K= 0.8, for SMAW

Table 3.2: Elemental composition of test materials

Element (wt %)	Base metal	E7016	E7018	E7024

C	0.15	0.12	0.07	0.05
Si	0.40	0.75	0.61	0.35
P	0.05	0.03	0.015	0.02
S	0.03	0.034	0.011	0.014
Ti	0.01	0.021	0.012	0.020
Al	0.02	0.03	0.03	0.02
Cr	0.08	0.06	0.03	0.03
Mn	0.35	0.45	0.40	0.35
Mo	0.05	0.30	0.02	0.01
V	0.12	0.01	0.06	0.01
Nb	0.03	-	-	-
Zn	0.002	0.001	0.002	0.001
Ca	0.001	0.002	0.001	0.001
Ni	1.1	0.04	0.02	0.02
Cu	0.16	0.130.120.11		
Fe	97.45	98.02	98.59	98.99

3.3Design matrix and response surface methodology

After careful screening of the vital factors (welding current, soaking time temperature).The optimal (custom) design was chosen because of it flexibility in accommodating different number of levels for each factor and also, placing equal emphasis on estimating main effects and interactions.The independent design variables with the corresponding design levels based on optimal design used in the research study are listed in Table 3.3. The maximum and minimum values for each of the independent variables were chosen based on preliminary studies carried out. The welding current range (90-106 ampere) selected for this study was based on the current range specified for the electrodes by the manufacturers. The tempering temperature range (250-450^{0}C) and soaking time (60-120 min.) were selected so as not to cause excessive decrease in hardness and strength of the micro-alloyed steel weldment while improving impact strength and percent elongation. The whole design consisted of 20 experimental runs as listed in Table 3.4. The experiments were performed at all the design points in randomized order.Each factor was replicated more than once in order to obtain a more stable average result. The RSM design on the three factors were generated with the aid of Design-Expert version10 software (2016).

Table 3.3 Factorsand levels for optimal design

Variable	Unit	Level			
		1	2	3	4
Current	amps.	90	94	98	102
Soaking time	min.	60	90	120	
Temperature	^{0}C	250	350	450	

Table 3.4: Experimental design for the welding and heat treatment of micro-alloyed steel

Run	Factor 1 Current (amps)	Factor 2 Soaking Time (min)	Factor 3 Temperature (^{0}C)	Response 1 Tensile Strength (KN/m^2)	Response 2 Impact Strength (J)	Response 3 Elongation (%)
1	102	120	450			
2	90	120	450			
3	94	120	350			
4	94	90	450			
5	90	90	350			
6	102	120	250			
7	94	120	350			
8	94	90	450			
9	98	60	350			
10	90	120	250			
11	102	120	350			
12	102	90	350			
13	98	60	250			
14	102	90	350			
15	94	120	350			
16	90	90	250			
17	90	60	350			
18	98	90	250			
19	102	60	450			
20	90	90	450			

3.4 Mechanical tests

3.4.1 Tensile test

The tensile test was performed in the strength of materials laboratory of the Department of Mechanical Engineering, Ahmadu Bello University, Zaria, on a universal tensile testing machine (Model: T42B2) with a maximum capacity of 500KN.The photograph of universal tensile testing machine is shown in Appendix 3. The tensile test samples were prepared according to America Petroleum Institute (API) code: 1104, where all the test samples were machined to 230x25mm dimensions.

3.4.1.1 Procedure for the tensile test

The tensile test was performed in accordance to API 1104 standard using a universal tensile testing machine to evaluate yield strength, tensile strength and percent elongation. The longitudinal weld test samples were clamped at both ends on the holding grips of the machine and hydraulic power was then applied to force the specimen apart. A pressure guage recorded the load applied. As the load increased the dial registered the load in Kilo Newton (kN) until fracture occured. The machine is designed to measure the instantaneous applied load and the resulting elongations simultaneously using an extensometer. A uniform gauge length of 100mm was used for all the test samples. In the longitudinal weld test, the direction of loading of the samples was parallel to the weld axis (Fig. 3.5). The reduced section of the sample contained the weld, heat affected zone, and base metal.During testing, all zones strained equally and simultaneously. Weld metal, regardless of strength, elongate with the base metal until failure occurs (America Welding Society 1987). Thus, the test provides a quantitative information about the weld strength. The tensile properties obtained after the test were yield strength, tensile strength and percent elongation.

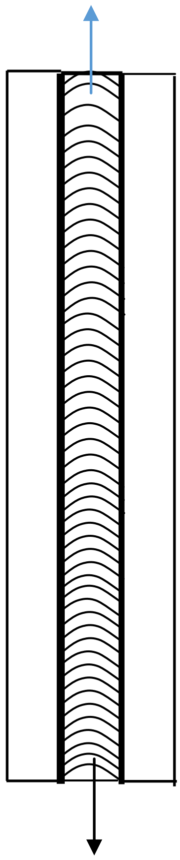


Fig. 3.5 Tensile test sample, showing the direction of loading.

(a) (b)

Fig. 3.6: (a) Tensile sample before testing and (b) Tensile sample after testing

3.5 Impact test.

The Charpy impact was conducted at the strength of materials laboratory, Department of Mechanical Engineering Technology, Delta State Polytechnic Ogwashi-uku. The photograph of the Charpy impact testing machine is shown in Appendix 4. The specimens for the Charpyimpact test were prepared in accordance to ASTM E23 standard using Charping impact testing machine (Model: JB-300B/500B). Based on the thickness of the base metal as-received, the ASTM E23 sub size dimensions which corresponded to the base metal thickness was 55mm x 5mm x 5mm, 1mm depth V-notch with an angle of 45^o

and a root radius of 0.25mm. The prepared test samples were placed in turn on a horizontal support with the notched face directly opposite to where the weighted pendulum would strike the sample. The weighted pendulum was released from it rest position at a fixed height to strike each of the sample and the energy absorbed to fracture the specimen was read and recorded.

(a) (b)

Fig. 3.8: (a) Impact samples before fracture (b) Impact samples after fracture.

3.6 Determination of hardness values

The hardness test was carried out in the Materials Testing Laboratory of the Department of Industrial Metallurgical and Foundry Engineering, Metallurgical

Training Institute, Onitsha. The photograph of Brinell hardness testing machine is shown in Appendix 4. The test was performed in accordance to ASTM D785 standard. Each of the prepared sample was placed on the anvil of the elevating screw of the manually operated Brinell hardness testing machine (Model: 900-355). Aforce of 7355N was then applied on the 5mm diameter tungsten ball indenter and maintained for 5 seconds to create surface indentation on the test sample. The force was applied at two different spots on each of the test specimen and the diameter of the indentation created was read using a micrometer with an inbuilt microscope with a magnification of 20x.The average reading was taken and was used to compute the Brinell hardness values directly from the machine.

3.7 Optical analysis of the welded and heat treated samples.

For effective study of the internal structure of the samples, five sequential processes were performed on each of the samples. They include mounting, grinding, polishing, etching, and micrographical examination under a optical microscope.

3.7.1 Mounting

Mounting was done to make for effective holding of the sample in order to grind conveniently.

3.7.2 Grinding

Both coarse and fine grinding were done. Coarse grinding involved the use of emery grit papers of grade 120, 180. 240, 320. while fine grinding involved using finer grit paper of grade 600. Both grinding were done by a to and fro rubbing of the specimen surface against the emery paper, thereby gradually wearing them away as the samples were transferred from one grit paper to the other. The specimens were washed and the direction of grinding changed by an angle of 90^0 in order to eliminate the previous scratch created by the former grinding. At the fine grinding stage, the scratches were almost invisible except for closer observation. The specimen were then taken for polishing to finally remove the fine scratches.Water was always applied to keep the temperaure at the minmum range within which no transformation of phase can occur.

3.7.3 Polishing

Polishing was done on a round rotating polishing plate on which the polishing cloth was properly fixed. Aluminimum oxide polishing compound (Al_2O_3) of particle size-0.05 microns was used for the polishing of the mild steel samples. In each case the fluid was applied to the cloth and as the plate rotated the sample was held against the direction of rotation on the plate with application of water at regular intervals. The product of the final fine polishing was a mirror like surface which reflected and shined brightly.

3.7.4 Etching

Etching is simply done by exposing the dried polished surface of the sample to an etchant in order to reveal the microstrcture under the polished surface. The samples were etched with 2% nital (solution of nitric acid in alcohol) to reveal the grain boundaries and internal structure. The surfaces were cleaned with water and gently dabbed with cotton wool soaked in alcohol.

3.7.5 Micro-examination.

The specimens were placed on the optical microscope which was adjusted to focusthe samples and the microstructures were photographed,using a magnification of X400.

3.8 SEM analysis of welded and heat treated samples

The physical structure changes of the welded and heat treated samples was done using SEM (model: Phenom ProX). The Samples were placed on double adhesive which was on a sample stub sputter coater by quorum technologies (Model: Q150R) with 5nm of gold. Thereafter the samples were taken to the chamber of the SEM machine where it was viewed via NaVCaM and the morphology stored in USB stick.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Microstructural analysis result

Fig. 4.1 shows the optical micrograph of the base metal (BM). The micrograph reveals white patches of fine grains of ferrite with dark spots indicating scattered carbide precipitates and small patches of pearlite. The characteristic features of these microstructure account for the relatively high values of hardness, yield strength, and tensile strength with corresponding low impact strength and percent elongation.

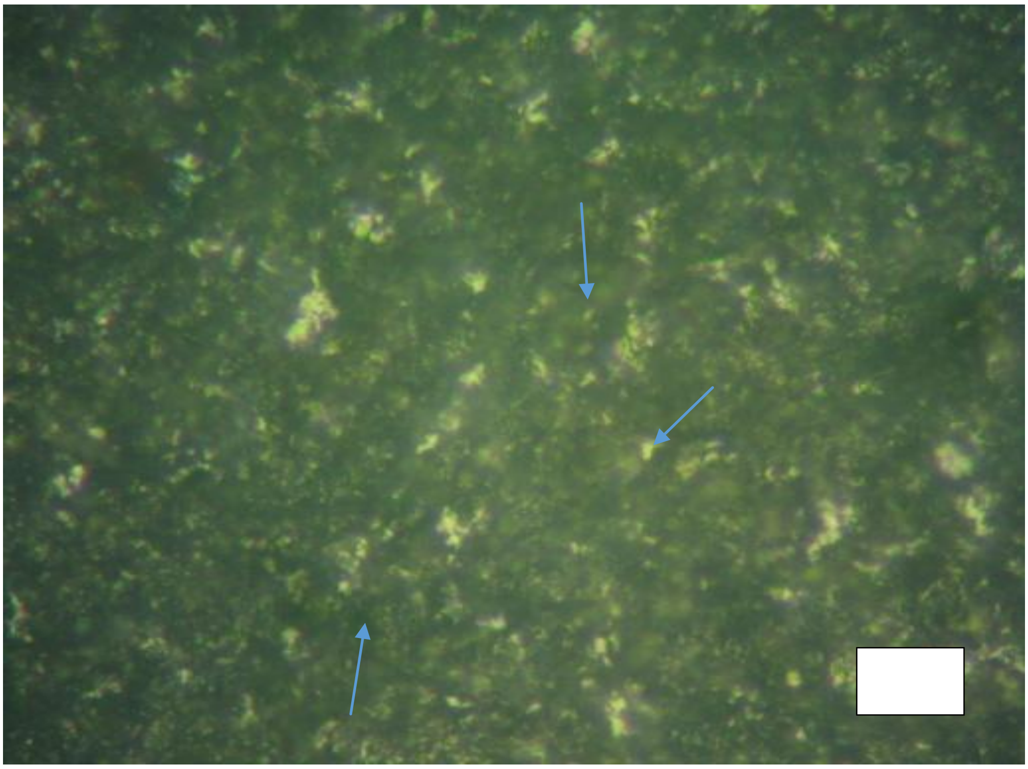
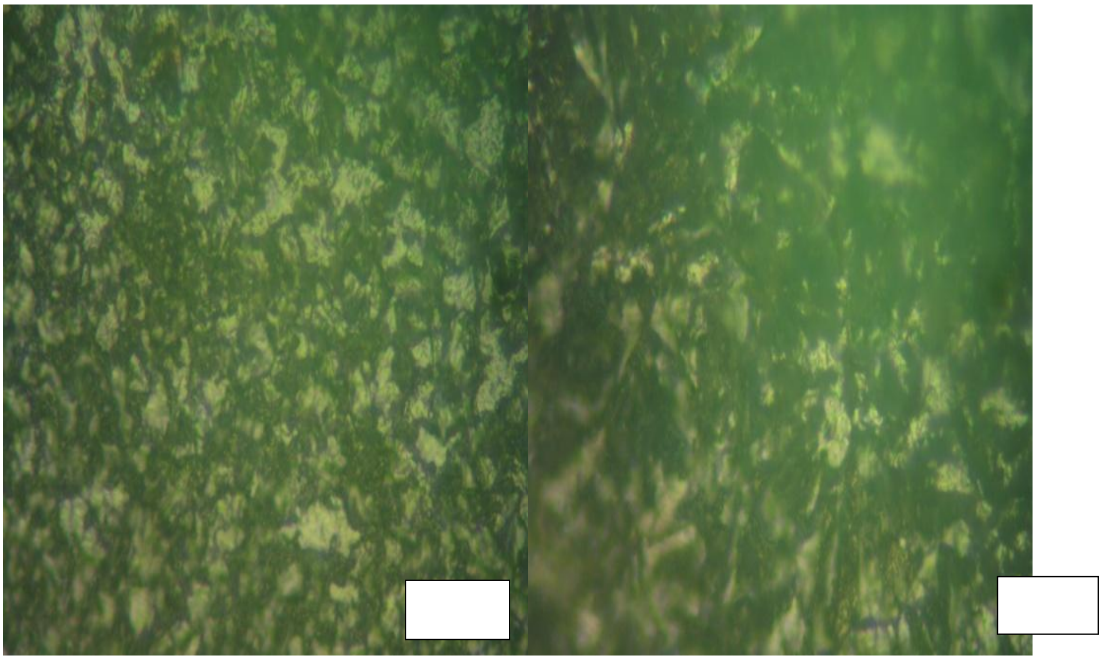


Plate 1: Optical micrograph of base metal (BM) as-received.

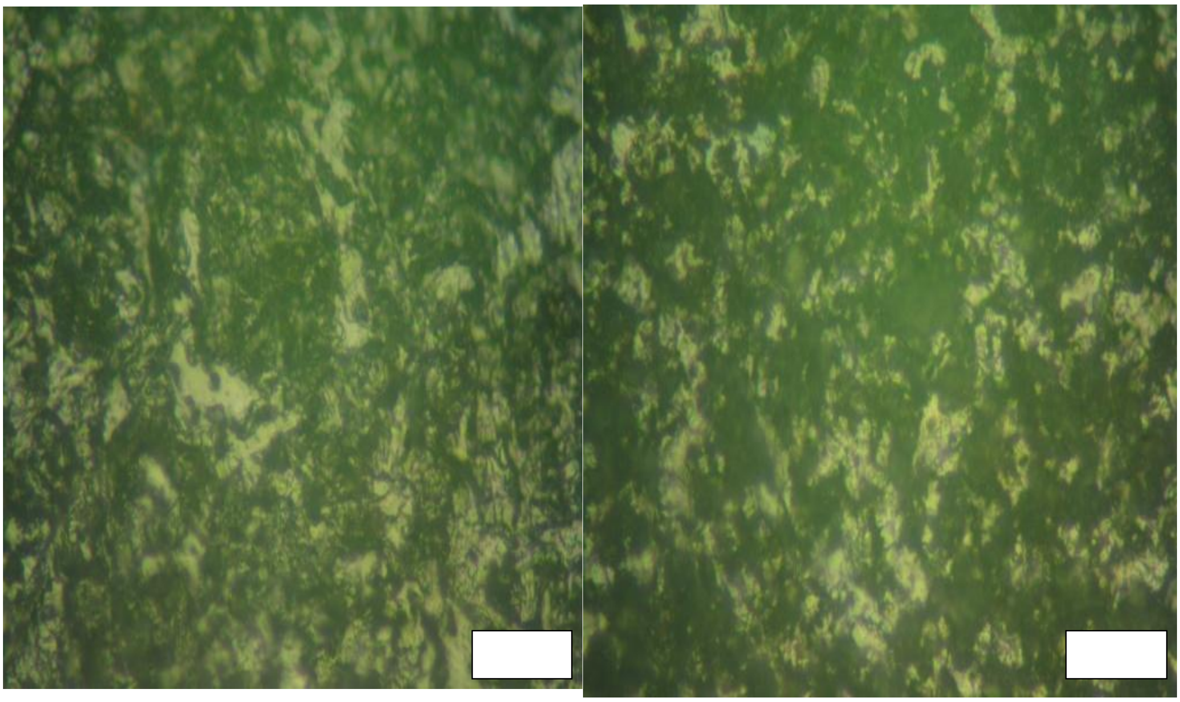
Plate 2 shows (a) weld metal (WM) and (b) heat affected zone (HAZ) of E7016 electrode as-welded specimen at welding current of 94 ampere. The microstructure of WM consists of finely dispersed carbide precipitates (dark patches), small patches of pearlite in ferrite microstructure. HAZ shows coarse distribution of ferrite and carbide precipitates. This explains the high hardness value obtained at the WM and low hardness at the HAZ, and improved yield strength, tensile strength, impact strength and percent elongation.



(a) (b)

Plate 2: Optical micrograph of (a) WM and (b) HAZ of the sample as-welded with E7016 electrode at 94 ampere.

Plate 3 shows (a) WM and (b) HAZ, of E7018 electrode as-welded specimen at the welding current of 94 ampere. The microstructure consists of fine distribution of Widmanstatten ferrite and carbide precipitates at the WM and coarse distribution of ferrite and carbide precipitates. The characteristic features of these microstructures account for the relatively improved mechanical properties of the weldment.

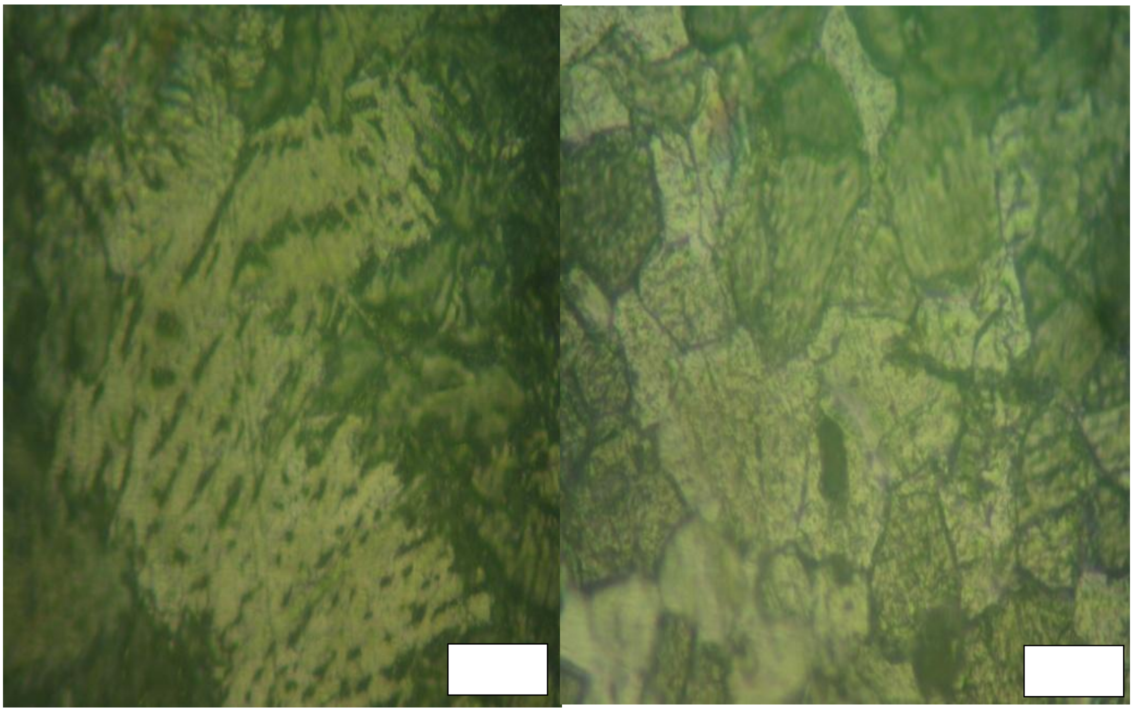


(a) **(b)**

Plate 3: Optical micrograph of (a) WM and (b) HAZ of the sample as-welded with E7018 electrode at 94 ampere.

Plate 4 shows (a) WM and (b) HAZ of E7024 electrode as-welded specimen at the welding current of 90 ampere. The microstructure reveals coarse distribution of carbide precipitates in ferrite matrix at the WM and coarser ferrite grains, pearlite and some carbides phase at the HAZ. This is responsible for the relatively lower hardness value recorded at the HAZ. The characteristic features of these microstructure account for the relatively lower values of hardness at the

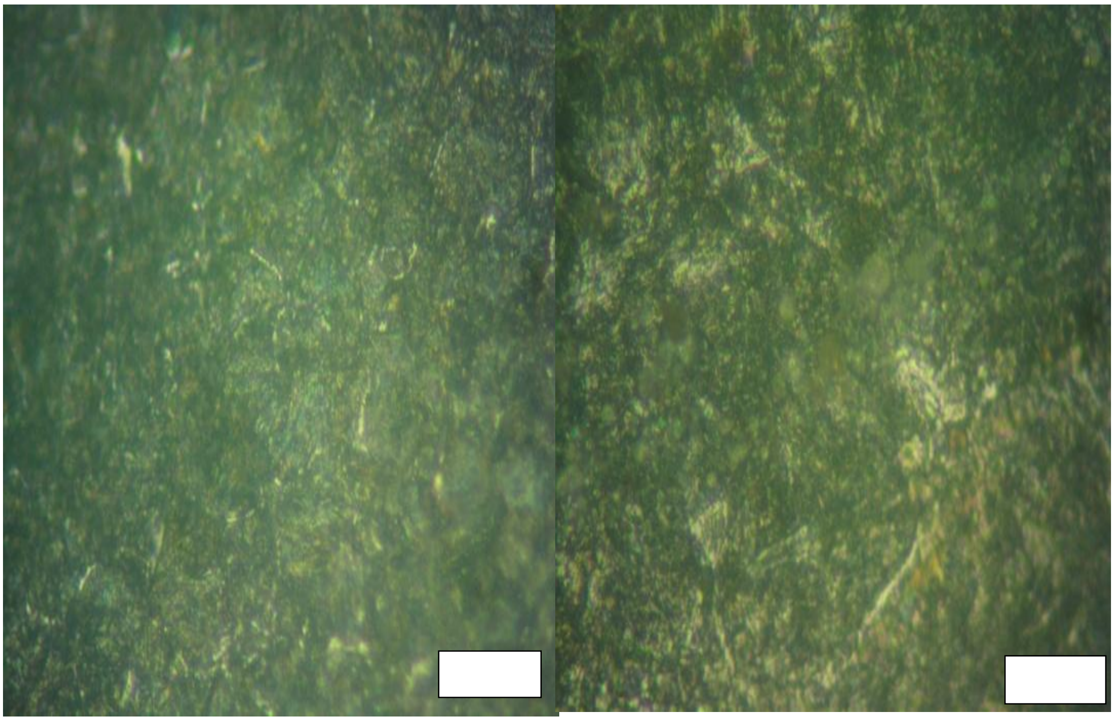
WM and HAZ regions, yield strength, tensile strength, but higher impact strength and percent elongation of the weldment.



(a) (b)

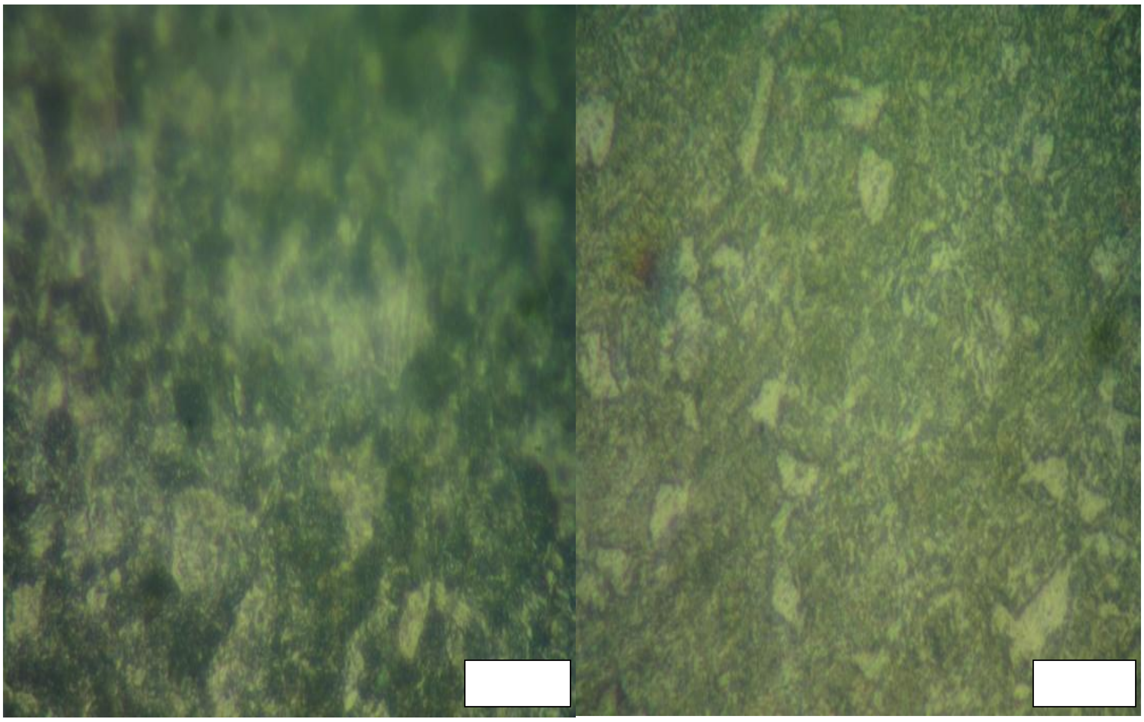
Plate 4: Optical micrograph of (a) WM and (b) HAZ of the sample as-welded with E7024 electrode at 90 ampere.

Plate 5-7 show the microstructure of (a) WM and (b) HAZ of E7016, E7018 and E7024 electrodes as-welded and quenched samples at the welding current of 102, 98 and 94 ampere respectively. The micrographs revealed various distribution of ferrite, carbide particles and pearlite whose proportion, amount and size at the WM and HAZ regions varies with the alloying contents of the different electrode types. The E7018 electrode welded specimen exhibited the best combination of tensile strength and percent elongation values followed by the E7016 and E7024 electrode types.



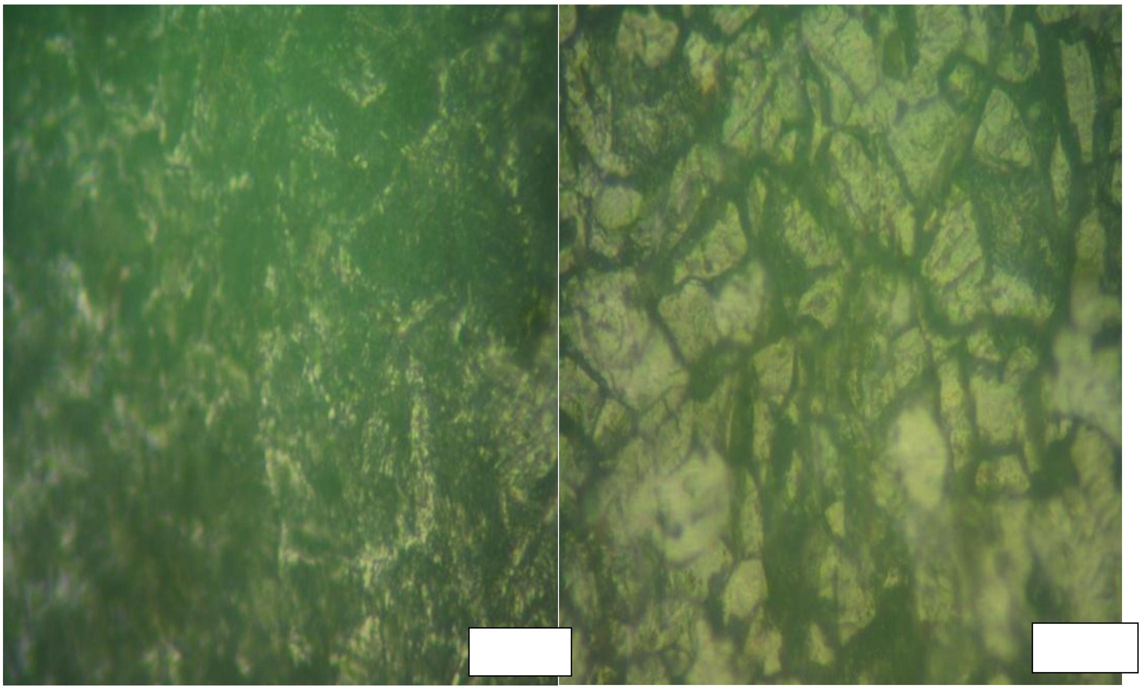
(a) (b)

Plate 5: Optical micrograph of (a) WM and (b) HAZ of the sample as-welded with E7016 electrode at 102 ampere and quenched.



(a) (b)

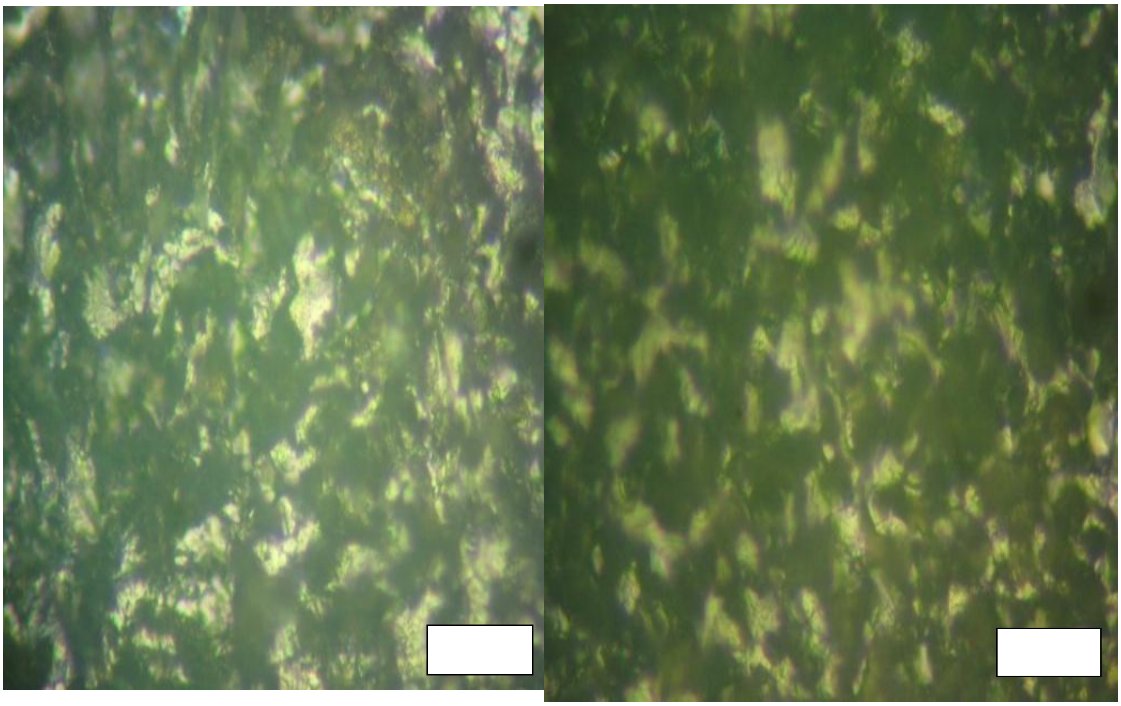
Plate 6: Optical micrograph of (a) WM and (b) HAZ of the sample as-welded with E7018 electrode at 98 ampere and quenched.



(a) **(b)**

Plate 7: Optical micrograph of (a) weld zone and (b) HAZ of the sample as-welded with E7024 electrode at 94 ampere and quenched.

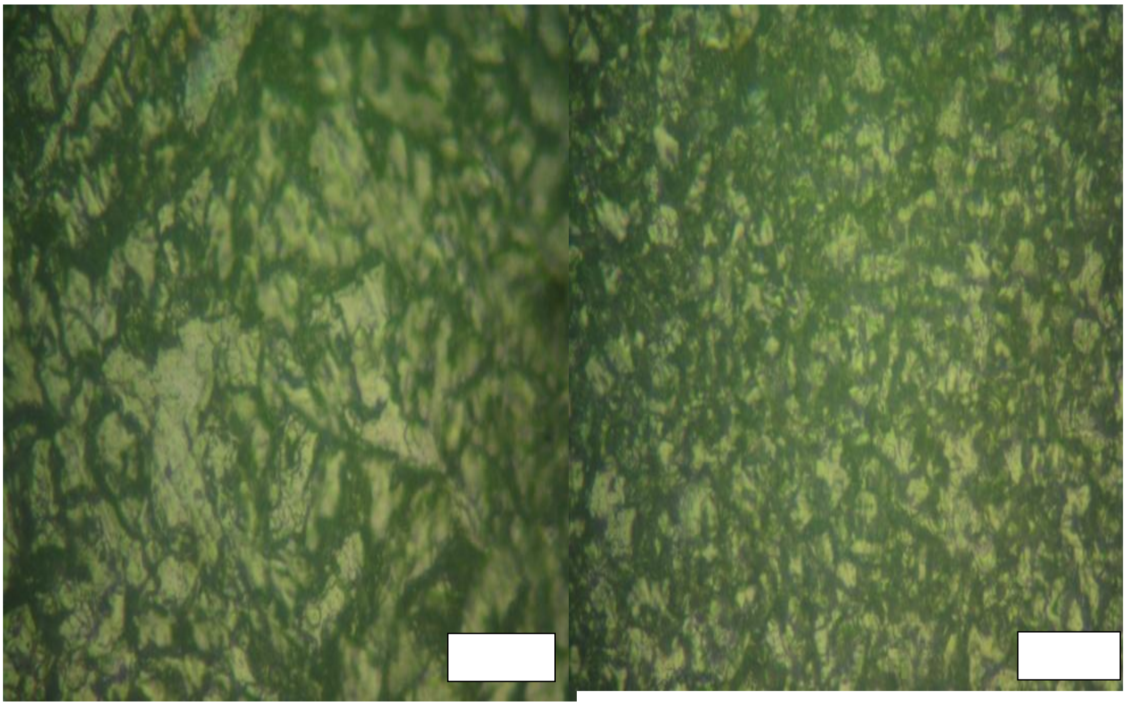
Plate 8 shows the micrograph of (a) WM and (b) HAZ of E7016 electrode welded sample at 102 ampere, tempered at 250^0C for 120 minutes. The micrograph revealed coarse ferrite matrix with dispersed carbide precipitates at the WM and coarser ferrite grains, some patches of pearlite and carbide phases in the ferritic matrix at the HAZ. The presence of these microstructures account for the relatively low hardness, yield strength, tensile strength and improved impact strength and percent elongation of the weldment.



(a) (b)

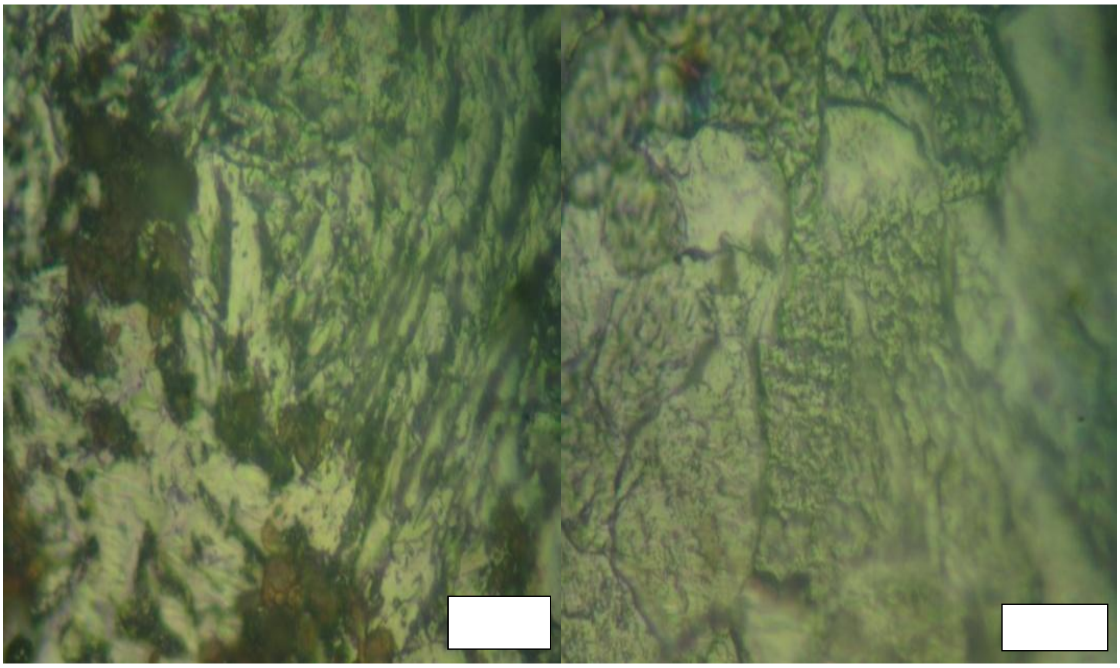
Plate 8: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7016 electrode at 102 ampere and tempered at 250^{0}C, soaked for 120 min.

Plate 9-10 show the micrographs of the specimens welded with E7018 and E7024 electrode types at the welding current of 90 ampere, tempered at 250^{0}C for 120 minutes. The coarse ferrite matrix with coarse carbide particles observed at the WM region and coarser ferrite matrix with coarse distribution of pearlite and carbide particles in HAZ of the E7018 electrode. Similar microstructures observed in the WM and HAZ regions of Plate 9 was also found in Plate10 but in this case, the extent of the coarseness of the microstructure at both zones of the E7024 electrode welded specimen was large, hence, the relatively lower hardness, strength properties and higher impact strength and percent elongation obtained for the weldment.



(a) (b)

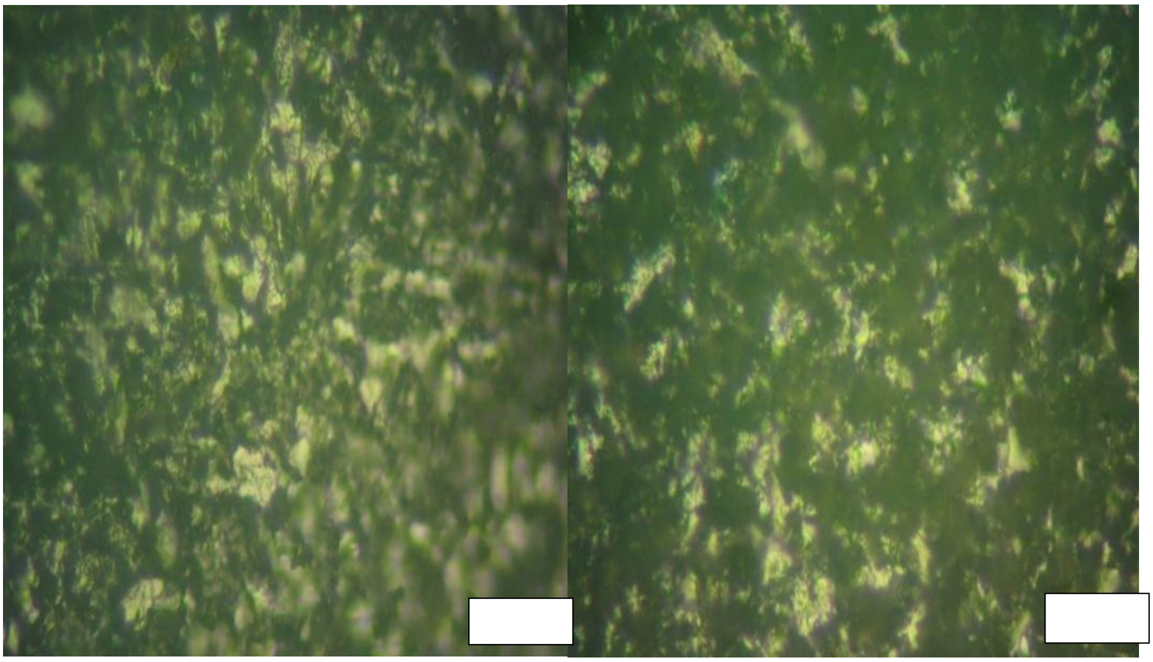
Plate 9: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7018 electrode at 90 ampere and tempered at 250^{o}C, soaked for 120 min.



(a) (b)

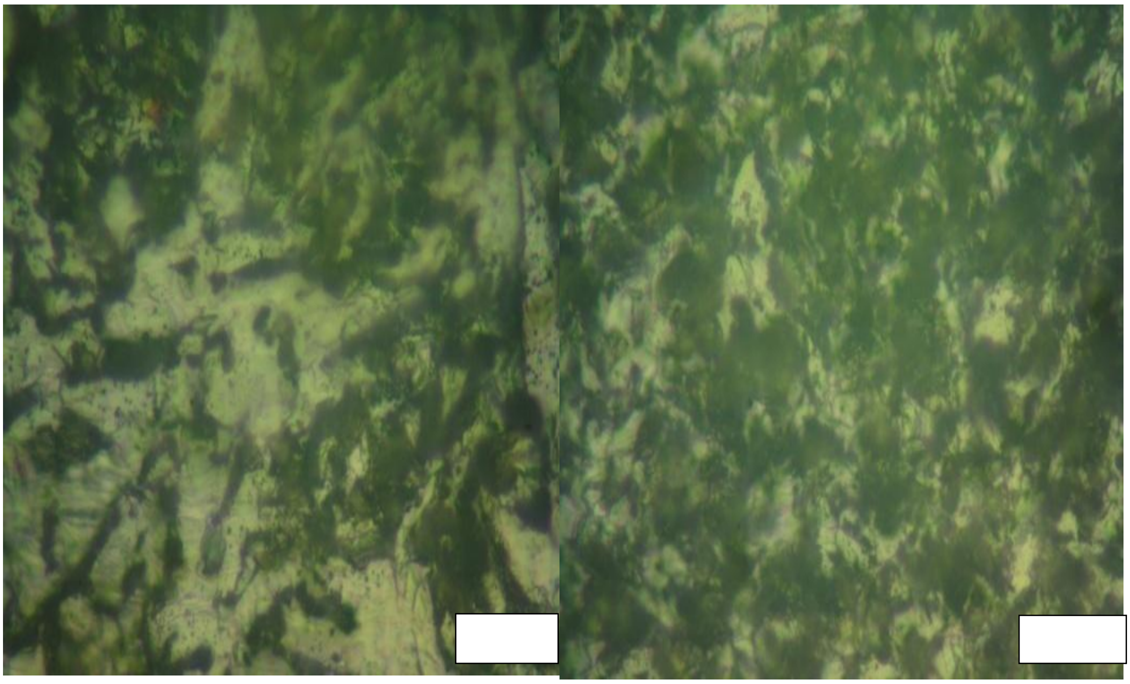
Plate 10: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7024 electrode at 90 ampere and tempered at 250^{o}C, soaked for 120 min.

Looking at the trend, the same explanation that holds for Plates 2-10 also applies to Plates 11, 13, and 4.16 (a) and (b), where the hardness at the WM regions are higher than at HAZ regions. The results of the hardness test in Tables 4.4-4.12 clearly demonstrated that the grain sizes of the WM region are finer than that of the HAZ region. However, the grain size of the microstructure, proportion and amount account for the different mechanical properties obtained at the different tempering temperature and soaking time. The coarse size of the precipitated carbide particles account for the enhanced impact strength and percent elongation, and reduced hardness and strength properties. Thus, the grain size of the microstructure in Plate 13 is responsible for the relatively high impact strength and percent elongation and relatively low hardness and strength properties. Likewise, the grain size of the microstructure in Plate 16 is also responsible for the improved impact strength and percent elongation and relatively lower hardness and strength properties.



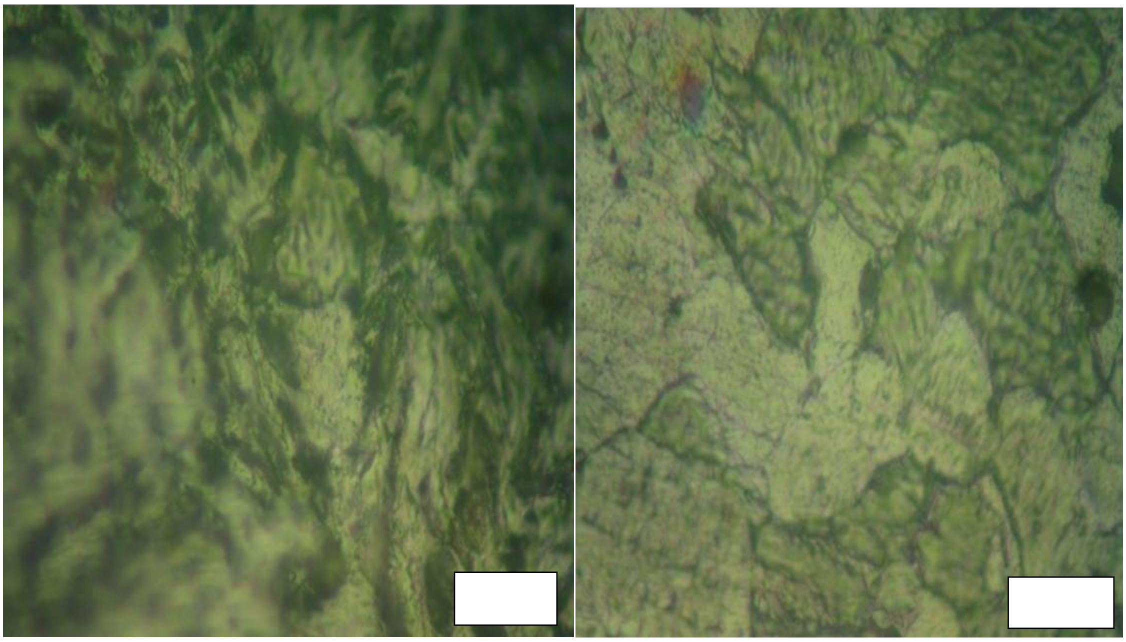
(a) (b)

Plate 11: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7016 electrode at 94 ampere and tempered at 350^0C, soaked for 60 min.



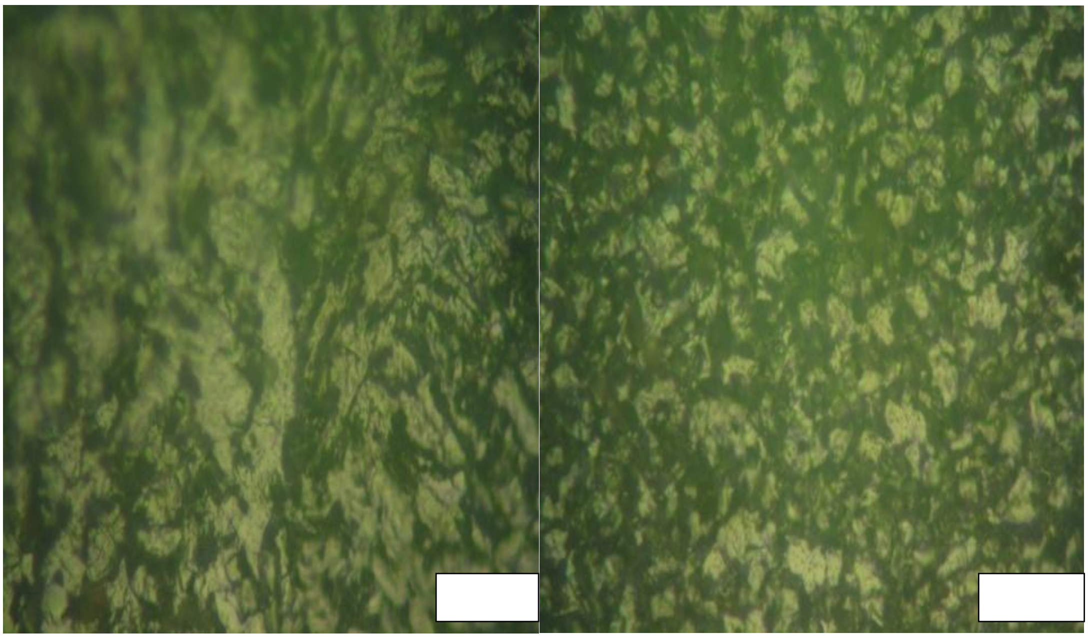
(a) (b)

Plate 12: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7018 electrode at 94 ampere and tempered at 350^oC, soaked for 60 min.



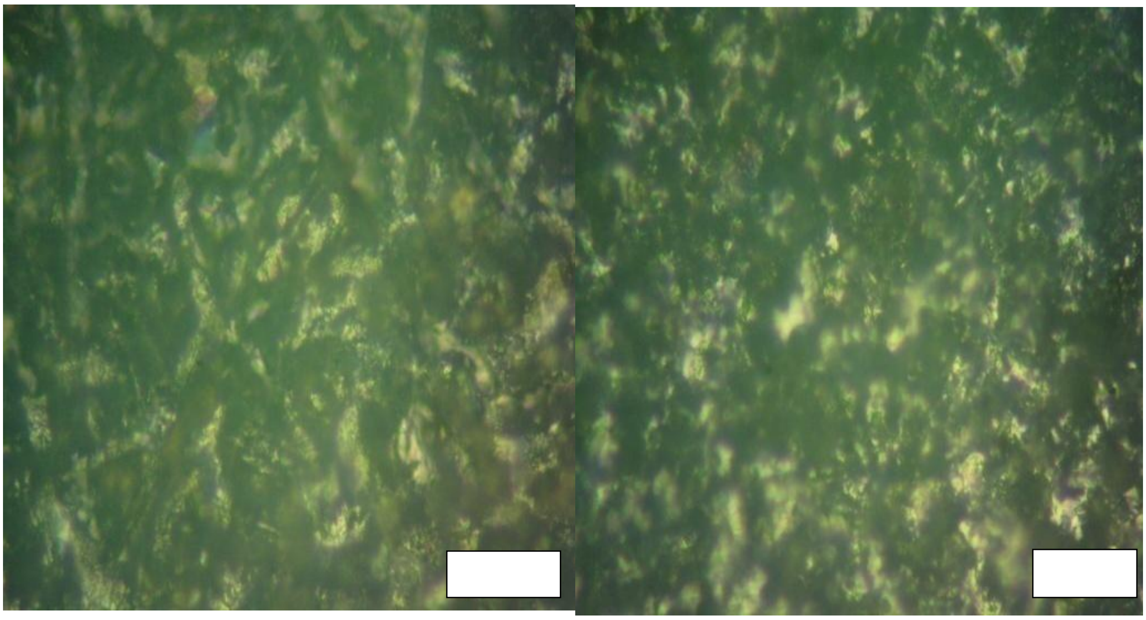
(a) (b)

Plate 13: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7024 electrode at 106 ampere and tempered at 350^{o}C, soaked for 60 min.



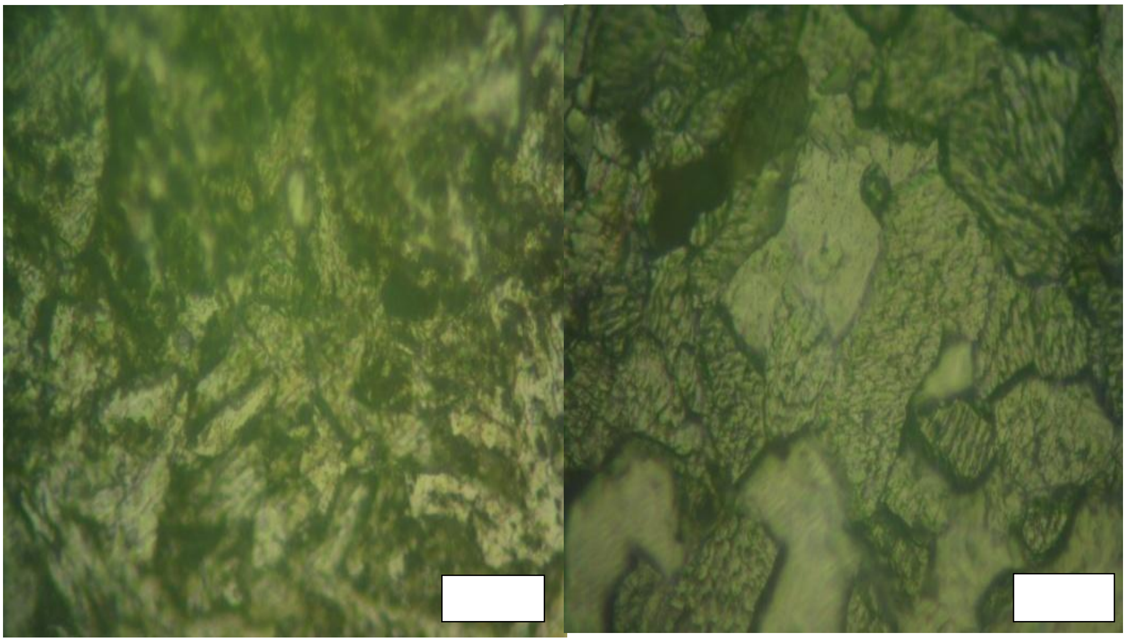
(a) (b)

Plate 14: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E07016 electrode at 106 ampere and tempered at 450^{o}C, soaked for 60 min.



(a) (b)

Plate 15: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7018 electrode at 90 ampere and tempered at 450^0C, soaked for 90 min.



(a) (b)

Plate 16: Optical micrograph of (a) WM and (b) HAZ of sample as-welded with E7024 electrode at 102 ampere and tempered at 450^oC.

Plate 17 shows the scanning electron microscope (SEM) micrograph and electron dispersive spectrometer (EDS) spectrum of the base metal showing fine ferrite grains, homogeneous distribution of pearlite in the ferrite matrix (dark patches) and segregated carbide particles along the grain boundaries. The present of these phases account for the relatively high hardness, yield and tensile strength with the correspondingly low impact strength and percent elongation. Aderemi and Hameed (2011) asserted that if the depth of impingement of EDS on the surface of steel sample is low the results may not be a true reflection of the elemental composition of the sample.

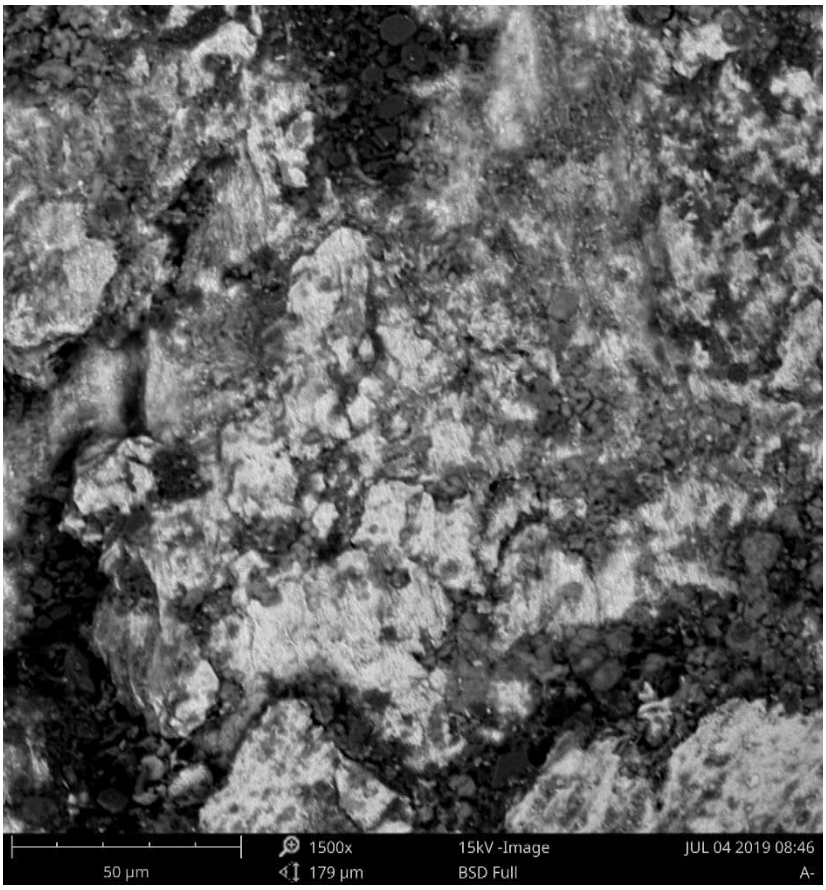


Plate 17: SEM micrograph of base metal as-received

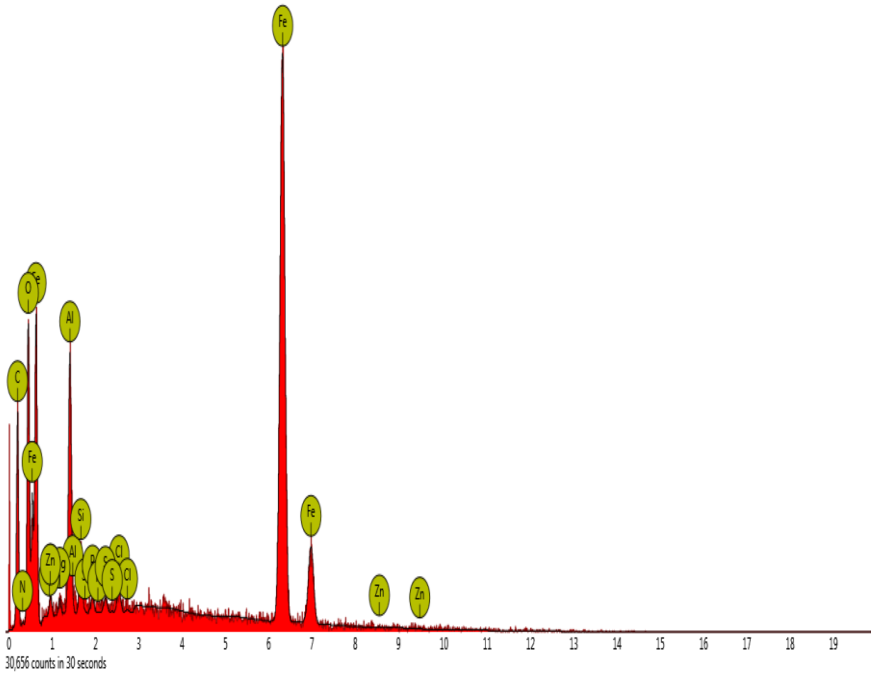


Fig. 4.1: EDS spectrum of base metal

Plate18 and Figure 4.2 show the SEM micrograph and EDS spectrum of E7016 electrode welds for the welding current setting of 102 ampere, tempered at 450^0C for 120 minutes. The coarse ferrite grain with inhomogeneous coarse distribution of carbide precipitates in ferrite matrix resulting from the high welding current and longer soaking duration are largely responsible for the decrease in tensile strength and increase in percent elongation recorded (Table 4.9).

Plate 18: SEM micrograph of E7016 electrode welds tempered at 450^{0}C for 120 minutes.

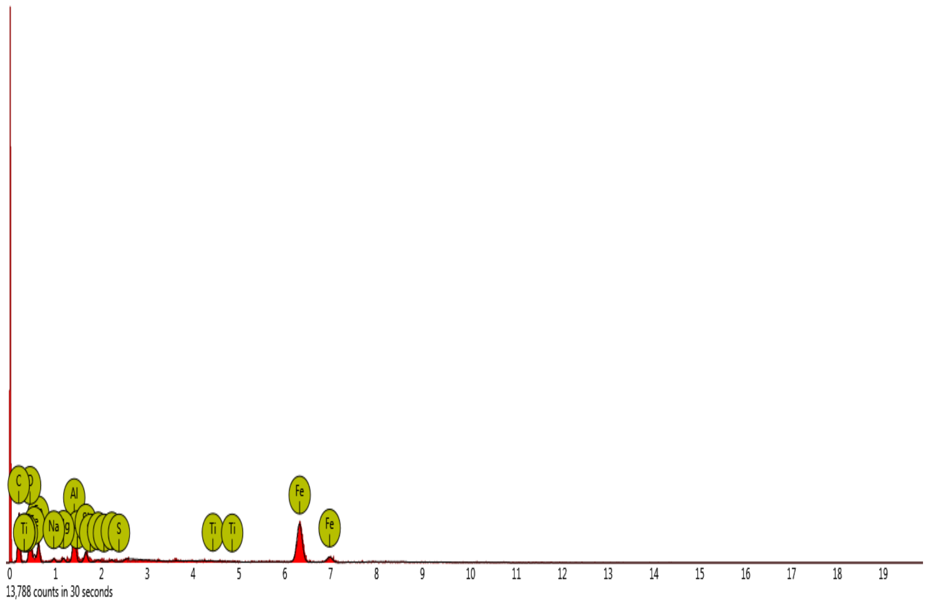


Fig. 4.2: EDS spectrum of E7016 electrode weld tempered at 450^{2}C for 120 minutes.

Plate 19 and Figure 4.3 show the SEM micrograph and EDS spectrum of E7016 electrode welds for the welding current setting of 106 ampere, tempered at 450^0C for 60 minutes. The relatively fine grained ferrite microstructure with homogeneous distribution of fine carbide particle sizes in the ferrite matrix arising from the relatively shorter soaking duration account for the improved tensile strength and plastic properties. Hence, the high quality index (QI) recorded (Table 4.9).

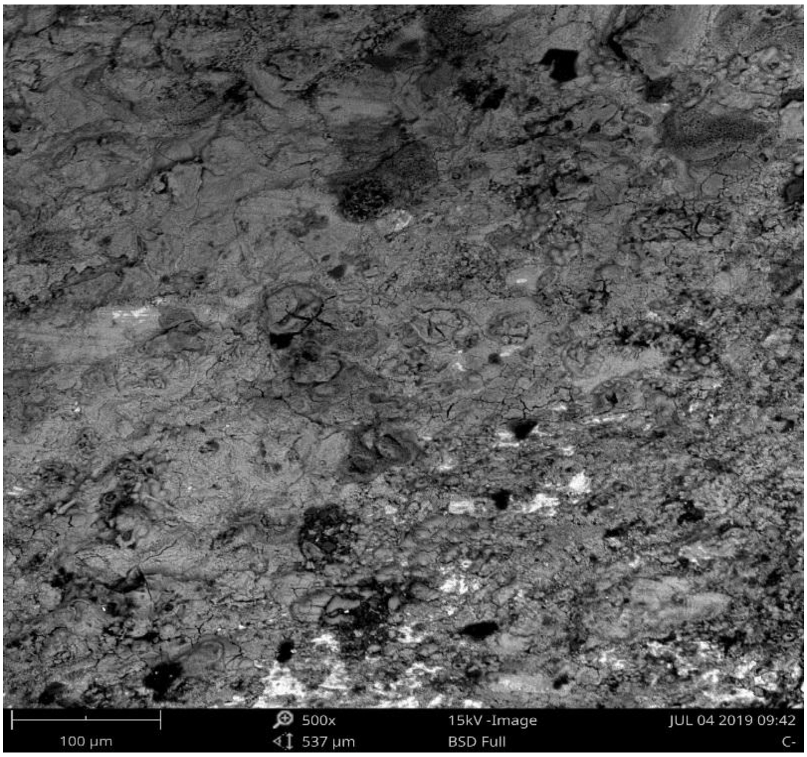


Plate 19: SEM micrograph of E7016 welds tempered at 450^0C for 60 minutes

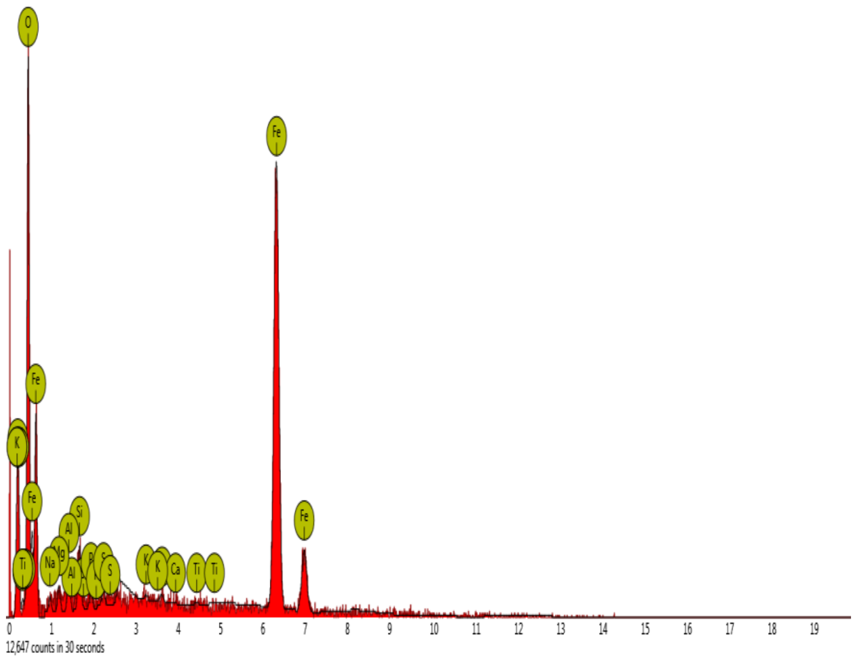


Fig. 4.3: EDS spectrum of E7016 electrode welds tempered at 450^{0}C for 60 minutes

Plate 20 and Figure 4.4 show the SEM micrograph and EDS spectrum of E7018 electrode welds for the welding current setting of 106 ampere, tempered at 450^{0}C for 120 minutes. The un-segregated coarse clusters of carbide particles at distinct location in the fairly coarse ferrite matrix formed as a result of the longer soaking time are responsible for the low tensile strength but high percent elongation.

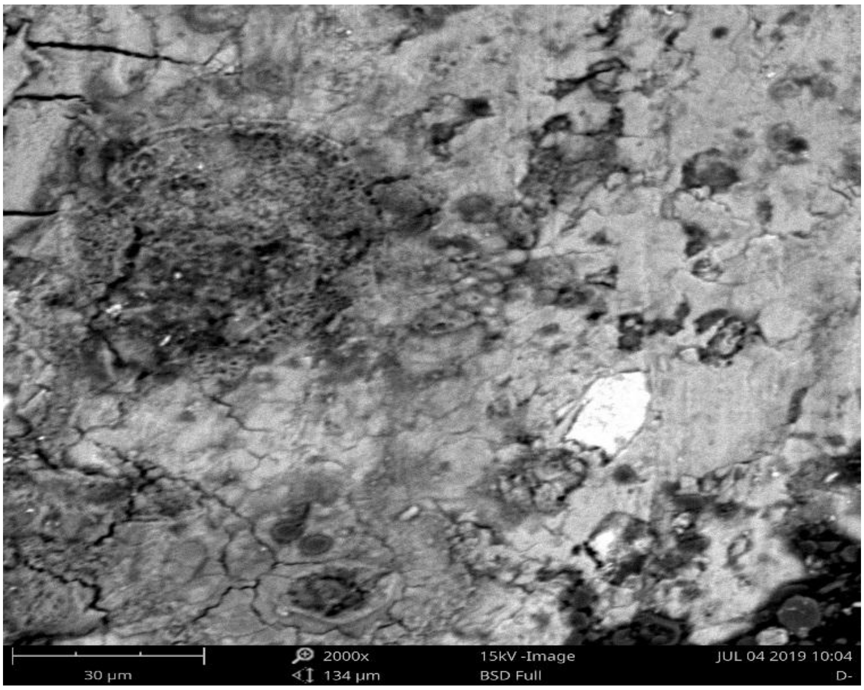


Plate 20: SEM micrograph of E7018 electrode welds tempered at 450^{0}C for 120 minutes.

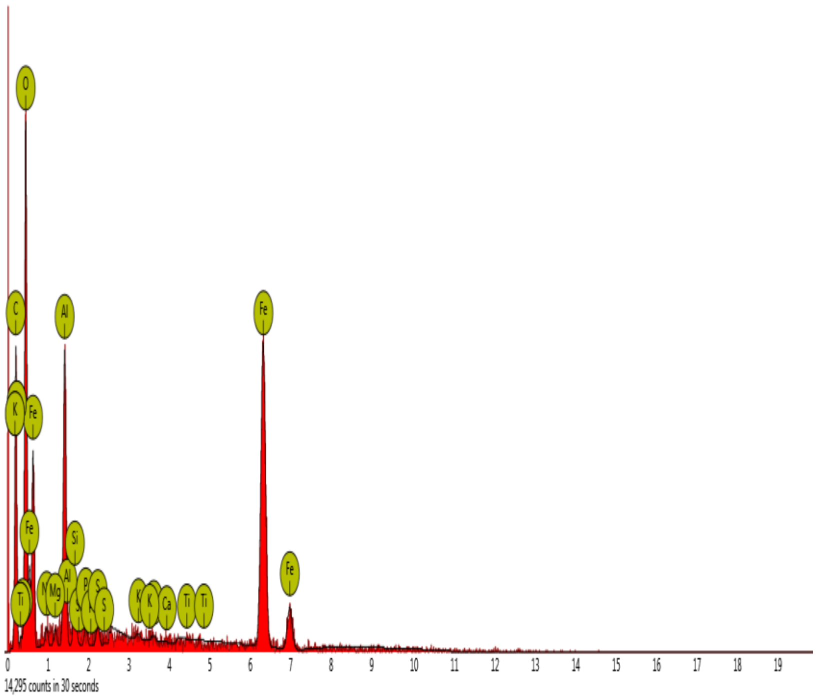


Fig. 4.4: EDS spectrum of E7018 electrode welds tempered at 450^{0}C for 120 minutes.

Plate 21 and Figure 4.5 indicate the SEM micrograph and EDS spectrum of E7018 electrode welds for the welding current setting of 90 ampere, tempered for 90 minutes. The homogeneous distribution of the ferrite grain and carbide precipitates account largely for excellent combination of tensile strength and percent elongation as depicted by QI value. Higher value of QI has been reported to be responsible for the improvement of steel weldment performance in service.

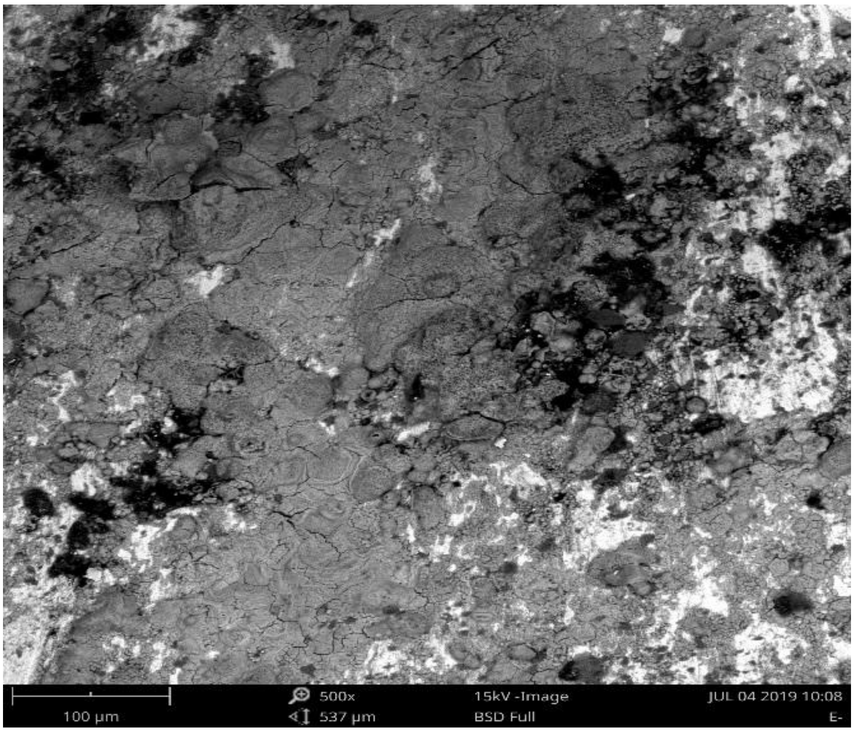


Plate 21: SEM micrograph of E7018 electrode welds tempered at 450^{0}C for 90 minutes.

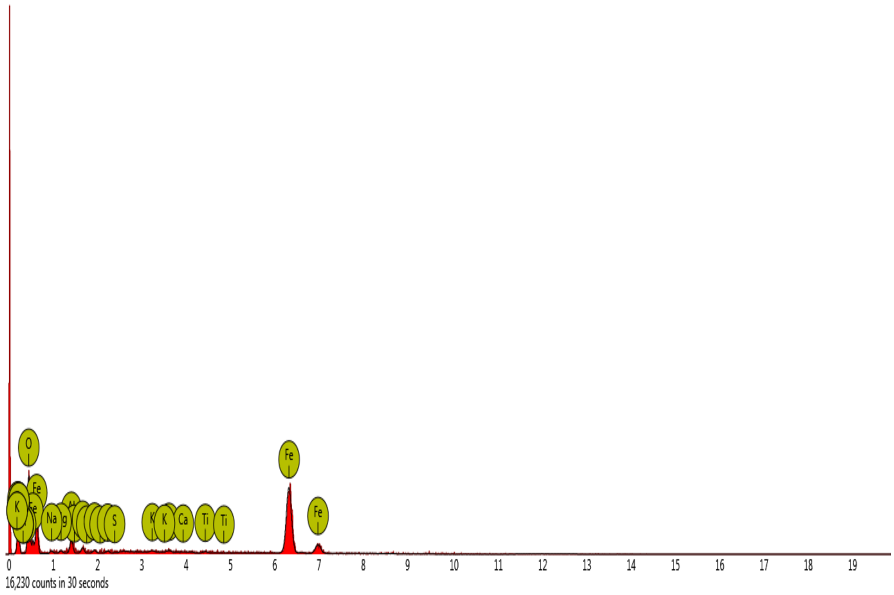


Fig. 4.5: EDS spectrum of E7018 electrode welds tempered at 450^{0}C for 90 minutes.

Plate 22 and Figure 4.6 show the SEM micrograph and EDS spectrum of E7024 electrode welds tempered at 450^{0}C for 120 minutes. The coarse distribution of the rod and nodule like morphology of the carbide phases in the fairly coarse ferrite matrix are responsible for the low combination of tensile strength and percent elongation as depicted in Table 4.11.

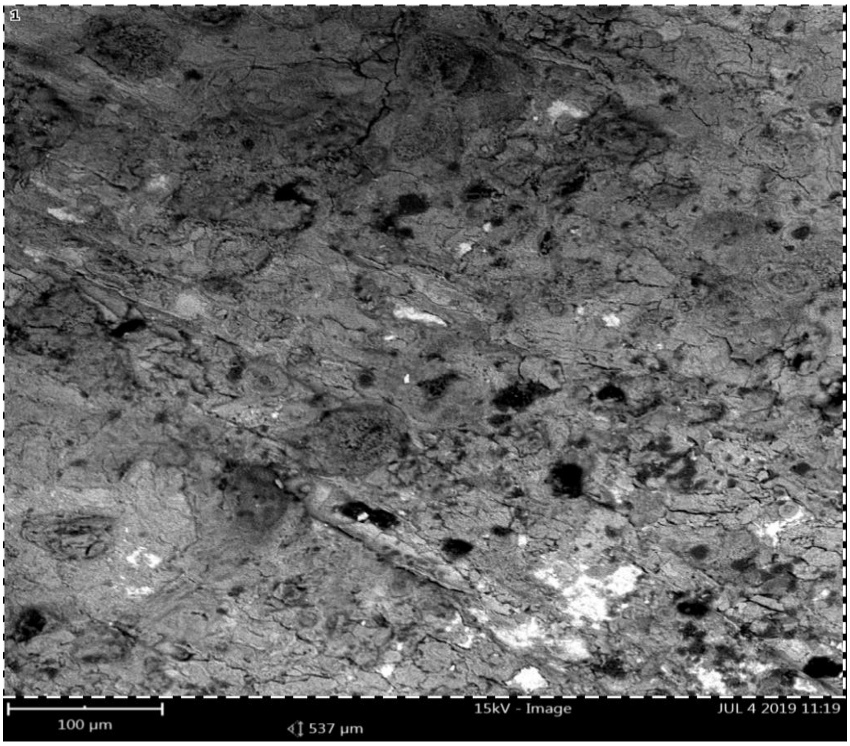


Plate 22: SEM micrograph of E7024 electrode welds tempered at 450^{0}C for 120 minutes.

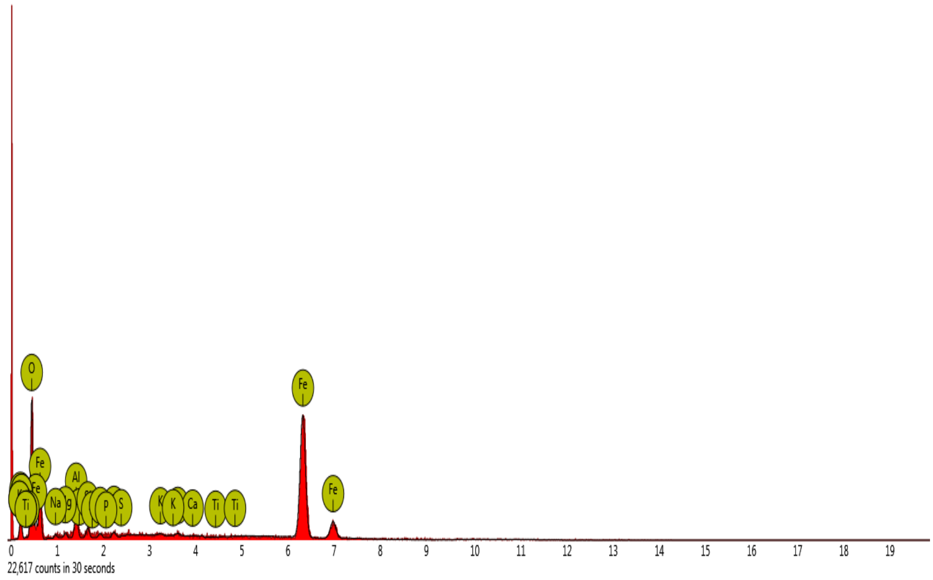


Fig. 4.6: EDS spectrum of E7024 electrode welds tempered at 450^{0}C for 120 minutes

Plate 23 and Figure 4.7 show the SEM micrograph and EDS spectrum of E7024 electrode welds for the welding current setting of 106 ampere, tempered at 450^0C for 60 minutes. The presence of the coarse ferrite and small island of carbide precipitates account for the excellent impact strength and percent elongation but lower hardness and tensile strength properties recorded (Table 4.11)

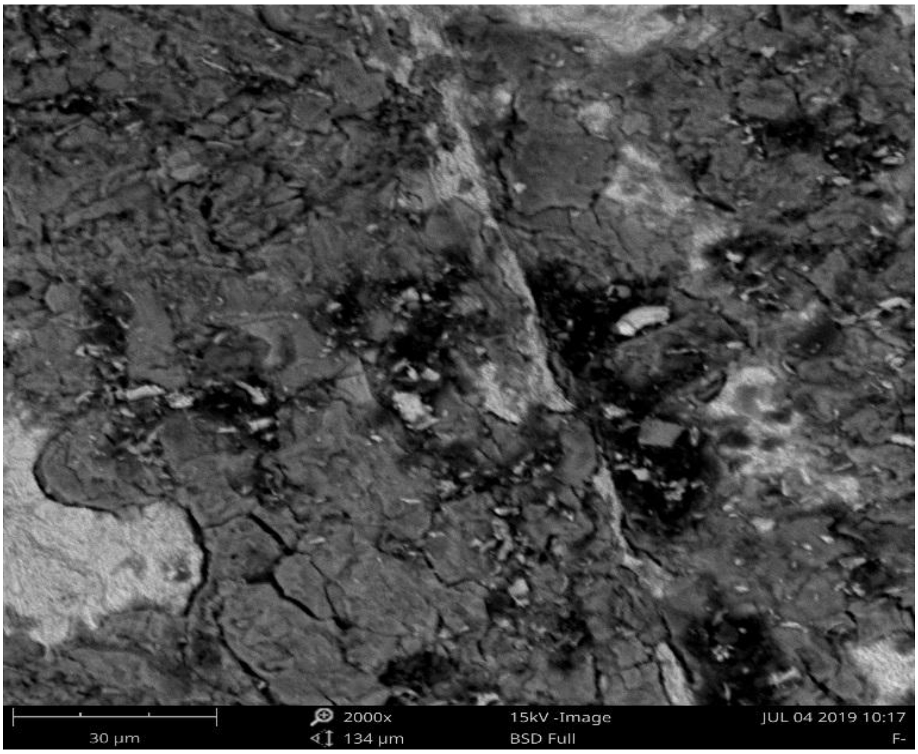


Plate 4.23: SEM micrograph of E7024 electrode welds tempered at 450^0C for 60 minutes.

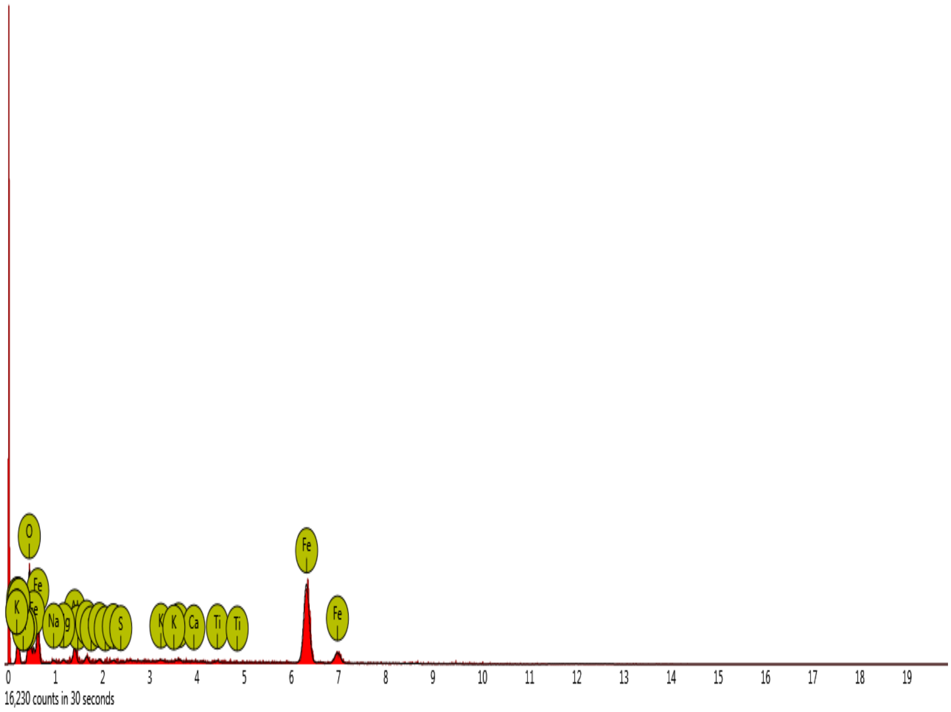


Fig. 4.7: EDS spectrum of E7024 electrode welds tempered at 450 for 60 minutes

4.2 Mechanical properties tests result

Table 4.1 shows the mechanical properties of the test piece (TP) in the as-welded condition (not subjected to any heat treatment). The results showed that for each electrode type, the hardness, yield strength and tensile strength decreased with increase in welding current but impact strength and percent elongation increased correspondingly. This could be attributed to the coarsening of the microstructural grains due to slow cooling rate as a result of the increase in heat input. Higher hardness values were obtained at the WM as compared to the HAZ and BM due to the synergetic interaction of the chemical elements present in varying composition in the base metal and the electrode core wires (Table 3.2), which probably served as recrystallization centres in the local melt thereby creating the required nuclei for the near instantaneous solidification with the attendant fine grained microstructure formed resulting in the higher hardness. These observation are in agreement with those of Nnuka *et al.*,(2008). Secondly, the cooling rate may have also impacted on the hardness at the WM. Fast cooling rate associated with low heat input has been reported to produce fine grain microstructure with improved hardness. The gradual decrease in the hardness values observed at the WM despite the increasing dilution of the alloying elements in the WM as a result of increasing heat input associated with current increase as indicated in Table 3.1, could be attributed to the coarsening of the ferritic grains arising from slow cooling rate linked to high welding current. This observation is in agreement with those of Kah *et al.*, (2014). Kou (2003) and Pournavari (2010) who revealed that increase in welding current raise heat input which slows cooling rate of weldment and encouraged coarse grains in the final microstructure. The variation in hardness at the HAZ could be attributed to the various forms of thermal cycles induced by the heat input from the welding current which gave rise to the different cooling rates with its attendant effect on the final microstructure formed. These results are consistent with those of Raghavan (1989) and Raj *et al.*,(2012). The E7016 electrode produced weldment with optimal hardness, yield strength, tensile strength but lowest impact strength and percent elongation followed by E7018 and E7024 electrodes respectively. Optimum impact strength and percent elongation were obtained from weldment established with E7024 electrode. The variation in the mechanical properties observed for the welds made with different electrode types could be attributed to the precipitation strengthening caused by the present of the carbide forming elements whose strengthening effect depends on their concentration. The highest amount of Mn, V and Cr content as listed in Table 3.2 were observed in E7016 followed by E7018 and E7024 electrode core wire respectively. However, the general decreasing trend observed in the hardness, yield strength, tensile strength but increasing impact strength and percent elongation with increase in welding current could be linked to coarsening of the microstructural grain due to slow cooling rate. This view is also supported by Kaiser and Shorowordi (2014) where they observed in their study that the coarsening of microstructural grain due to increasing welding current resulted to higher toughness in the HAZ. The calculated values of the quality index show that the optimal combination of tensile strength and percentage elongation was obtained from the welds made with the E7018 electrode followed by E7016 and E7024 electrode respectively. The values of the tensile strength and percent elongation that produced the maximum values of the quality index for the different electrode types are 250KN/m^2 and 19.2% for E7018 electrode at the welding current of 94 ampere, 256.6KN/m^2 and 17.5% for E7016 at the welding current of 94 ampere, and 232KN/m^2 and 19.5% for E7024 electrode at the welding current of 90 ampere. A larger value of quality index implies higher weldment performance in service.

Table 4.1: Mechanical properties of base metal and as-welded samples

Sample ID	Electrode type	Welding current (amps)	Hardness BHN			Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
			WM	HAZ	BM					
TP0	-	-	-	-	138	14.0	168	216.8	8	376,018
TP1	E7016	90	170	135	-	15.0	192.8	255.2	17.2	1,120,185
TP2	E7016	94	167	134	-	16.3	178.4	253.6	17.5	1,125,477
TP3	E7016	98	165	130	-	16.7	173.6	246.4	17.8	1,080,691
TP4	E7016	102	155	127	-	17.2	172	244	18.1	1,077,602
TP5	E7016	106	148	123	-	17.6	170	243	18.4	1,086,502
TP6	E7018	90	157	129	-	17.5	183	252	18.7	1,187,525
TP7	E7018	94	155	126	-	17.9	179	250	19.2	1,200,000
TP8	E7018	98	152	124	-	18.3	176	244.6	19.6	1,172,652
TP9	E7018	102	149	119	-	18.9	172	242	19.9	1,165,424
TP10	E7018	106	146	115	-	19.3	168	236	20.3	1,130,629
TP11	E7024	90	154	136	-	18.1	176	232	19.5	1,049,568
TP12	E7024	94	151	118	-	18.4	164	206	19.9	844,476
TP13	E7024	98	150	113	-	18.7	152	202	20.5	836,482
TP14	E7024	102	144	108	-	19.6	152	200	20.8	832,000
TP15	E7024	106	142	107	-	20.0	150	190	21.3	768,930

Table 4.2 shows the mechanical properties of the samples in the as-welded and quenched condition. The results clearly showed that quenching (fast cooling) significantly increased the hardness, yield strength and tensile strength but decreased impact strength and percent elongation. These trend could be attributed to the amount of the alloying elements present in the electrode core wires. Therefore, the higher the amount of the strong carbide formers in the electrode core wire, the more amount of the carbide precipitate forms on cooling to produce more precipitation hardening effect, apart from the grain refining effect associated to fast cooling. As the amount of carbide precipitates increases during cooling the higher the hardness and strength but the lower the impact strength and percent elongation due to the embrittle nature of the platelet carbide precipitate morphology. Welds made with E7016 electrode produced the maximum WM hardness of 236BHN, tensile strength of 390KN/m^2, percent elongation of 2.3% and impact strength of 4J at the welding current of 90 ampere followed by welds made with E7018 and E7024 electrodes respectively. The E7024 electrode welded samples had the highest impact strength and percent elongation, and lowest hardness and strength values because of the lower amount carbon and alloying element contents of the strong carbide stabilizing elements present in its electrode core wire whose precipitation hardening effects are less effective. The optimal combination of tensile strength and percent elongation as indicated by the calculated quality index values show that E7018 electrode welded and quenched samples had the highest followed by E7016 and E7024 electrode welded samples. The values of the tensile strength and percentage elongation that produced the maximum value of quality index are 254.4KN/m^2 and 14.4% for E7018 electrode at 102 ampere, 356KN/m^2 and 6.7% for E7016 electrode at 98 ampere, and 154.8KN/m^2 and 18.6% for E7024 electrode at 94 ampere.

Table 4.2: Mechanical properties of as-welded and quenched samples

Sample ID	Electrode type	Welding current (amps)	Austenitic tempt (^{O}C)	Soaking time (min.)	Hardness BHN		Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
					WM	HAZ					
TP16	E7016	90	910	30	236	201	4	385.6	390	2.3	349,830
TP17	E7016	94	910	30	221	198	7	356	386	4	595,984
TP18	E7016	98	910	30	218	186	8	344	368	6.2	839,629
TP19	E7016	102	910	30	198	183	10	316	356	6.7	849,131
TP20	E7016	106	910	30	188	173	12	236.8	324	7.3	766,325
TP21	E7018	90	910	30	219	188	16	198.4	264.8	12	841,428
TP22	E7018	94	910	30	200	173	15	194.4	257.6	13	862,651
TP23	E7018	98	910	30	183	168	13	169.6	254.4	14.4	931,959
TP24	E7018	102	910	30	179	159	9.6	169	244.8	15	898,906
TP25	E7018	106	910	30	175	151	6	132	173.6	17	512,328
TP26	E7024	90	910	30	185	155	13.5	119.2	155.2	18	433,567
TP27	E7024	94	910	30	181	146	14.2	117.6	154.8	18.6	445,713
TP28	E7024	98	910	30	173	144	16	113.6	152	18.8	434,355
TP29	E7024	102	910	30	171	128	18	112.7	151.2	19.0	434,367
TP30	E7024	106	910	30	168	120	19	112	150.8	19.3	438,894

Table 4.3 illustrates the mechanical properties of the E7016 electrode welded samples tempered at 250^0C. The results showed marginal decreased in hardness, yield strength tensile strength and a corresponding increase in impact strength and percent elongation as soaking time was increased. When compared with the results in Table 4.2 (as-welded condition) it was observed that the hardness, yield strength and tensile strength values of the tempered as-welded samples were relatively lower, but the impact strength of the WM and percent elongation values were much higher. The decreased in the hardness, yield strength, tensile strength and increased in impact strength and percent elongation clearly showed that soaking time had significant impact in the mechanical properties. This observation is in agreement with the reports of Hashmi and Olabi (1993) and Olabi and Hashmi (1995). Warner and Brandt (2005) and Singh (2011) reported that low tempering temperature (150-250^0C) does not cause any phase change in the crystal lattice of tempered steel due to the inability of the solute atoms to migrate from their original position to new sites where structural modification can occur. It is well known that low tempering temperature does not produce appreciable decrease in the hardness and strength properties due to the low amount of thermal residual stresses that are relieved. Also, the slow mobility of dislocation arising from the interaction between the interstitial solute elements and dislocation are effective. However, slight improvement in the impact strength and percent elongation was observed.

Warner and Brandt (2005) who posited that, the longer the time a heat treated sample stayed at any given tempering temperature, the more the grains get coarsen resulting in decrease in the hardness and strength and corresponding increase in impact strength and ductility. Therefore, the coarsening of the grain size of the microstructure of the tempered samples with increase in soaking time account largely for the decrease in the hardness at the WM and HAZ, yield strength and tensile strength, and increase in impact strength and percent elongation. The maximum hardness, yield strength and tensile strength of 167BHN, 158KN/m^2 and 229.6KN/m^2 respectively were obtained from the welding current of 90 ampere at the soaking time of 60 minutes which later decreases at 90-120 minutes of soaking. The maximum impact strength and percentage elongation of 22.3J and 25.5% were obtained at 106 ampere for 120 minutes of soaking. The best combination of tensile strength and percent elongation that gave rise to larger value of quality index was 235KN/m^2 and 26.3% at 102 ampere for 120 minutes of soaking.

Table 4.3: Mechanical properties of E7016 electrode welded samples tempered at 250^{0}C

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^{o}C)	Soaking time (min.)	Hardness BHN WM	Hardness BHN HAZ	Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
TP31	E7016	90	250	60	167	134	17.1	158	229.6	20.3	1070138
TP32	E7016	90	250	90	165	132	17.8	152	228	24.0	1247616
TP33	E7016	90	250	120	163	130	18.3	150	220	24.2	1171280
TP34	E7016	94	250	60	165	133	18.5	162	233	22.6	1123875
TP35	E7016	94	250	90	162	132	18.8	160	232	24.7	1329453
TP36	E7016	94	250	120	161	130	19.2	153.6	230	25.2	1333080
TP37	E7016	98	250	60	163	129	19.4	166	236.8	22.9	1284100
TP38	E7016	98	250	90	161	128	19.8	164	235.1	25.1	1387327
TP39	E7016	98	250	120	159	126	20.1	156	233	25.8	1400656
TP40	E7016	102	250	60	153	118	20.3	171	242.2	23.1	1355065
TP41	E7016	102	250	90	151	117	20.6	170.4	238.4	25.4	1443598
TP42	E7016	102	250	120	149	115	20.9	170	235	26.3	1452418
TP43	E7016	106	250	60	140	122	21.3	168	240.2	23.4	1350087
TP44	E7016	106	250	90	138	121	21.7	166	238.5	25.1	1427744
TP45	E7016	106	250	120	136	120	22.3	165	236	25.5	1420248

Tables 4.4-4.5 Show the mechanical properties of the samples welded with E7018 and E7024 electrodes at different welding current settings, tempered at 250^{0}C with varying soaking time. A critical observation of the results (Tables 4.5-4.6) clearly showed that the mechanical properties followed the same trend as in Table 4.3 where the hardness, yield strength and tensile strength decreased but impact strength and percent elongation increased with increase in soaking time. Optimum hardness, yield strength and tensile strength were obtained in E7018 electrode welds followed by E7024 electrode samples. However, E7024 electrode welded samples exhibited the highest impact energy and percent elongation. The maximum hardness, yield strength and tensile strength of 155BHN, 186KN/m^2 and 258KN/m^2 respectively were obtained with the E7018 electrode welded samples at 90 ampere for 60 minutes. The highest impact strength and percentage elongation values of 30.5J and 29.8% were obtained with E7024 electrode welded samples at 106 ampere for 120 minutes. The value of the quality index which gave the best combination of tensile strength and percentage elongation values for both electrodes are 250KN/m^2 and 25.2%, and 154.4KN/m^2 and 25.4% for E7018 and E7024 electrode respectively at 90 ampere for 120 minutes. The high values of hardness, yield strength, tensile strength and lower values of impact strength and percent elongation recorded with E7018 electrode welded samples compared to the E7024 electrode samples may be attributed to the contents of Mn, V, Cr and V present in the two electrode core wires which has the potential to precipitate carbides in the ferrite matrix to an amount that is based on their composition.

Table 4.4: Mechanical properties of E7018 electrode welded samples tempered at 250^{0}C

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^{o}C)	Soaking time (min.)	Hardness BHN		Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
					WM	HAZ					
TP46	E7018	90	250	60	155	128	19.0	180	258	22.8	1517659
TP47	E7018	90	250	90	154	126	19.5	175.5	252	24.5	1555848
TP48	E7018	90	250	120	152	125	19.8	178.1	250	25.2	1575000
TP49	E7018	94	250	60	156	125	20.2	176	256	23.2	1520435
TP50	E7018	94	250	90	154	123	20.6	174	244	24.9	1482446
TP51	E7018	94	250	120	153	121	20.9	172	242	25.8	1510951
TP52	E7018	98	250	60	150	123	21.3	173	252	23.6	1498694
TP53	E7018	98	250	90	148	122	21.5	170	243	25.7	1517559
TP54	E7018	98	250	120	146	120	21.7	168	240	26.4	1520640
TP55	E7018	102	250	60	147	117	22.1	169	239	24.5	1399465
TP56	E7018	102	250	90	146	116	22.4	166	236	25.9	1442526
TP57	E7018	102	250	120	144	114	22.7	164	234	26.5	1451034
TP58	E7018	106	250	60	145	113	22.9	166	233	24.8	1346367
TP59	E7018	106	250	90	143	111	23.0	163.3	231	26.4	1408730
TP60	E7018	106	250	120	141	110	23.5	161	229	26.7	1400175

Table 4.5: Mechanical properties of E7024 electrode welded samples tempered at 250^{0}C

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^{o}C)	Soaking time (min.)	Hardness BHN WM	HAZ	Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
TP61	E7024	90	250	60	152	126	20.0	117	160	23.1	591,360
TP62	E7024	90	250	90	149	124	20.4	116	156	24.7	601,099
TP63	E7024	90	250	120	147	122	20.7	112	154.4	25.4	605,520
TP64	E7024	94	250	60	150	123	20.5	116	156	23.7	576,763
TP65	E7024	94	250	90	148	122	20.7	111.2	154	25.0	592,900
TP66	E7024	94	250	120	146	120	21.1	110	152	26.2	605,325
TP67	E7024	98	250	60	149	120	21.5	112	151.2	23.8	544,102
TP68	E7024	98	250	90	147	118	21.9	108	150.8	26.1	593,531
TP69	E7024	98	250	120	145	116	22.2	106	146	26.5	564,874
TP70	E7024	102	250	60	144	114	22.6	111	150.5	24.7	559,461
TP71	E7024	102	250	90	142	112	22.9	106.4	148	26.3	576,075
TP72	E7024	102	250	120	140	110	23.1	100	144	26.8	555,725
TP73	E7024	106	250	60	141	113	23.5	106	150	25.1	564,750
TP74	E7024	106	250	90	140	111	23.7	104	147.2	26.9	582,865
TP75	E7024	106	250	120	138	109	24.0	98	140	27.2	533,120

Tables 4.6-4.8 show the mechanical properties of samples welded with E7016, E7018 and E7024 electrodes tempered at 350^0C for 60, 90 and 120 minutes respectively. The results showed that higher hardness, yield strength and tensile strength values were obtained at the soaking time of 60 minutes followed by a marginal decrease at 90-120 minutes of soaking. This trend is expected since Entrekin (1983) reported that as the tempering temperature increases; the more the heat treated steel soften and the interspacing of atoms increases with high potential for solute atoms to be segregated uniformly to new sites in the crystal lattice. However, increase in soaking time beyond 60 minute triggered the coarsening of the ferritic grains and carbide particle size resulting in significantly improvement in impact strength and percent elongation and decreased in hardness, yield strength and tensile strength. The E7016 electrode welded samples had the highest hardness, yield strength, tensile strength but lowest impact strength and percentage elongation values followed by E7018 electrode welded samples. The E7024 electrode welded samples had the lowest hardness, yield strength, tensile strength but highest impact strength and percent elongation values. It is well recognized that, the amount of precipitate carbide formed depends on the composition of the carbide forming elements. Table 3.2 indicated that the weight percent of the carbide stabilizing elements are higher in E7016 electrode followed by E7018 and E7024 electrodes. The calculated values of quality index show that welds produced with E7018 electrode gave the best combination of tensile strength and percent elongation value of 253KN/m^2 and 25.0% followed by 248KN/m^2 and 25.1% for E7016 electrode at 94 ampere for 60 minutes respectively and 152KN/m^2 and 28.5% for E7024 at 106 ampere for 60 minutes.

Table 4.6: Mechanical properties of E7016 electrode welded samples tempered at 350^oC

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^oC)	Soaking time (min.)	Hardness BHN WM	Hardness BHN HAZ	Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
TP76	E7016	90	350	60	165	132	19.0	184	246.8	22.8	1388753
TP77	E7016	90	350	90	163	130	21	164	246	24.0	1452384
TP78	E7016	90	350	120	161	128	22.1	148	212	26.2	1177533
TP79	E7016	94	350	60	159	131	22.6	172	248	25.1	1543750
TP80	E7016	94	350	90	157	129	23.3	171.2	244	25.3	1506261
TP81	E7016	94	350	120	155	127	23.9	149	224	25.9	1299558
TP82	E7016	98	350	60	154	127	24.2	172	251.2	23.3	1470264
TP83	E7016	98	350	90	148	125	24.6	170	240	25.8	1486080
TP84	E7016	98	350	120	147	122	24.8	159	226	26.0	1327976
TP85	E7016	102	350	60	151	123	25.1	173	253	23.4	1497811
TP86	E7016	102	350	90	150	121	25.4	168	236	25.8	1436957
TP87	E7016	102	350	120	148	119	25.8	161	227	26.6	1370671
TP88	E7016	106	350	60	145	118	26.4	176	253.2	23.7	1519413
TP89	E7016	106	350	90	143	116	26.7	166	244	25.6	1524122
TP90	E7016	106	350	120	142	114	27.0	162	234	26.2	1434607

Table 4.7: Mechanical properties of E7018 electrode welded samples tempered at 350°C.

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (°C)	Soaking time (min.)	Hardness BHN WM	Hardness BHN HAZ	Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
TP91	E7018	90	350	60	154	127	23.6	178	256	24.2	1585971
TP92	E7018	90	350	90	153	125	23.9	176	254	24.5	1580642
TP93	E7018	90	350	120	151	123	24.4	172	252.8	24.8	1584914
TP94	E7018	94	350	60	150	124	24.8	172	253	25.0	1600225
TP95	E7018	94	350	90	148	122	25.1	170.4	250	25.3	1581250
TP96	E7018	94	350	120	147	121	25.5	167	230	25.9	1370110
TP97	E7018	98	350	60	146	122	25.8	168	229.6	25.6	1349534
TP98	E7018	98	350	90	144	121	26.2	164	227	26.1	1344907
TP99	E7018	98	350	120	143	119	26.7	159	219	26.5	1270967
TP100	E7018	102	350	60	140	118	26.9	162	225	26.3	1331438
TP101	E7018	102	350	90	139	116	27.4	158	215	26.7	1234208
TP102	E7018	102	350	120	138	114	27.8	153	212	26.9	1208994
TP103	E7018	106	350	60	128	112	28.1	155	216	27.2	1269043
TP104	E7018	106	350	90	127	100	28.4	151	213	27.5	1247648
TP105	E7018	106	350	120	125	98.1	28.7	147	209	27.8	1214332

Table 4.8: Mechanical properties of E7024 electrode welded samples tempered at 350^{0}C

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^{o}C)	Soaking time (min.)	Hardness BHN		Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
					WM	HAZ					
TP106	E7024	90	350	60	149	120	23.8	110	158	25.0	624,100
TP107	E7024	90	350	90	147	109	24.2	107	155	26.0	624,650
TP108	E7024	90	350	120	145	97.3	24.5	102	146	26.7	569,137
TP109	E7024	94	350	60	148	110	24.9	108	153	25.3	592,248
TP110	E7024	94	350	90	146	105	25.3	106	152	26.8	619,187
TP111	E7024	94	350	120	144	98.1	25.7	103	148	27.3	597,979
TP112	E7024	98	350	60	147	114	25.9	111	154	26.9	637,960
TP113	E7024	98	350	90	145	104	26.4	106	150	27.4	616,500
TP114	E7024	98	350	120	143	102	26.8	103	147	27.6	596,408
TP115	E7024	102	350	60	142	116	27.1	108	151	27.2	620,187
TP116	E7024	102	350	90	140	100	27.6	104	149	27.8	617,188
TP117	E7024	102	350	120	138	105	28.2	102	144	28.1	582,682
TP118	E7024	106	350	60	140	119	28.4	110	152	28.5	658,464
TP119	E7024	106	350	90	138	107	28.8	100	146	28.8	613,901

TP120	E7024	106	350	120	136	99.6	29.3	98	142	29.3	590,805

Tables 4.9-4.11 show the mechanical properties of E7016, E7018 and E7024 electrodes welded samples tempered at 450^{0}C and soaked for 60, 90 and 120 minutes respectively. The results showed similar trend with those tempered at 350^{0}C. The samples at 450^{0}C exhibited higher mechanical properties as compared to those tempered at 350^{0}C. However, the hardness, yield strength, tensile strength decreased with increase in soaking duration but impact strength and percent elongation increased. Optimum hardness, yield strength and tensile strength values were obtained at the soaking duration of 60 minutes. Whereas maximum impact strength and percent elongation values were produced at 120 minutes of soaking. The enhanced mechanical properties obtained at 450^{0}C, higher than that observed at 350^{0}C could be attributed to the precipitation of more carbide particles and its subsequent uniform distribution in the ferritic matrix. Ahmed and Krishnan (2000) revealed that the temperature attained during stress relief treatment has greater far effect in relieving tensile welding stresses and improving the mechanical properties than the time the sample is held at that temperature. The best combination of tensile strength and percent elongation of 258.4KN/m^2 and 26.8% was obtained from E7018 electrode welded samples at 90 ampere for 90 minutes followed by 242.4KN/m^2 and 28.7% for E7016 electrode welded specimens at 106 ampere for 60 minutes soaking time, and 153.2KN/m^2 and 30.6% for E7024 electrode welded samples at 106 ampere for 60 minutes soaking time.

A critical examination of the calculated quality index values for the as-welded samples, as-welded and quenched samples, and as-welded and tempered samples considered in this study, showed that the electrode type that produced welds with the overall best combination of tensile strength and percent elongation was the weld made with E7018 electrode at 90 ampere tempered at 450^{0}C, soaked for 90 minutes. The essence of tempering welded samples immediately after welding is to relieve welding stresses which are likely to cause premature failure of welded component in service as well as obtain better combination of tensile strength and percent elongation suitable for structural applications.

Table 4.9: Mechanical properties of E7016 electrode welded samples tempered at 450^{o}C

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^{o}C)	Soaking time (min.)	Hardness BHN WM	HAZ	Impact strength at WM (J)	Yield strength (KN/m^{2})	Tensile strength (KN/m^{2})	Elongation (%)	Quality index (KN/m^{2})
TP121	E7016	90	450	60	168	130	22.0	184	253.6	26.0	1672137
TP122	E7016	90	450	90	166	128	24.0	180	249.6	26.4	1644724
TP123	E7016	90	450	120	164	127	24.6	176	244	27.1	1613426
TP124	E7016	94	450	60	165	129	25.4	176	246	26.8	1621829
TP125	E7016	94	450	90	163	127	25.8	173.6	244.8	27.3	1636008
TP126	E7016	94	450	120	162	125	26.3	172	236	27.7	1542779
TP127	E7016	98	450	60	160	127	26.6	173	245	27.5	1650688
TP128	E7016	98	450	90	158	126	26.9	171.2	240	27.9	1607040
TP129	E7016	98	450	120	157	125	27.4	169..6	235.2	28.4	1571061
TP130	E7016	102	450	60	155	126	27.7	172	242.8	28.2	1662442
TP131	E7016	102	450	90	154	124	28.2	165.6	234	28.6	1566022
TP132	E7016	102	450	120	152	123	28.7	164	227.2	28.9	1491813
TP133	E7016	106	450	60	151	125	29.1	168.8	242.4	28.7	1686348
TP134	E7016	106	450	90	148	123	29.5	163.2	233.6	29.1	1587957
TP135	E7016	106	450	120	146	121	29.9	160.8	225.6	29.5	1501413

Table 4.10: Mechanical properties of E7018 electrode welded samples tempered at 450^oC.

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (^oC)	Soaking time (min.)	Hardness BHN WM	Hardness BHN HAZ	Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
TP136	E7018	90	450	60	155	127	25.6	206	260	26.4	1784640
TP137	E7018	90	450	90	154	125	25.8	191.2	258.4	26.8	1789451
TP138	E7018	90	450	120	152	123	26.2	185.6	250	27.4	1712500
TP139	E7018	94	450	60	151	124	27.3	180	249	27.2	1686427
TP140	E7018	94	450	90	149	122	27.7	176	248	27.5	1691360
TP141	E7018	94	450	120	148	121	27.9	174	245	27.9	1674698
TP142	E7018	98	450	60	147	122	28.2	176	242	28.3	1657361
TP143	E7018	98	450	90	146	121	28.6	173	240	28.1	1618560
TP144	E7018	98	450	120	144	119	28.8	172	236	28.9	1609614
TP145	E7018	102	450	60	143	118	29.1	172	235	29.3	1618093
TP146	E7018	102	450	90	142	116	29.4	170	233	29.6	1606954
TP147	E7018	102	450	120	140	114	29.7	164	231	29.8	1590158
TP148	E7018	106	450	60	139	112	30.3	161.6	230	30.2	1597580
TP149	E7018	106	450	90	137	100	30.7	155.4	221	30.5	1489651
TP150	E7018	106	450	120	134	98.1	30.9	152	218	30.7	1458987

Table 4.11: Mechanical properties of E7024 electrode welded samples tempered at 450°C.

Sample ID	Electrode type	Welding current (amps)	Tempering tempt (°C)	Soaking time (min.)	Hardness BHN WM	Hardness BHN HAZ	Impact strength at WM (J)	Yield strength (KN/m^2)	Tensile strength (KN/m^2)	Elongation (%)	Quality index (KN/m^2)
TP151	E7024	90	450	60	151	122	26.6	122	160	26.8	686,080
TP152	E7024	90	450	90	149	120	26.8	113.6	150	27.2	612,000
TP153	E7024	90	450	120	147	118	27.3	108	148	27.5	602,360
TP154	E7024	94	450	60	149	119	27.8	117	159.2	27.8	704,581
TP155	E7024	94	450	90	147	117	27.5	112	154	28.1	666,420
TP156	E7024	94	450	120	145	115	28.0	100	151	28.4	647,548
TP157	E7024	98	450	60	148	116	27.9	115	156	28.7	698,443
TP158	E7024	98	450	90	146	114	28.2	110	152	28.9	667,706
TP159	E7024	98	450	120	144	110	28.6	101.6	149	29.3	650,489
TP160	E7024	102	450	60	145	115	28.5	114	154	29.5	699,622
TP161	E7024	102	450	90	144	113	28.7	111	151	29.7	677,190
TP162	E7024	102	450	120	142	109	29.0	108	147	30.2	652,592
TP163	E7024	106	450	60	141	110	30.3	112	153.2	30.6	718,189
TP164	E7024	106	450	90	139	107	30.5	109	150	30.8	693,000
TP165	E7024	106	450	120	137	104	30.7	102	148	32.0	700,928

Table 4.12 shows the design matrix and the corresponding result of the RSM experiments to determine the effects of the three independent variables; welding current, soaking time and temperature. Interactions of the experimental variables indicate a total of twenty experimental runs. Each of the factors had substantial effect on the responses of the twenty runs. Through multiple regression analysis on the experimental data, the predicted responses (tensile strength, impact strength and percent elongation) were expressed by the second-order polynomial equation in terms of coded values. Equations: (4.1), (4.2) and (4.3).

Table 4.12: Design matrix with experimental results

Run	Current (ampere)	Soaking Time (min)	Temperature (^0C)	Tensile Strength (KN/m^2)	Impact Strength (J)	Elongation (%)
1	102	120	450	231	29.7	29.8
2	90	120	450	250	26.2	27.4
3	94	120	350	230	25.5	25.9
4	94	90	450	248	27.7	27.5
5	90	90	350	254	23.9	24.5
6	102	120	250	234	22.7	26.5
7	94	120	350	230	25.5	25.9
8	94	90	450	248	27.7	27.5
9	90	60	250	258	19.0	22.8
10	90	120	250	250	19.8	25.2
11	102	120	350	212	27.8	26.9
12	102	90	350	215	27.4	26.7
13	98	60	250	252	21.3	23.6
14	102	90	350	215	27.4	26.7
15	94	120	350	230	25.5	25.9
16	90	90	250	252	19.5	24.5
17	98	60	350	229.6	25.8	25.6
18	98	90	250	243	21.5	25.7
19	102	60	450	235	29.1	29.3
20	90	90	450	258	25.8	26.8

4.2.2 Statistical analysis of predictive models

The statistical testing of the models was performed in the form of analysis of variance (ANOVA). The ANOVA for the fitted quadratic polynomial model of tensile strength, impact strength and percent elongation are shown in Tables 4.13-4.15. The ANOVA results of the quadratic regression model (Table 4.13) indicated that the model used to fit the response variable was significant ($p < 0.0001$). The model F-value of 19.99 greater than the P-value also attest to the model significant. The high coefficient of regression (R^2) and adjusted regression coefficient (adj. R^2)values of 94.73% and 89.99% respectively indicate that the suggested model can adequately approximate the actual response data in the design space. The R^2 is defined as the ratio of the explained variation to the total variation, and is a measure of the degree of fit (Joglekar *et al.,* 1999). Hazard *et al.,* (2007) suggested that a good model fit should yield an R^2 of at least 0.8. The adj. R^2 is also a correlation measure for testing goodness-of-fit of regression model (Kim *et al.,* 2012). The value shows that only 10% of the total variation could not be explained by the model. The modeladequacy precision value of 13.536 clearly suggest that there isa strong correlation between the response and the independent variables (Hossain *et al.,* 2012). The relatively lower value of coefficient of variation (CV = 1.82%) in Table 4.23 (Appendix 10)implies a better precision and reliability of the experiments carried out. The model parameters Probability values ($P<0.05$) with the exception of temperature indicate their strong influence on tensile strength.

Table4.13: ANOVA results for tensile strength model

Source	Sum of Square	Df	Mean Square	F value	P-value Prob>F	

Model	3462.73	9	384.75	19.99	< 0.0001	Significant
A-Current	1999.33	1	1999.33	103.87	< 0.0001	
B-Soaking time	434.06	1	434.06	22.55	< 0.0008	
C-Temperature	7.71	1	7.71	0.40	< 0.5411	
AB	71.43	1	71.43	3.71	0.0829	
AC	19.39	1	19.39	1.01	0.3392	
BC	0.53	1	0.53	0.028	0.8716	
A^2	0.66	1	0.66	0.034	0.8571	
B^2	25.10	1	25.10	1.30	0.2801	
C^2	192.49	10	19.25	50.68	<0.0001	
Residual	192.49	10	19.25			
Lack of Fit	192.49	5	38.50			
Pure Error	0.000	5	0.000			
Cor Total	3655.22	19				
R-Squared = O.9473				Adj R-Squared = 0.8999		
Predicted R-Squared = 0.4255				Adequate Precision = 13.536		

In terms of coded and actual factors, the prediction of tensile strength is expressed by equation (4.1)

Tensile strengh=+230.00-14.03*A-6.53*B-0.88*C+3.54*AB-1.90*AC+0.32*BC+0.46*A^2+2.42*B^2+14.38*C^2
(4.1)

The analysis of variance (ANOVA) results (Table 4.14) indicate that the model used to fit the response variable was significant ($p < 0.0001$) as indicated by the low probability value, hence adequate to represent the relationship between the response and the independent variables (Hossain, 2012). The high values of the coefficient of regression (R^2) of 99.83% and adjusted R^2 of 99.67% are clear demonstration that the model can adequately approximate the actual response surface. The model F-value of644.61 higher than the P-value, also indicate its significant. The relatively lower value of coefficient of variation (CV = 0.68%) as listed in Appendix10lend credence to the precision and reliability of the experiments carried out. The significant of themodel parameters was also tested using F-value and p-value. The results alsoshowed that impact strength was significantly affected by all the input variables (welding current, soaking time and temperature at $p < 0.001$).

Table4.14: ANOVA results of impact strength model

Source	Sum of Square	Df	Mean Square	F value	P-value Prob>F	
Model	172.95	9	19.22	644.61	< 0.0001	Significant
A-Current	27.00	1	27.00	905.77	< 0.0001	
B-Soaking time	1.24	1	1.42	41.56	< 0.0001	
C-	120.70	1	120.70	4048.83	< 0.0001	

Temperature						
AB	0.018	1	0.018	0.60	0.4560	
AC	0.073	1	0.073	2.45	0.1483	
BC	0.021	1	0.021	0.69	0.4246	
A^2	0.21	1	0.21	7.08	0.0239	
B^2	0.16	1	0.16	5.29	0.0443	
C^2	7.07	1	7.07	237.08	<0.0001	
Residual	0.30	10	0.30			
Lack of Fit	0.30	5	0.060			
Pure Error	0.000	5	0.000			
Cor Total	173.25	19				
R-Squared = 0.9983			Adj R-Squared = 0.9967			
Predicted R-Squared = 0.9838			Adequate Precision = 84.893			

In terms of coded and actual factors, the prediction of impact strength is expressed by equation (4.2).

$$\textbf{Impact strength}=+25.97+1.63*A+0.35*B+3.48*C+0.056*AB+0.12*AC-0.064*BC-0.26*A^2-0.19*B^2-1.22*C^2 \qquad \textbf{(4.2)}$$

The quadratic regression model (Table 4.15) showed the value of coefficient determination (R^2) of 97.77%.This implies that the model was able to explain 97.77% of the results. Bradley (2007) posited that when the R^2 value is closer to 1 (100%), the better the estimation of the regression equation fits the actual data. Themodel adequacy precision value of 24.322indicate a very strongcorrelation between the response and the independent variables. The significance of the model was also judged by F-test. The high model F-value (F= 48.68) greater the P-value is a further demonstration of it significant. The adjusted R^2 of 95.76%, implies that only 4.24% of the total variations was not explained by model. However, the relatively lower value of coefficient of variation (CV = 1.28%) in Table 4.25 (Appendix 11)validate the precision and reliability of the experiments carried out.

Table 4.15: ANOVA result for percent elongation model

Source	Sum of Square	Df	Mean Square	F value	P-value Prob>F	
Model	47.11	9	5.23	48.68	< 0.0001	Significant
A-Current	9.69	1	9.69	90.14	< 0.0001	
B-Soaking time	3.85	1	3.85	35.78	< 0.0001	
C-Temperature	25.11	1	25.11	233.53	0.6049	
AB	0.031	1	0.031	0.29	0.4560	
AC	0.63	1	0.63	5.88	0.0357	
BC	0.63	1	0.63	5.84	0.0362	
A^2	0.050	1	0.050	0.46	0.5124	
B^2	0.013	1	0.013	0.12	0.7378	

C^2	3.64	1	3.64	33.84	<0.0002	
Residual	1.08	10	0.11			
Lack of Fit	1.08	5	0.22			
Pure Error	0.000	5	0.000			
Cor Total	48.19	19				
R-Squared = O.9777				Adj R-Squared = 0.9576		
Predicted R-Squared = 0.6771				Adequate Precision = 24.322		

In terms of coded and actual factors, the prediction of percent elongation is expressed by equation (4.3).

$$\%\mathbf{Elongation}=+25.60+0.98*A+0.62*B+1.59*C-0.073*AB+0.34*AC-0.35*BC+0.13*A^2-0.054*B^2+0.88*C^2 \quad \mathbf{(4.3)}$$

4.3 Graph of predicted versus actual results

Figures 4.8-4.10 show the predicted versus actual values of tensile strength, impact strength and percent elongation. Figure 4.8 shows the plot of predicted versus actual results. The graph shows that not all the points were much closer to the regressed diagonal line. However, those that were closer to the diagonal line clearly infer that there is some level of correlation that existed between the predicted and actual result. Closer points along the diagonal line indicate more significant model fits and is associated to high R^2 value (Sympa, 2014). Therefore, the high values of R^2 and adjusted R^2 in Table 4.13 of the model for tensile strength validate the model significant and its predictive capacity.

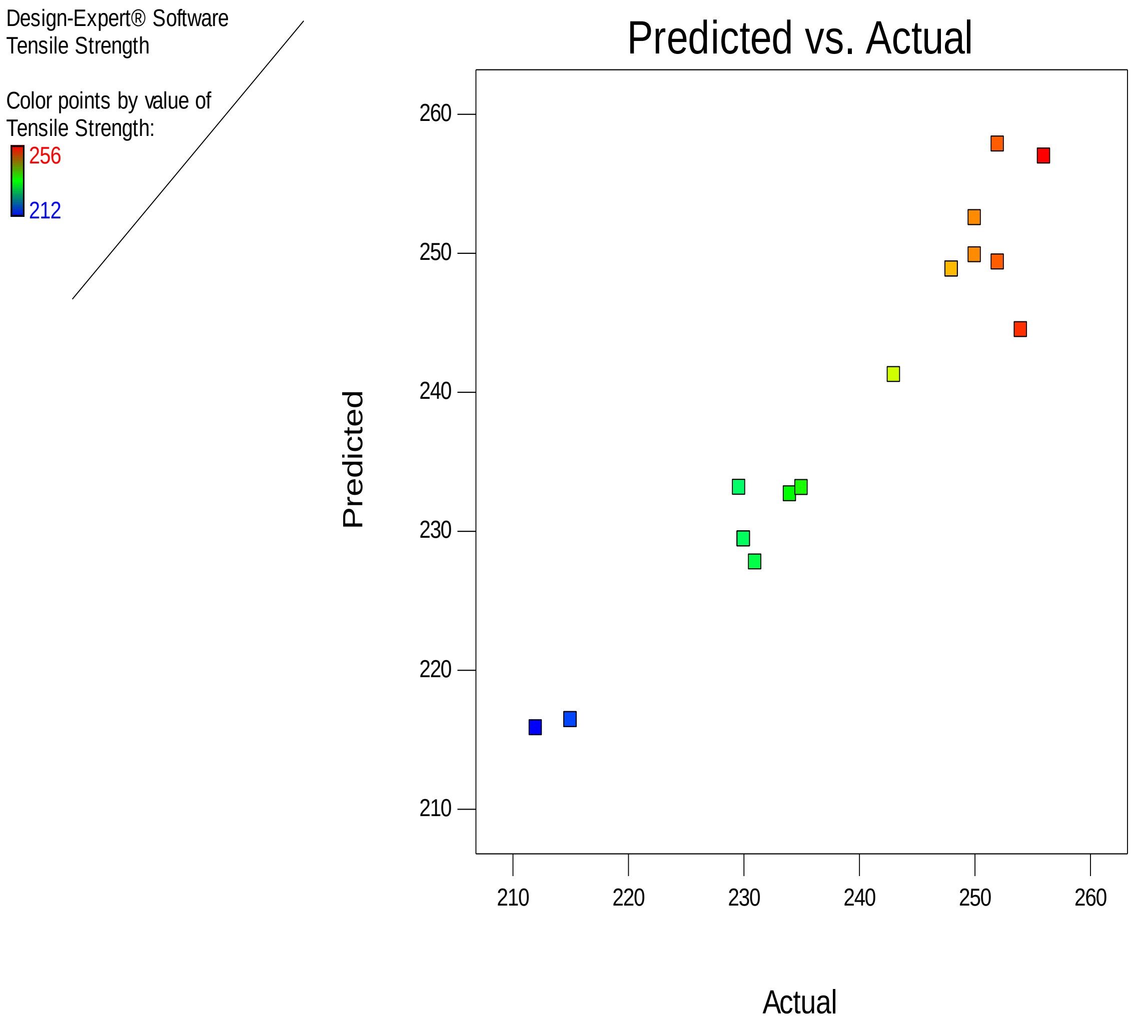


Fig. 4.8: Plot of predicted versus actual values of tensile strength

Figure 4.9 shows the plot of predicted versus actual results for impact strength. The graph indicates that there is strong correlation between the predicted and actual results. The closeness of the predicted and actual values along the regressed diagonal line justified the correlation of these values.

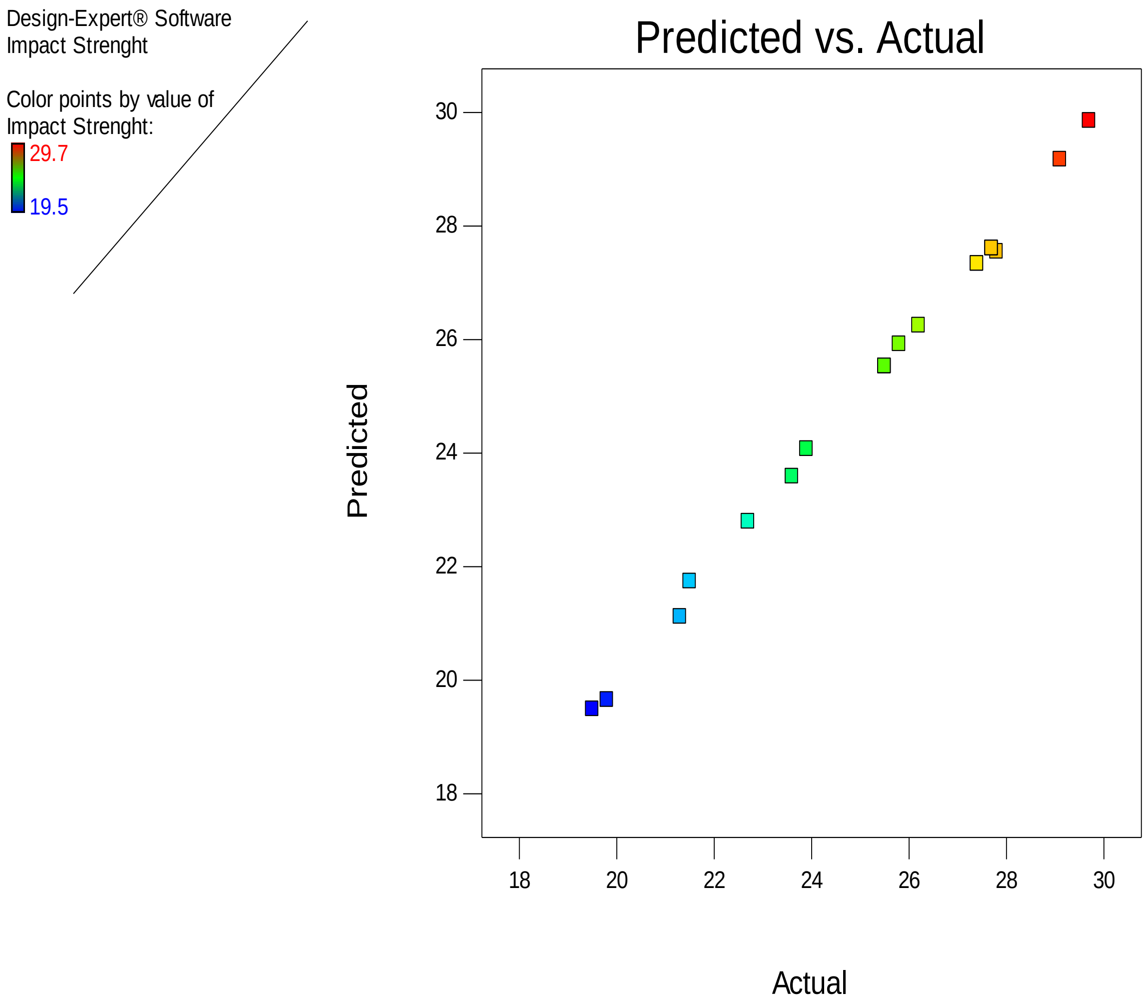


Fig. 4.9: Plot of predicted versus actual values of impact strength

Figure 4.10 shows the plot of predicted versus actual values for percent elongation. The graph showed that not all the predicted and actual points lies along the regressed diagonal line. This implies that there is a mix level of correlation between the predicted and actual. Those points that lies along the regressed diagonal line exhibited strong correlation with each other, while points that are outside the diagonal line indicate weak correlation. However, the high values of R^2 and adjusted R^2 of the model indicated that only 4.24% of the variation that was not explained by the model.

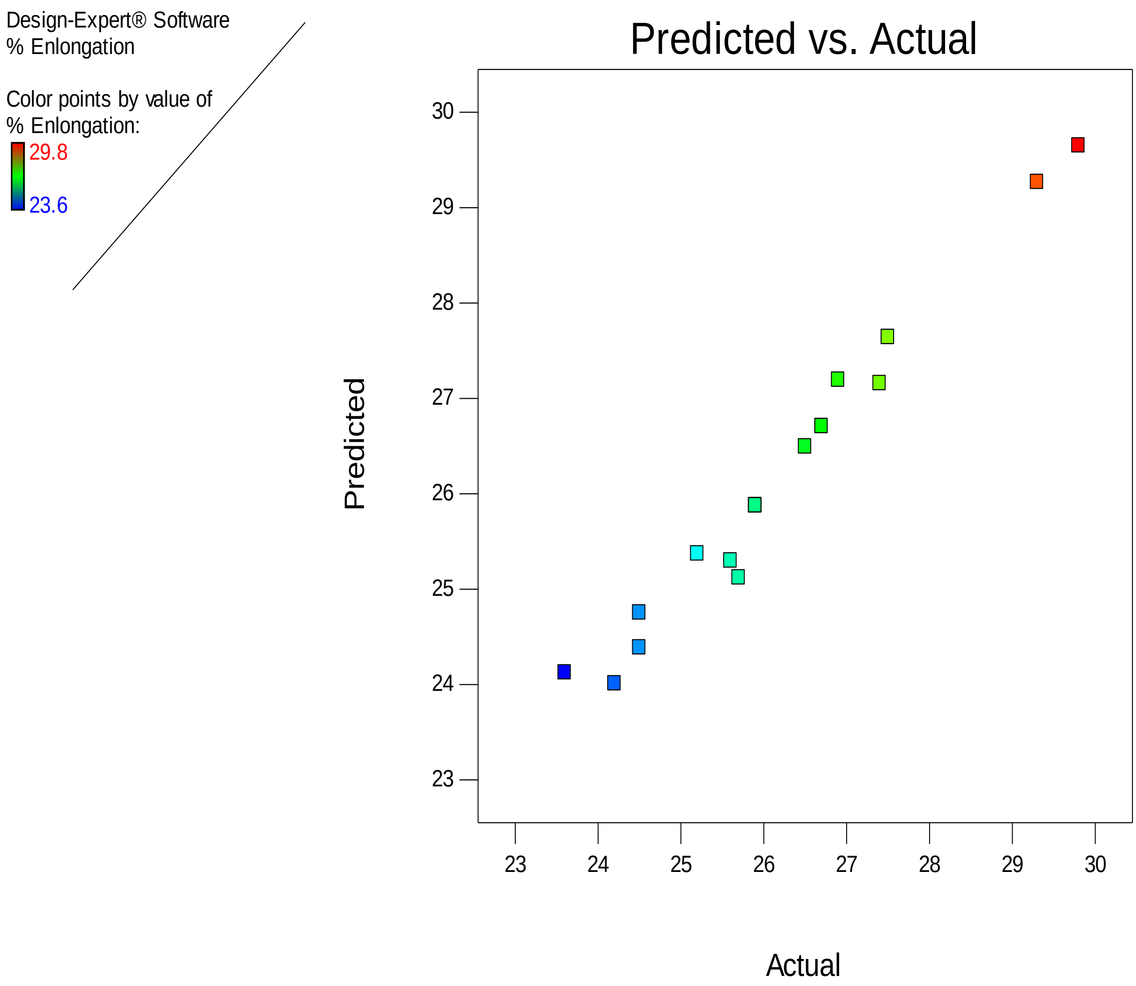


Fig. 4.10: Plot of predicted versus actual value of percent elongation

4.4 Perturbation plot results

The perturbation plot helps to compare the effects of all the variable factors at a particular point in the design space. The response is plotted by changing only one factor over its range while holding all the other factors constant. The plot is used to find the factors that affect the response most (Design-Expert Stat-Ease, 2018).

Figure 4.11 shows the perturbation plot of three factors; welding current (A) and soaking time (B) and temperature (C) on tensile strength. The steep slope and curvature exhibited by the three variable factors show how the response (tensile strength) was affected differently by these factors. The steep slope as well as the high F-value of 103.87 exhibited by welding current shows that welding current had the most influence followed by soaking time. Whereas temperature had no influence on the response due to it P-value (P>0.1).

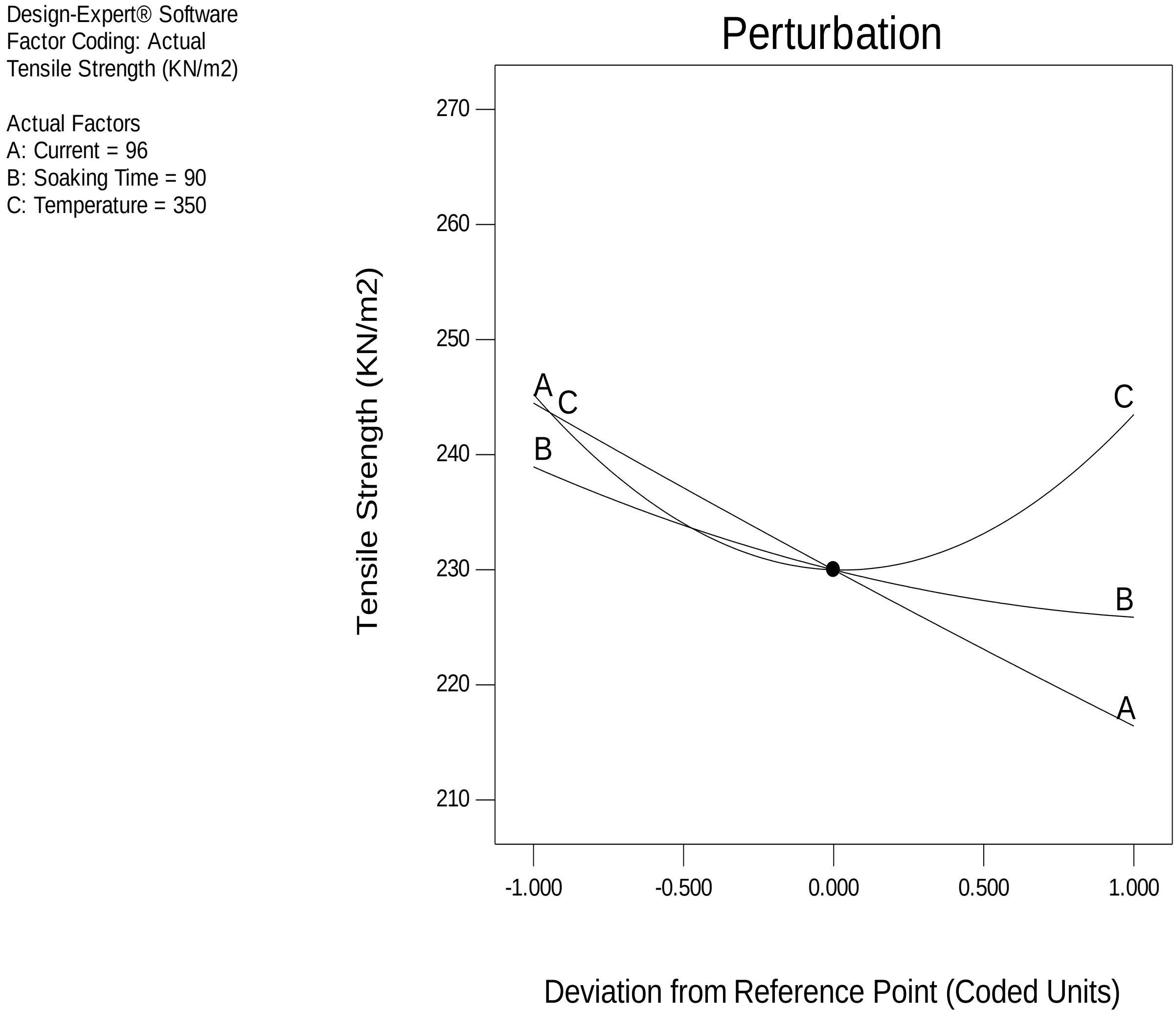


Fig.4.11: Perturbation plot of welding current, soaking time and temperature on tensilestrength.

Figure 4.12 shows the perturbation plot of welding current, soaking time and temperature on the impact strength. The curve nature of the individual factor indicates that they all had strong influence on the response (impact strength). This is also shown in the ANOVA for impact strength (Table 4.14) where each of the variable factors P-values are significant at p<0.0001. However, the F-values of 4048.83, 905.77 and 41.56 for temperature, welding current and soaking time respectively indicated that temperature affected the response most followed by welding current and soaking time. A very high F-value in a factor indicate its high significant.

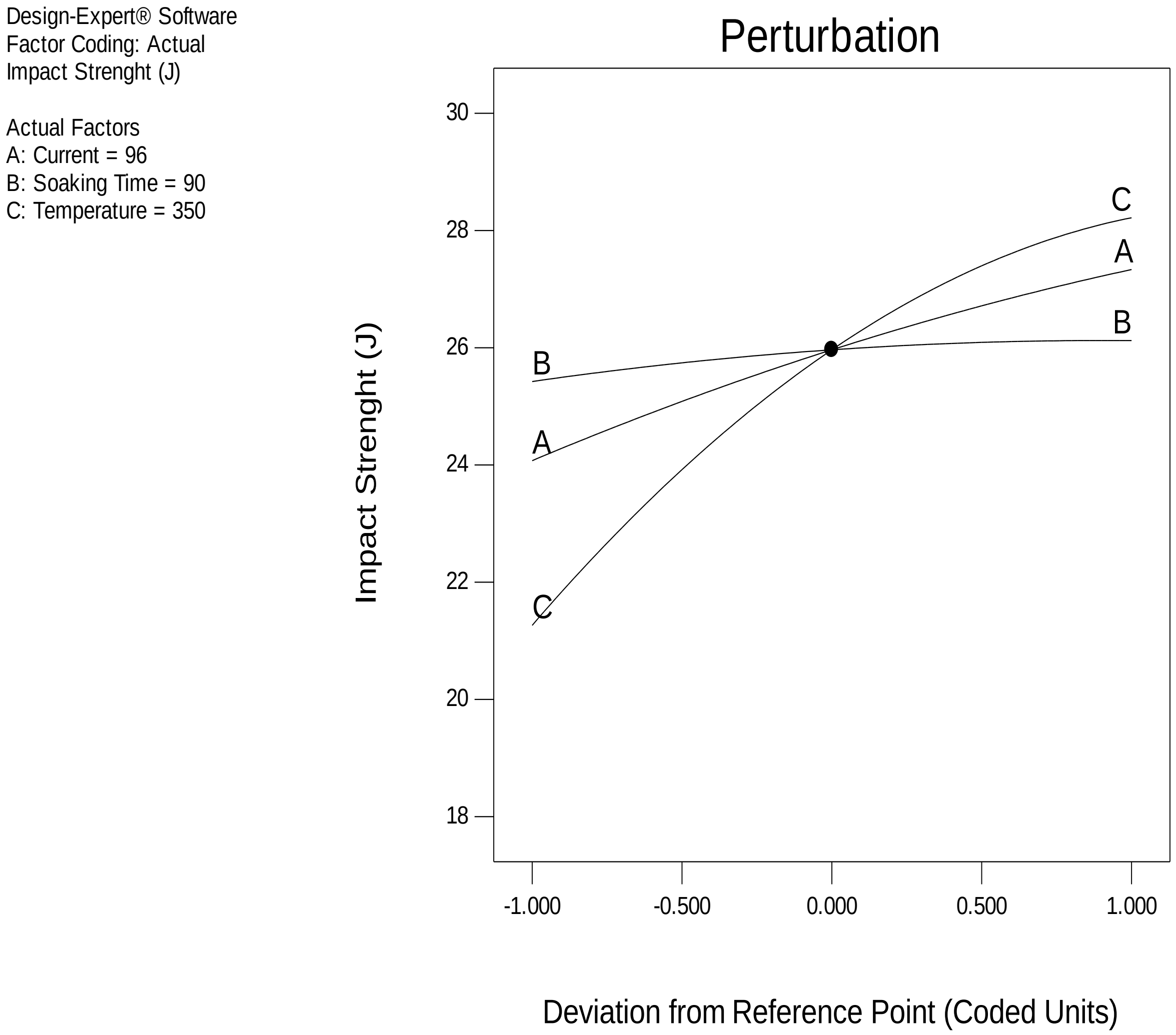


Fig.4.12: Perturbation plot of welding current, soaking time and temperature on impact strength.

Figure 4.13: shows Perturbation plot of welding current, soaking time and temperature on percent elongation. The nature of the curvature displaced by the individual factor shows that the three factors affected the response (percent elongation) although at different degree. However, the results of the analysis of variance (Table 4.15) depict that welding current and soaking time had profound influence on the response based on their lower probability values ($P<0.0001$). Whereas temperature showed no influence on the response as indicated by $P>0.1$.

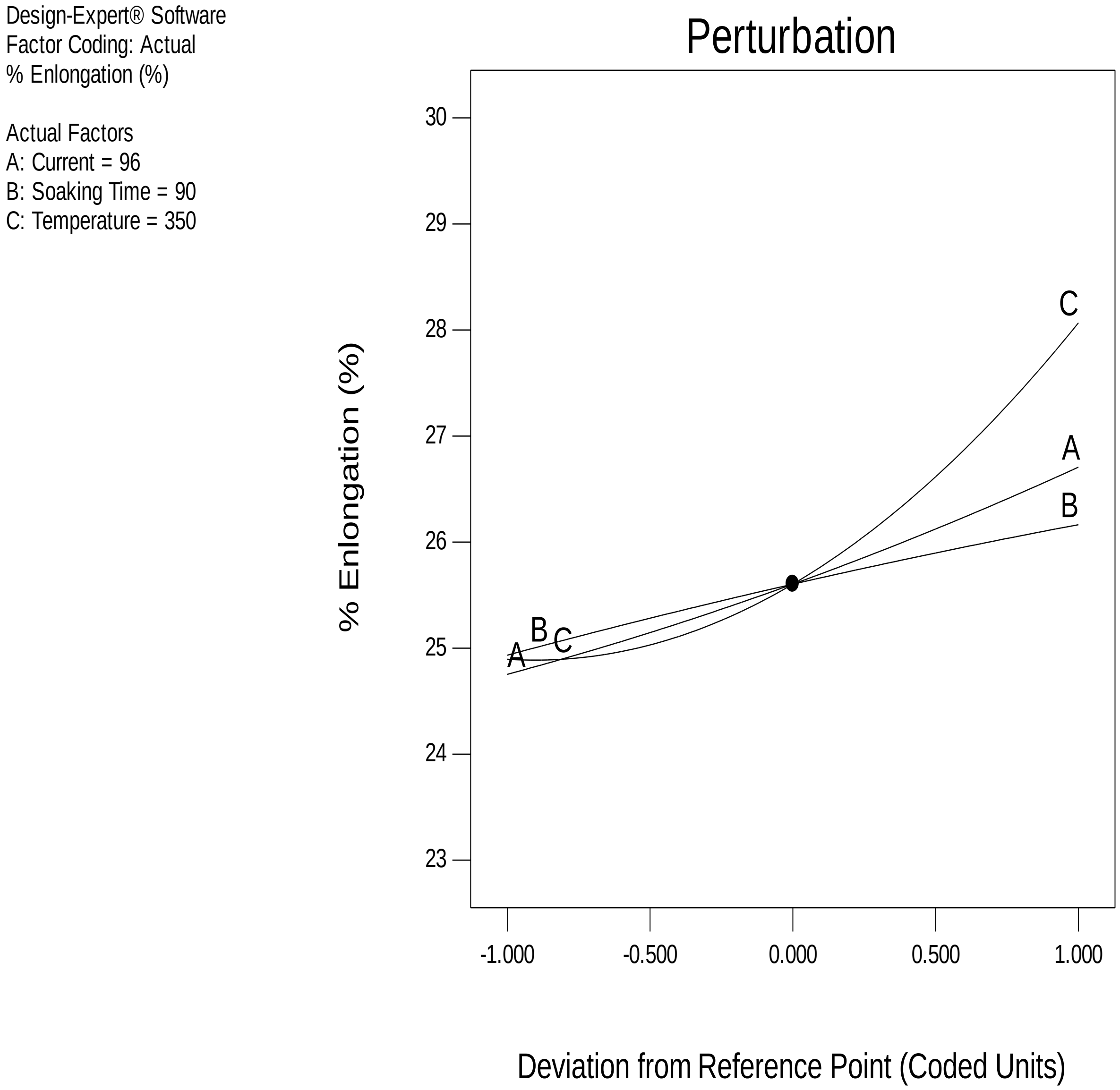


Fig.4.13: Perturbation plot of welding current, soaking time and temperature on percent elongation.

4.5 3D response surface plot result

Figures 4.14–4.16. Show the graphical representation of the interaction effects of two variable factors. Hazard *et al.*, (2007) reported that an elliptical plot indicates that interaction existed between the factors. Figure 4.14 shows that there is interaction between welding current (A) and soaking time (B).The probability value of the two interaction factors (AB) was significant at $P<0.1$. This implies that the mutual interaction between the two variable factors affected the response (tensile strength) significantly.

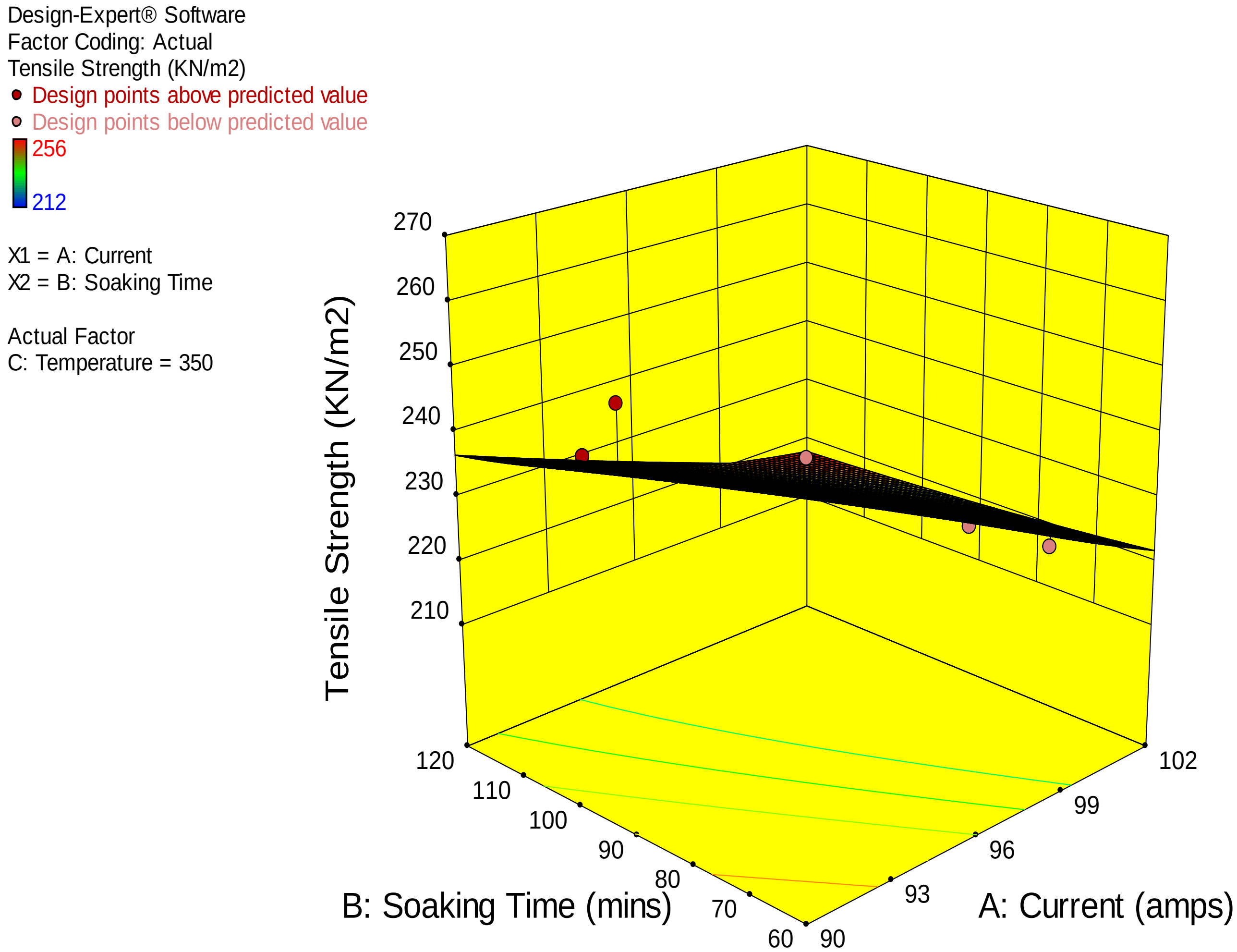


Fig.4.14: 3D response surface plot of welding current and soaking time on tensile strength

Figure 4.15 shows interaction existed between soaking time (B) and temperature (C) as depicted by the elliptical nature of the plot. However, the probability value ($P>0.1$) of the interaction factors (BC) indicated that their interaction did not affect the response (tensile strength).

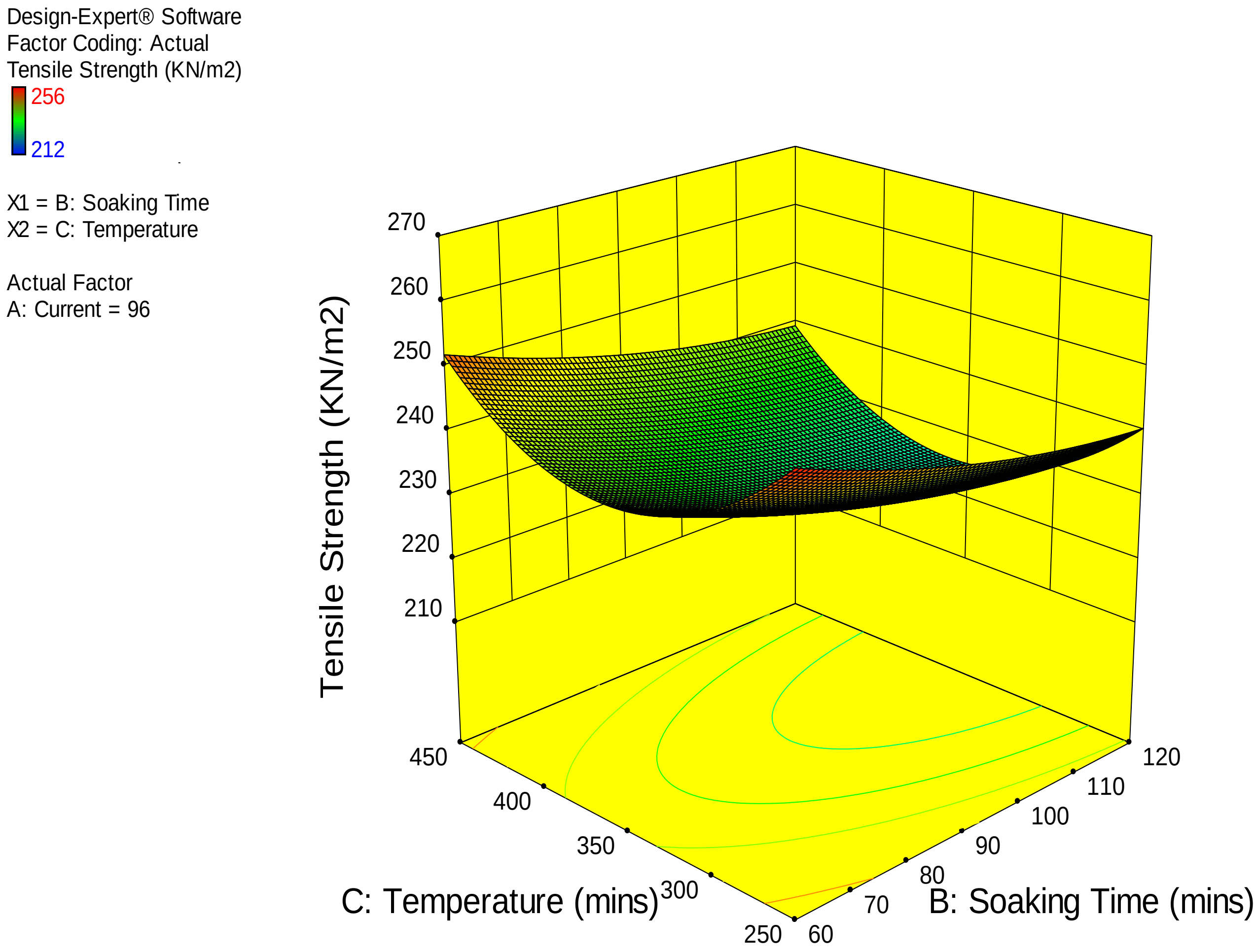


Fig. 4.15: 3D response surface plot of soaking time and temperature on tensile strength.

Figure 4.16 shows the interaction of welding current and temperature on tensile strength. The elliptical nature of the plot depicts that there is a mutual interaction between the two variable factors. However, the probability value (P>0.1) of the interaction factors (AC) in Table 4.13 shows that the interaction had no significant influence on the response.

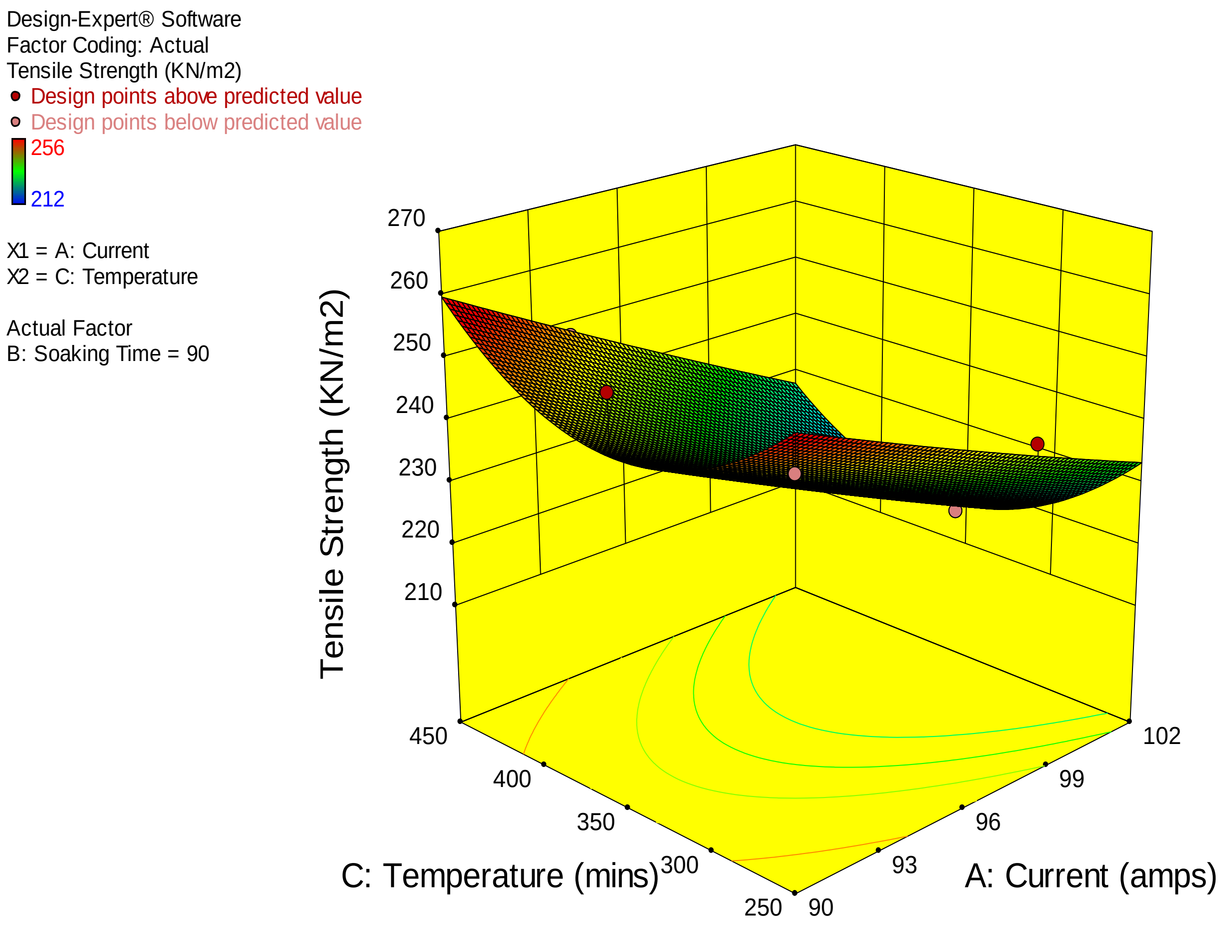


Fig.4.16: 3D response surface plot of welding current and temperature on tensile strength.

Figures 4.17-4.19 show graphically the interaction effects of two variable factors on impact strength. Figure 4.17 depicts the mutual interaction effect of soaking time and temperature on impact strength. The elliptical nature of the plot indicates that mutual interaction existed between the two variable factors. However, the probability value (P>0.1) of the interaction factors (BC) in Table 4.14 indicated that the interaction between the two variable factors had no significant effect on the response (impact strength).

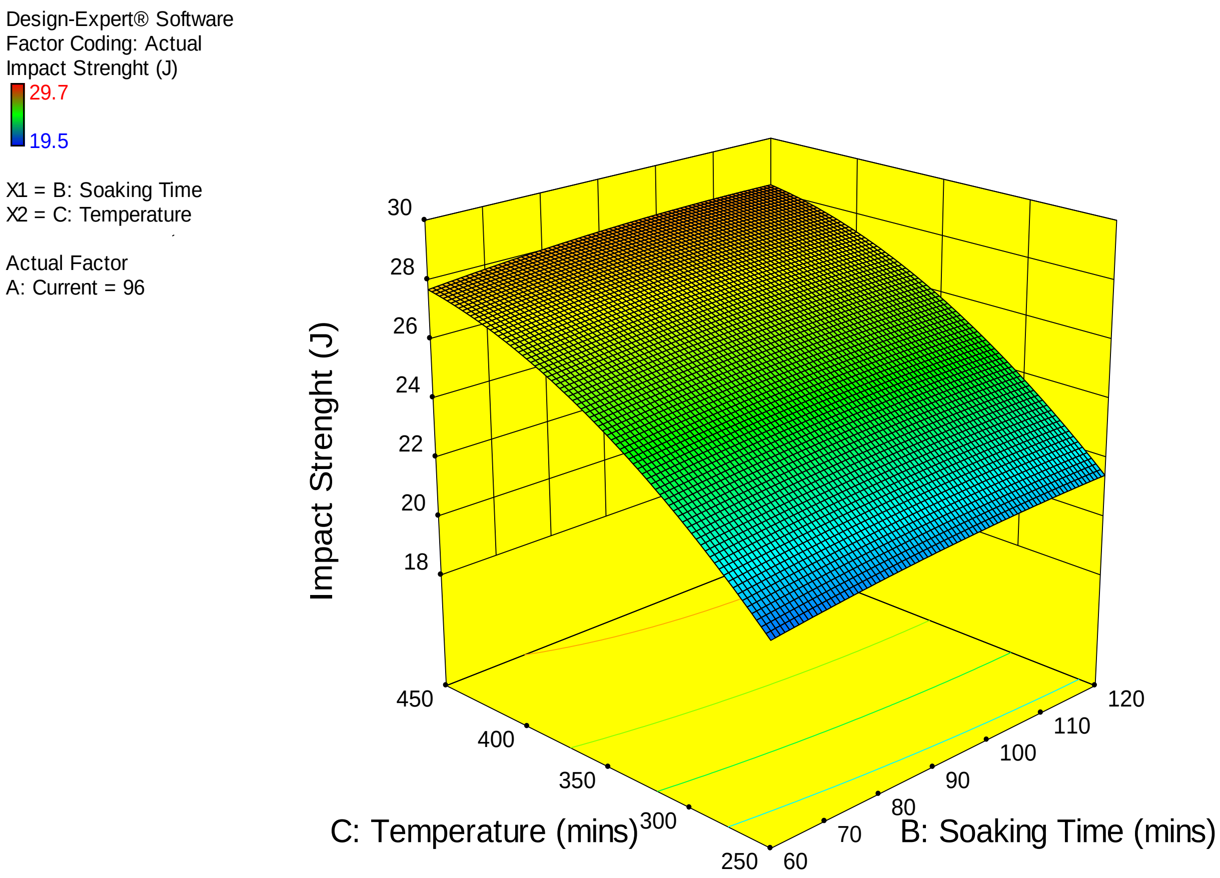


Fig. 4.17: 3D response surface plot of soaking time and temperature on impact strength.

Figure 4.18 shows graphically the interaction effect of welding current and temperature on impact strength. The elliptical nature of the plot signifies good mutual interaction. The low probability value (P<0.1) of the interaction factors (AC) in Table 4.14 indicated that the interaction had significant influence on the response (impact strength).

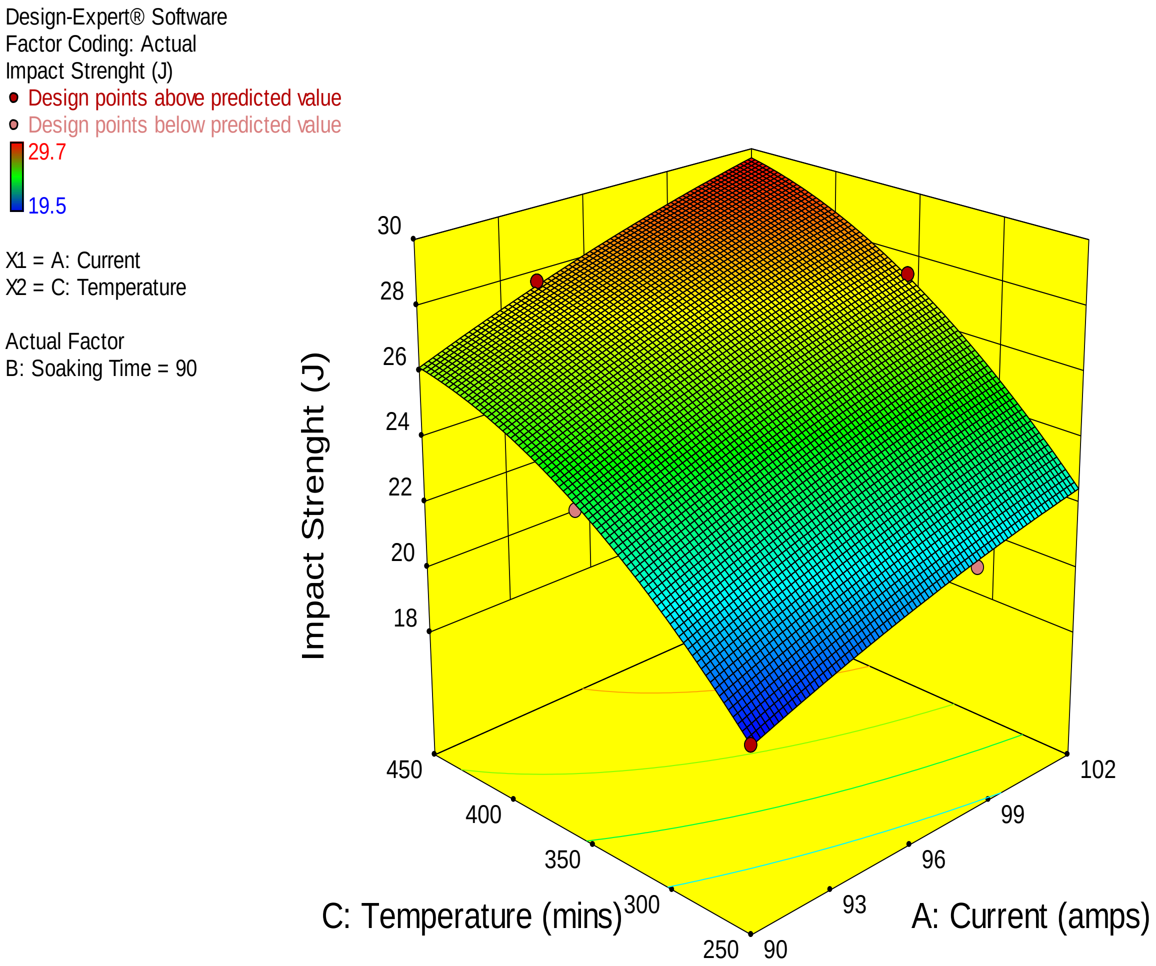


Fig. 4.18: 3D response surface plot of welding current and temperature on impact strength.

Figure 4.19 shows graphically the interaction effect of welding current and soaking time (AB) on impact strength. Mutual interaction between the two variable factors could be observed due to elliptical nature of the plot. However, the probability value (P>0.1) of the interaction factors (AB) indicates a relatively weak influence on the response.

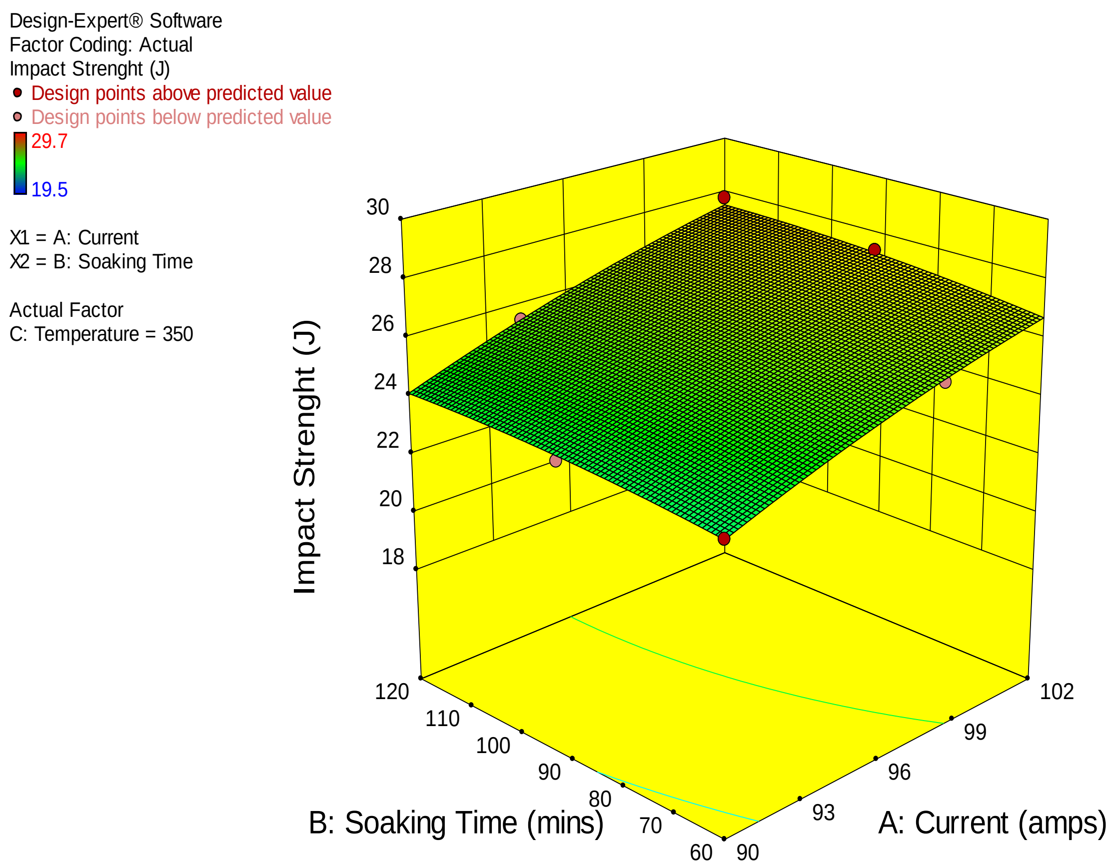
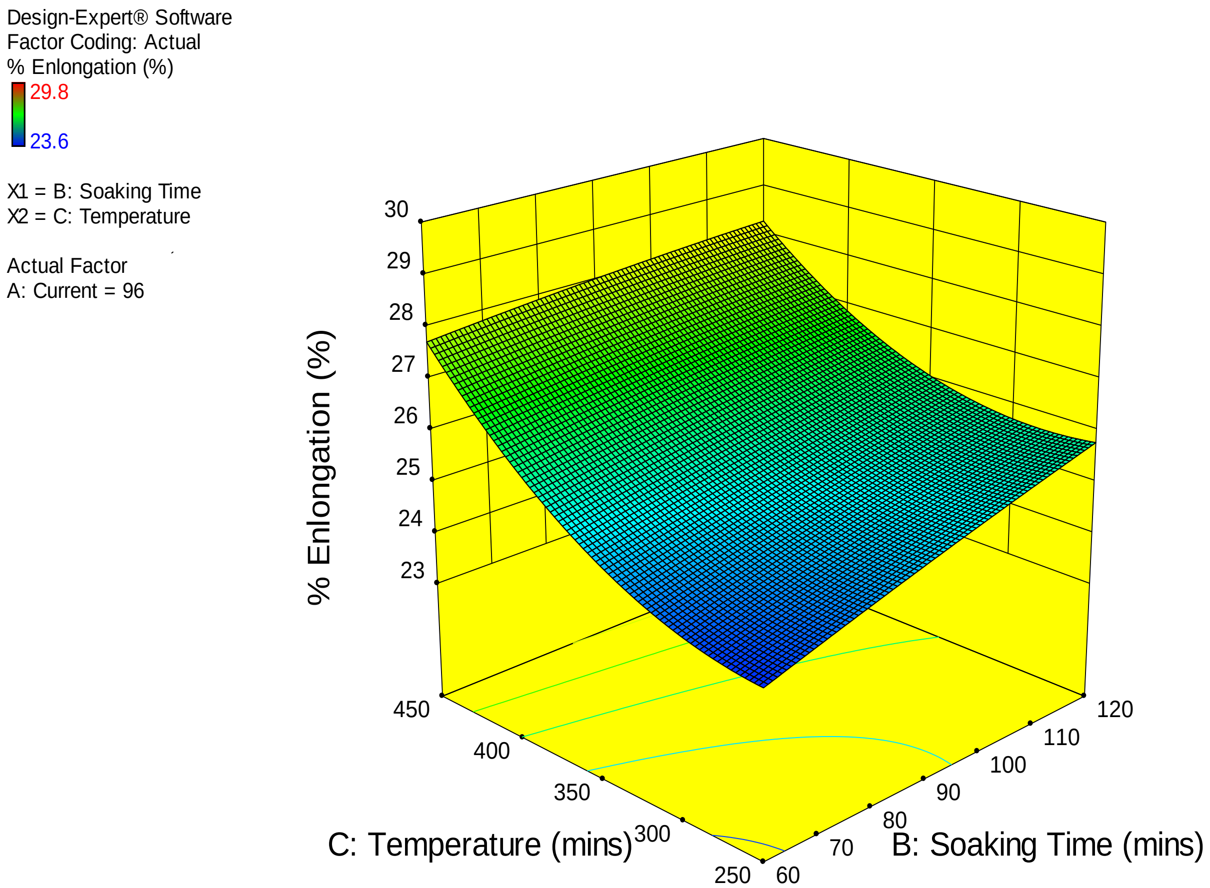


Fig. 4.19: 3D response surface plot of welding current and soaking time on impact strength.

Figure 4.20 shows graphically the interaction effect of temperature and soaking time on percent elongation. The elliptical nature of the plot suggest mutual interaction existed between the variable factors. The probability value (P<0.05) of the interaction factors (BC) as shown in Table 4.15 shows that the interaction



factors (BC) had substantial effect on the response.

Fig. 4.20: 3D response surface plot soaking time and temperature on percent elongation.

Figure 4.21 represents graphically the interaction effect of welding current and temperature on percent elongation. Mutual interaction between the two variable factors could be observed due to elliptical nature of the plot. The probability value (P<0.05) as indicated in Table 4.15 clearly demonstrates the sensitivity of the response to the interaction of the two variable factors.

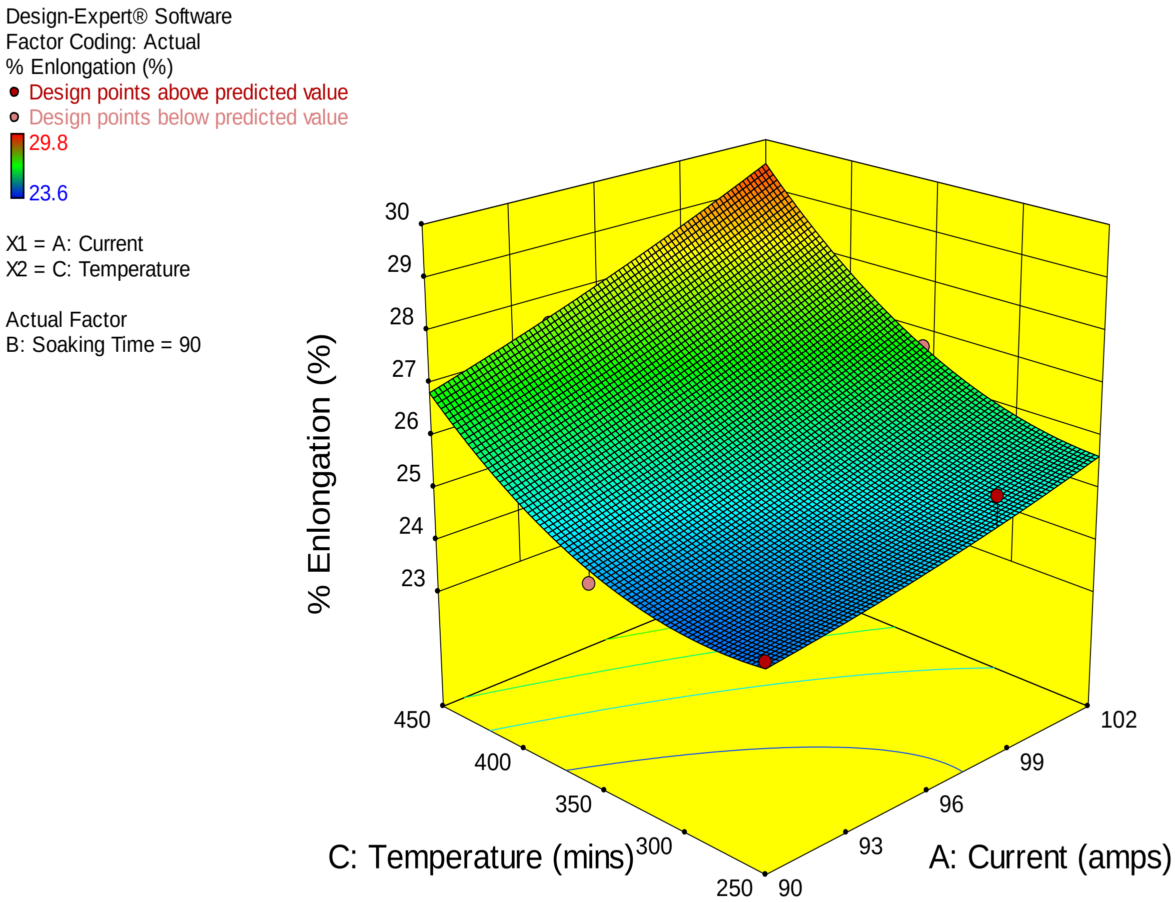


Fig. 4.21: 3D response surface plot of welding current and temperature on percent elongation.

Figure 4.22 shows graphically the interaction effect of the variable factors (welding current and soaking time) on percent elongation. The elliptical nature of the plot entails mutual interaction existed between the two variable factors. However, the probability value (P>0.1) of the two variable factors (AB) indicates that the interaction factors are less sensitive to the response.

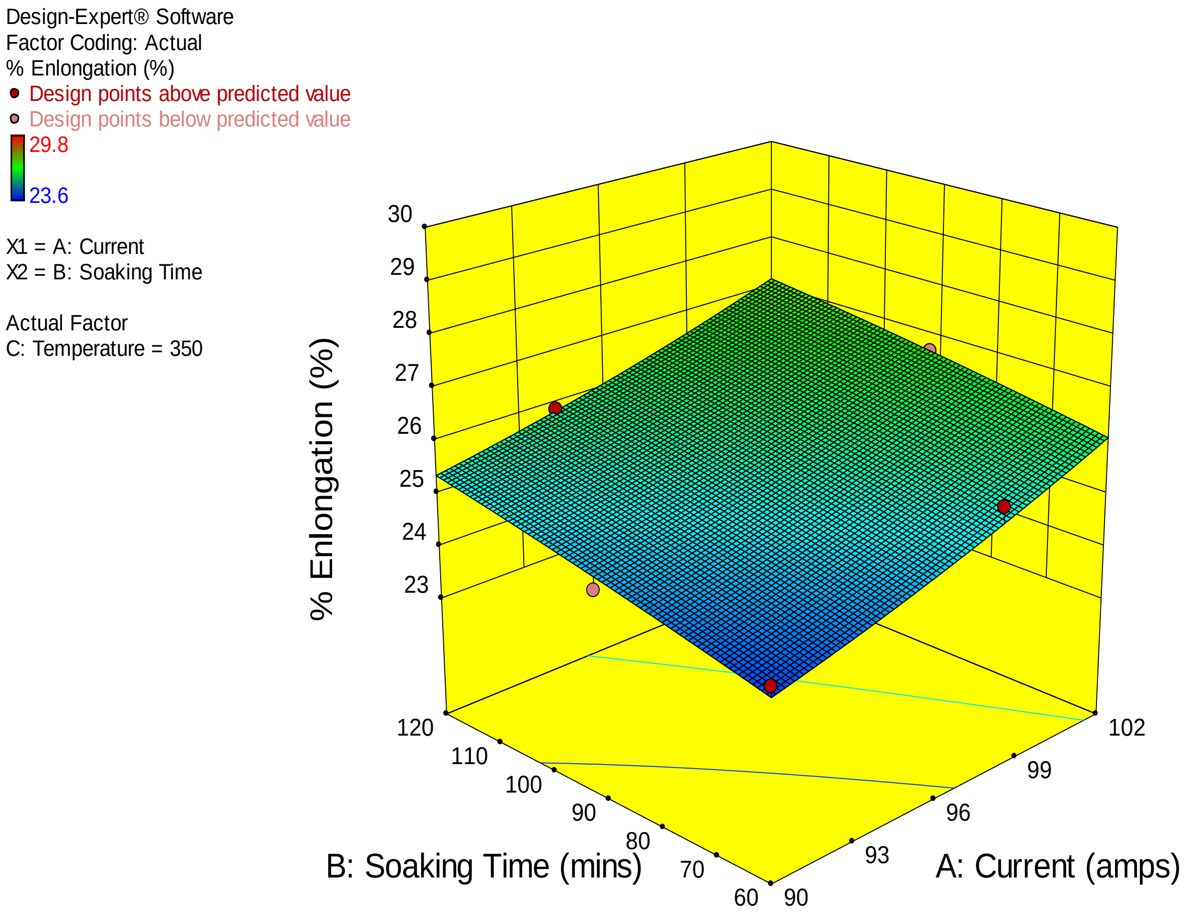


Fig. 4.22: 3D response surface plot of welding current and soaking time on percent elongation.

4.6 Optimization of response variables

The objective of optimization is to set the variable factors at the levels that would produce optimal response values. In other words, it is intended to minimize the difference between the measured and the predicted output parameters by minimizing errors and cost. In this way, the process parameter is calculated in such a way that the response approach the desired values. Therefore Table 4.16 shows the variable factors and responses at their different levels with criteria used.

Table 4.16: Optimization criteria used in the study

Factorand Response	Limits		Criterion	Goal
	Lower	Upper		
Current	90	102	In range	In range
Soaking time	60	120	In range	In range
Temperature	250	450	In range	In range
Tensile strength	212	256	In range	Maximize
Impact strength	19.5	29.7	In range	Maximize
Percent elongation	23	29.8	In range	Maximize

4.7 Optimum conditions and response values

The determination of the appropriate welding and heat treatment conditions to be applied in the welding and heat treating of micro-alloyed steel will reduce time and cost in subsequent experimental runs or test. Therefore, Tables 4.17-4.19 show the optimum conditions (set of values) of the welding and heat treatment operational conditions that are appropriate in obtaining maximum response in the experimental design space. In Table 4.17 the design expert software generated three different operational conditions that would result in optimal tensile strength of the micro-alloyed steel weldment. Each set of values for the variable factors were averaged in order to obtain the final set of values for each of the variable factor. The desirability index for each of the optimum conditions generated by the design expert software was 0.789. Granato and Calado (2014) posited that if the desirability index ≥0.70, it implies that the optimum conditions chosen are appropriate and will result in optimal response. The optimum conditions generated by the design expert to obtain maximum impact strength and percent elongation are shown in Tables 4.18-4.19. The desirability index are 0.778 and 0.803 for impact strength and percent elongation respectively. These values entail that the generated conditions are appropriate and would result in optimal impact strength and percent elongation of the micro-alloyed steel weldment.

Table 4.17: Optimal solution as obtained by Design Expert software based on the criterion and goal on Tensile strength

Number	Current (amps)	Soaking time (min)	Temperature (^0C)	Tensile strength (KN/m^2)	Desirability
1	90.526	60.0001	250	258.485	0.789
2	90.472	60.0001	250	256.618	0.789
3	90.592	60	250.007	259.321	0.789
Average	90.530	60.000	250.002	258.141	0.789

Table 4.18: Optimal solution as obtained by Design Expert software based on the criterion and goal on impact strength

Number	Current (amps)	Soaking time (min)	Temperature (^0C)	Impact strength (J)	Desirability
1	101.393	120.0001	450	28.8399	0.778
2	101.367	120.0001	450	29.9342	0.778
3	101.446	120.0003	450	28.8515	0.778
Average	101.402	120.0002	450	29.2085	0.778

Table 4.19: Optimal solution as obtained by Design Expert software based on the criterion and goal on percent elongation

Number	Current	Soaking time	Temperature	Percent elongation	Desirability

	(amps)	(min)	(^{0}C)	(%)	
1	101.883	120.0003	450	29.2669	0.803
2	101.883	120.0002	450	29.2349	0.803
3	101.957	120.0003	450	29.2551	0.803
Average	101.908	120.0003	450	29.2523	0.803

4.8: Validation of optimized predictive results

The optimization technique was applied to find the conditions which gave the maximum desirable mechanical properties of the tempered micro-alloyed steel weldment. The Design Expert software generated the optimum conditions of 101.526 ampere, 60 minutes and 250^{0}C for welding current, soaking time and tempering temperature respectively, that would result in optimal value of tensile strength of 258.1413KN/m^2. The optimum conditions for optimal impact strength of 29.2085J and percent elongation of 29.2523% were 101.402 ampere, 120.0002 minutes and 450^{0}C, and 101.908 ampere, 120.0003 minutes and 450^{0}C respectively. A comparison of the experimental values with the values predicted by Design Expert 10, revealed that the actual and the predicted values are very close (Tables 4.20, 4.21 and 4.22).The deviation of predicted values from actual values were found to be very low and quite within the acceptable range for experimental results. The observed deviation of the predicted results from the actual results could be attributed to the fact that the surface properties of the welded metal and the physiochemical interactions between the weld metal zones and the surrounding which played vital roles during the welding and heat treatment operations were not considered as criteria during optimization. The results (Tables 4.20, 4.21 and 4.22) revealed that the optimization achieved in the present study was reliable.

Table 4.20: Predicted and actual values of tensile strength at the optimum conditions

Condition	Welding current (amps)	Soaking time (min)	Tempt. (^{0}C)	Tensile strength (KN/m^2)	Deviation (%)
Optimum condition (predicted)	90.53	60.0001	250.002	258.1413	0.05
Optimum condition (actual)	90	60	250	258	

Table 4.21: Predicted and actual values of impact strength at the optimum conditions

Condition	Welding current (amps)	Soaking time (min.)	Tempt. (^{0}C)	Impact strength (KN/m^2)	Deviation
Optimum condition (predicted)	101.402	120.0002	450	29.2085	-1.65
Modified condition (actual)	102	120	450	29.7	

Table 4.22: Predicted and actual values of percent elongation at the optimum conditions.

Condition	Welding current (amps)	Soaking time (min)	Tempt. (^{0}C)	Elongation (%)	Deviation
Optimum condition (predicted)	101.408	120.0003	450	29.523	-0.93
Modified condition (actual)	102	120	450	29.8	

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A detailed study of the effects of electrode type and heat treatment on the structure and mechanical properties of micro-alloyed steel has been conducted and the following conclusion drawn:

1. The study established that increase in heat input as a result of welding current increase caused microstructural grain coarsening which result in decreased in hardness, yield strength, tensile strength with corresponding increase in impact strength and percent elongation of the micro-alloyed steel weldment.
2. The study showed that the weld metal zones exhibited higher hardness than the heat affected zones and base metal in the proportion that depends on the alloying elements content of the electrode types.
3. The study established that the carbon content as well as the high amount of strong carbide forming elements in the E7016 electrode contributed considerably to the optimal hardness, yield strength, tensile strength and lowest impact strength and percent elongation obtained in the micro-alloyed steel weldment.
4. The low amount of carbon and carbide forming elements in the E7024 electrode was found to be responsible for the optimal impact strength, percent elongation and lowest hardness, yield strength and tensile strength obtained in the micro-alloyed steel weldment.
5. The study found that for each PWHT tempering temperature, impact strength and percent elongation substantially increased with increase in soaking time but hardness, yield strength and tensile strength decreased.

6. The study established that the thermal and cooling cycles induced at the HAZ by the welding current caused microstructural changes that varied the hardness of the HAZ of the micro-alloyed steel weldment.
7. The mathematical models developed were shown to be in proximate agreement with the experimental results. The deviation of the models predicted results from the experimental was found to be ±0.05. Hence, the models could serve as useful tool in engineering for predicting tensile strength, impact strength and percent elongation of the micro-alloyed steel weldment.

5.2 Contribution to knowledge

Selecting the appropriate welding consumables and heat treatment parameters that could be utilized to improve the mechanical properties of micro-alloyed steel weldment to meet service requirements has always been a huge challenge to the engineers and welders. Based on the research findings the following contributions to knowledge were made:

1. The PWHT tempering temperature of 450^0C and soaking duration of 90 minutes has been established as the most effective in ensuring optimal combination of tensile strength and percent elongation in the micro-alloyed steel weldment.

2. E7016 electrode has been established as the most appropriate in producing optimal hardness, yield strength and tensile strength in the micro-alloyed steel weldment.
3. E7024 electrode has been established as the most appropriate for producing optimal impact strength and percent elongation in the micro-alloyed steel weldment
4. The study has developed new mathematical models for predicting closely tensile strength, impact strength and percent elongation of micro-alloyed steel weldments.

5.3 Recommendations

Based on the conclusion of the research work, the following recommendations were made:

1. In applications where hardness and strength are the most desired properties E7016 electrode with a welding current of 90 ampere is recommended.

2. In applications where impact strength and percent elongation are the most desired properties E7024 electrode with a welding current of 106 ampere is recommended.
3. In applications where optimal combination of tensile strength and percent elongation are the most desired properties E7018 electrode with a current setting of 90 ampere and PWHT tempering temperature of 450^0C and soaking duration of 90 minutes are recommended.
4. Further study should include other welding parameters like welding positions, voltage and varied electrode travel speed.

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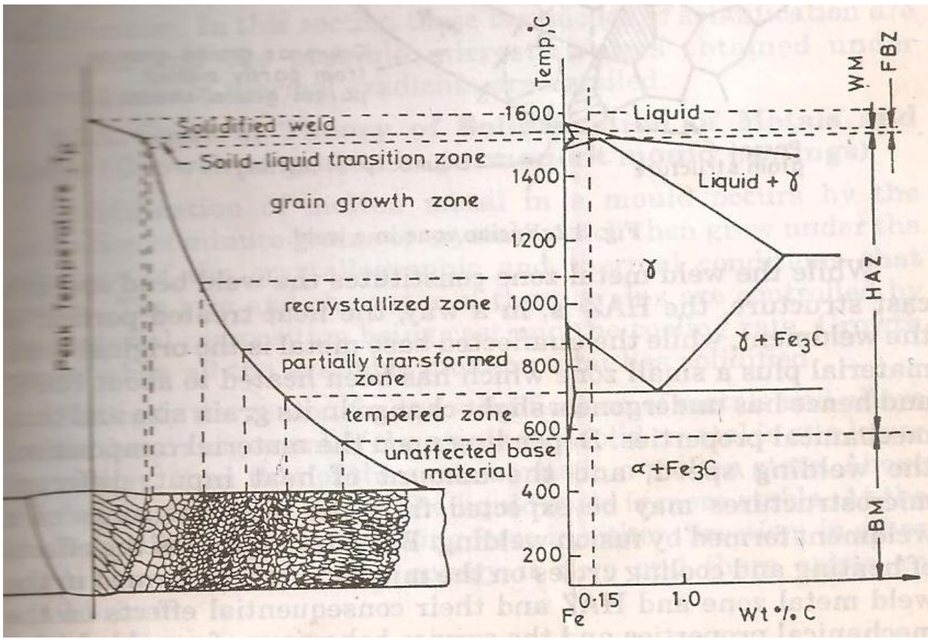
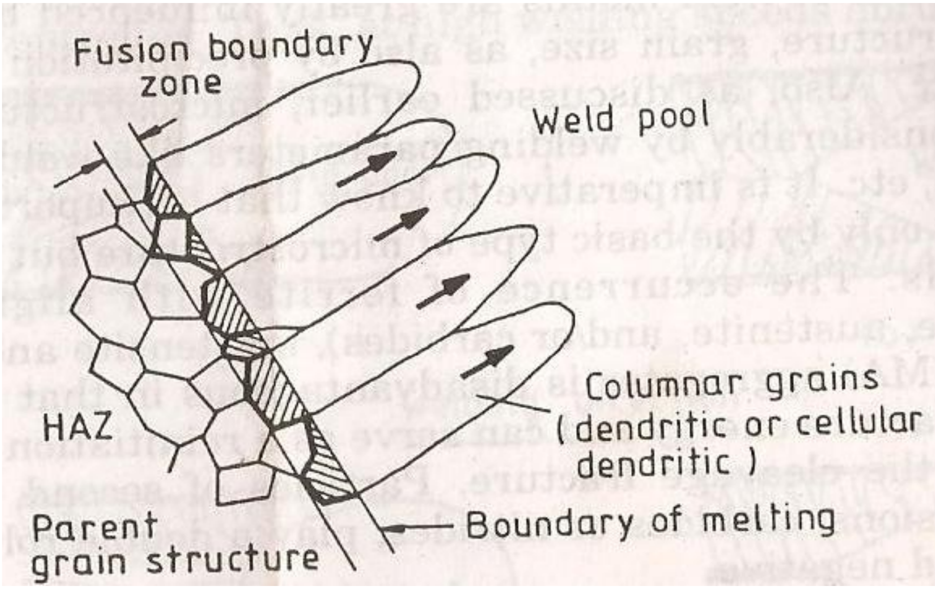
APPENDIX 1



(a)



(b)

Fig. 2.1:(a) Different zones of steel weldment as represented on Fe-C Phase diagram and (b) Fusion boundary zone in arc weld

APPENDIX 2

Fig. 3.1: Photograph of the welding machine

Fig. 3.2: Photograph of some welded samples

APPENDIX 3

Fig. 3.3: Photograph of the muffle furnace used

Fig. 3.4: Photograph of the Universal tensile testing machine used.

APPRNDIX 4

Fig. 3.7: Charpy impact testing machine used

Fig. 3.9: Photograph of the Brinell hardness testing machine used

APPENDIX 5

Fig. 3.10: Photograph of the optical microscope used

Fig. 3.11: Photograph of the SEM used

APPENDIX 6

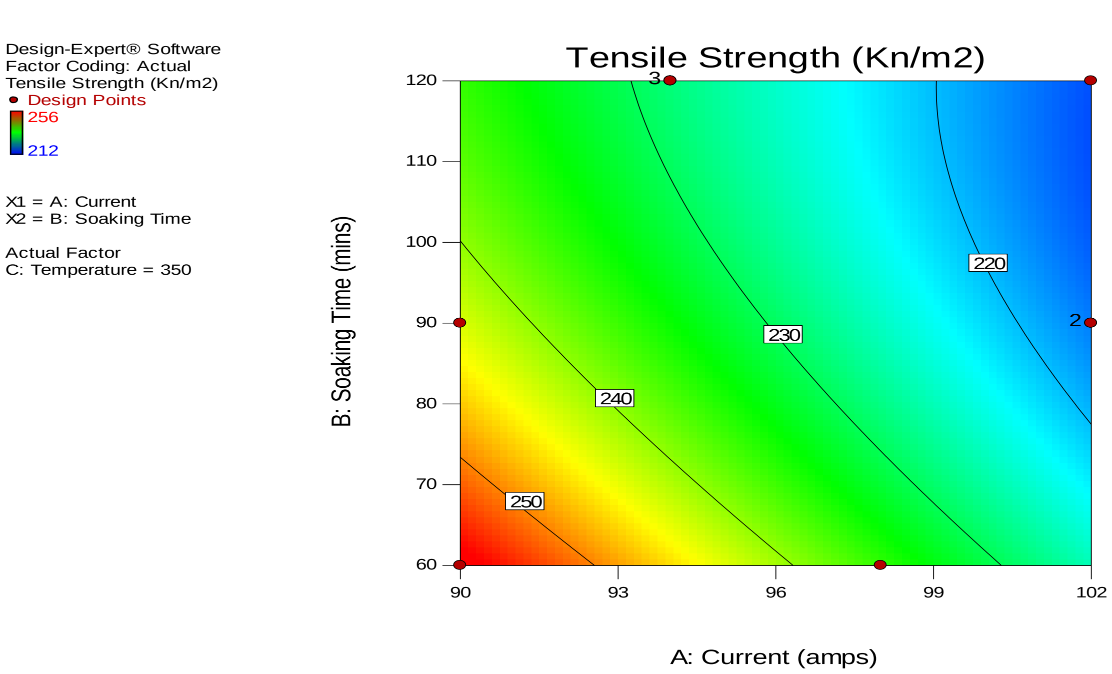


Fig. 4.23: Contour plot of welding current and soaking time on tensile strength.

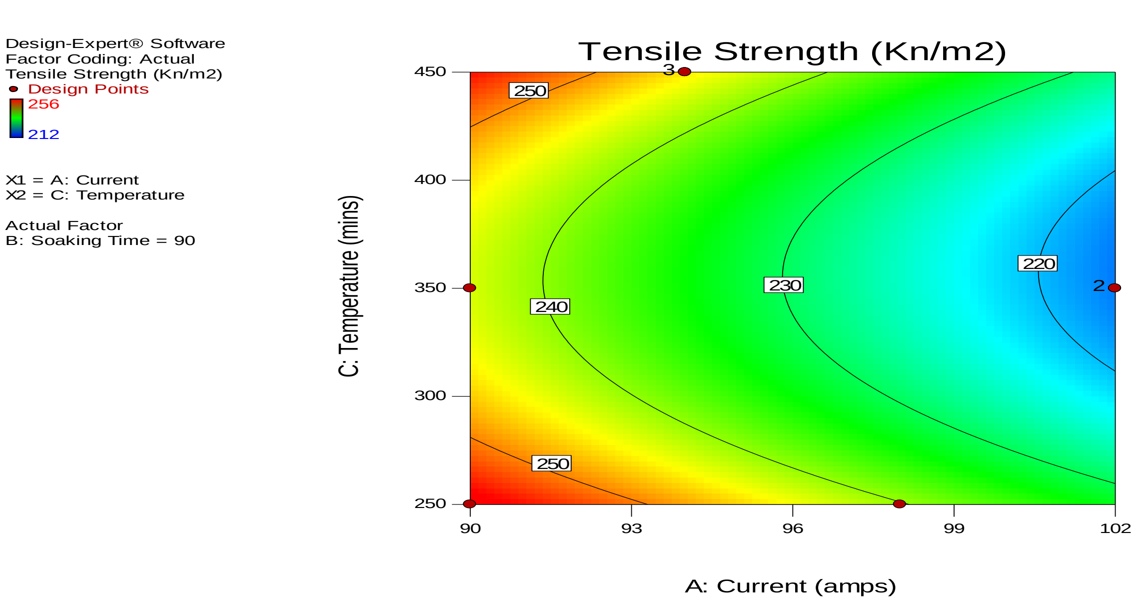


Fig. 4.24: Contour plot of welding current and temperature on tensile strength.

APPENDIX 7

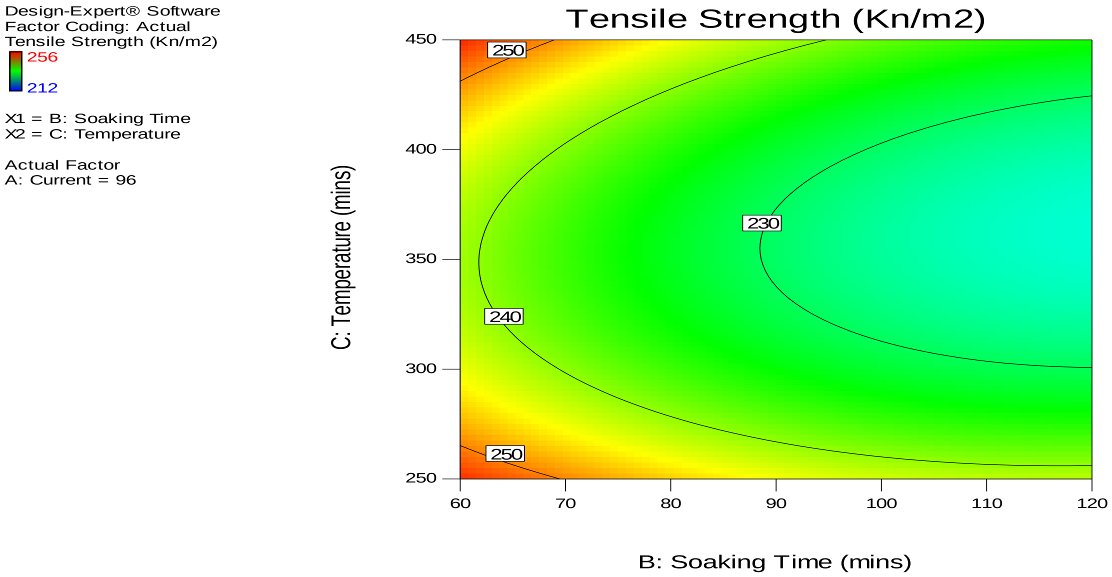


Fig. 4.25: Contour plot of soaking time and temperature on tensile strength.

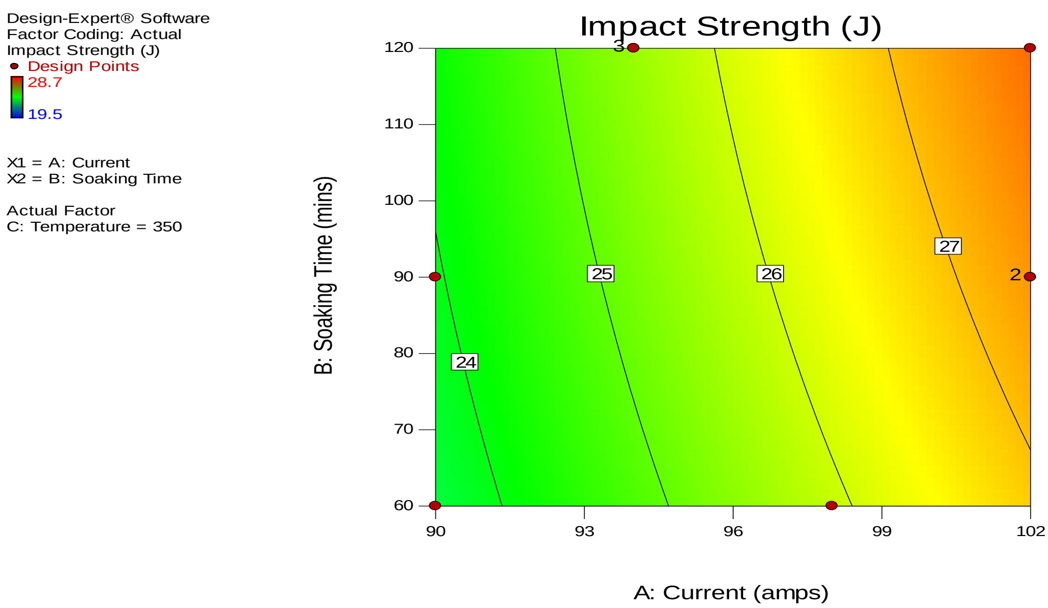


Fig. 4.26: Contour plot of welding current and soaking time on impact strength

APPENDIX 8

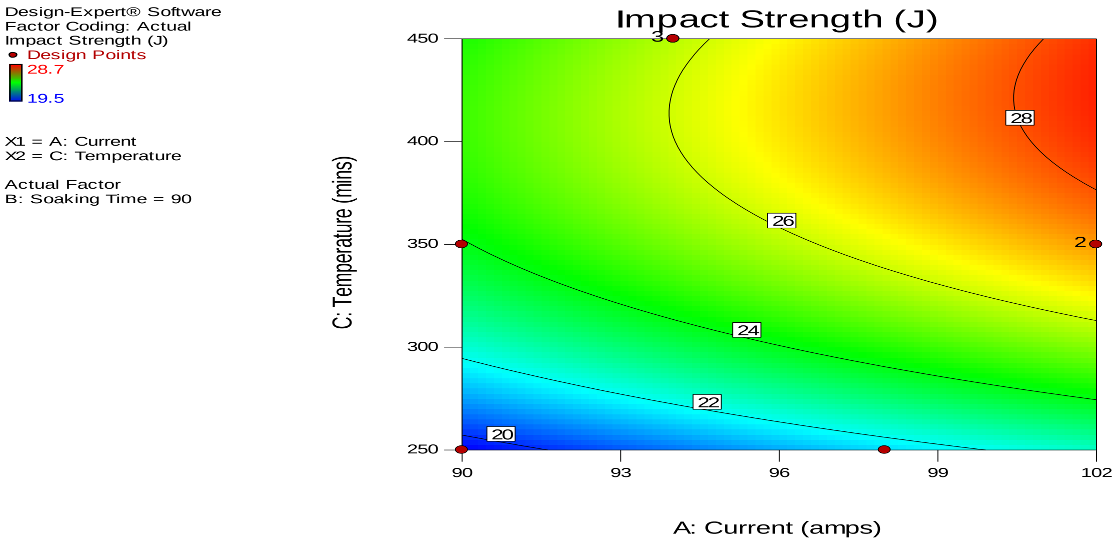


Fig. 4.27: Contour plot of welding current and temperature on impact strength.

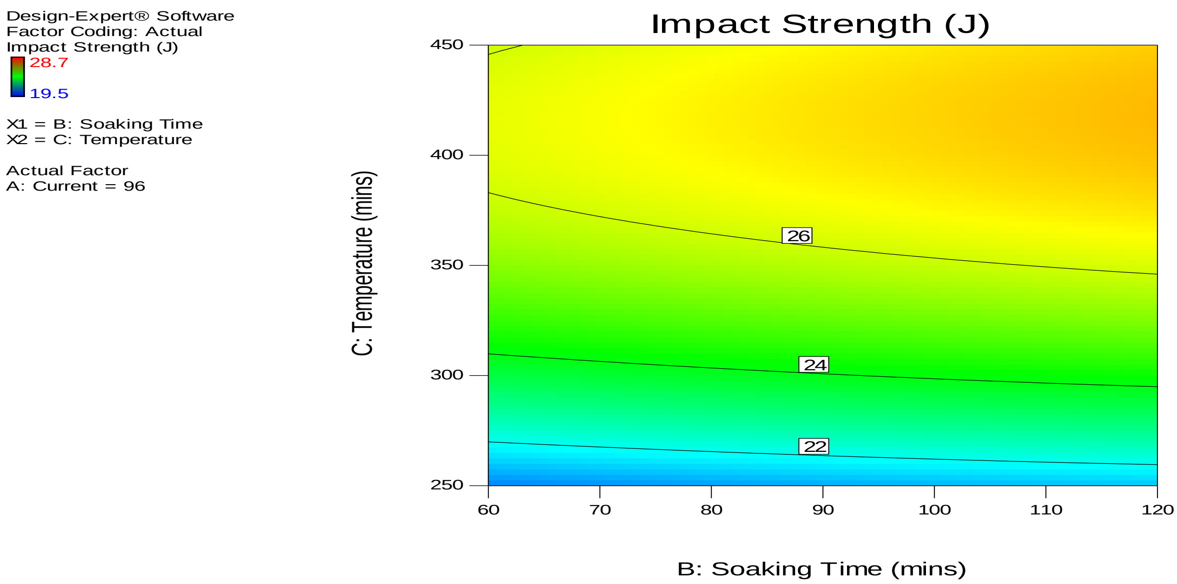


Fig. 4.28: Contour plot of soaking time and temperature on impact strength

APPENDIX 9

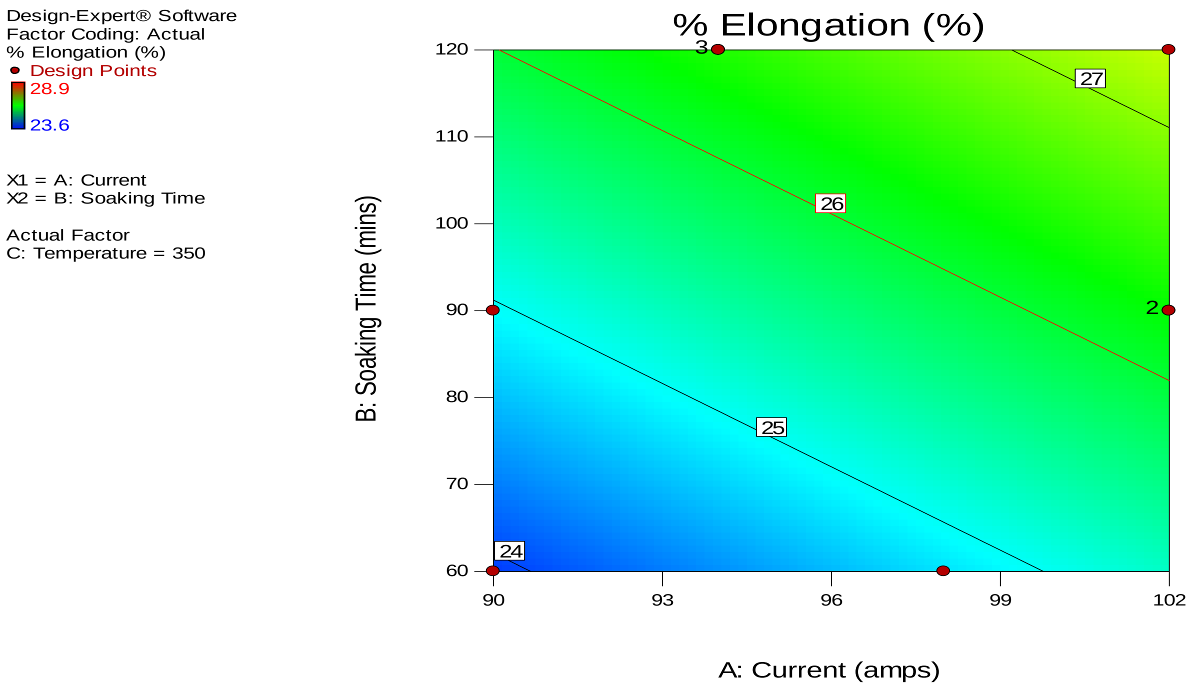


Fig. 4.29: Contour plot of welding current and soaking time on percent elongation

APPENDIX 10

Table 4.23: Statistical summary of the model for tensile strength

Std. Dev.	4.39	R-Squared	0.9473
Mean	238.13	Adj. R-Squared	0.8999
C.V. %	1.84	Pred. R-Squared	0.4255
PRESS	2099.97	Adeq. Precision	13.536
-2 Log Likelihood	102.04	BIC	132.00
		AICc	146.49

Table 4.24: Statistical summary of the model for impact strength

Std. Dev.	0.17	R-Squared	0.9983
Mean	25.27	Adj R-Squared	0.9967
C.V. %	0.68	Pred R-Squared	0.9838
PRESS	2.80	Adeq Precision	84.893
-2 Log Likelihood	-27.36	BIC	2.59
		AICc	17.08

APPENDIX 11

Table 4.25: Statistical summary of the model for percent elongation

Std. Dev.	0.33	R-Squared	0.9777

Mean	26.34	Adj R-Squared	0.9576
C.V. %	1.24	Pred R-Squared	0.6771
PRESS	15.56	Adeq Precision	24.322
-2 Log Likelihood	-1.70	BIC	28.25
		AICc	42.74