METALLURGICAL STUDIES OF WELDED JOINTS OF LOCAL AND IMPORTED LOW CARBON STEELS

by

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DECLARATION

I hereby declare that this thesis is my original work towards the Master of Science and that, to the best of my knowledge, has not been presented for a degree in any other University, except where due acknowledgment has been made in the text.

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ABSTRACT

The effects of heat-treatment and variations in alloy content on the microstructure and mechanical properties welded joints of local and imported low carbon steels have been studied. The joints were fabricated using the shielded metal-arc welding technique. The chemical analyses of the samples revealed that in imported steel the contents of the main alloying elements responsible for strength (i.e. carbon and manganese) were 0.19% and 0.54% by weight respectively, whereas in the local steel they constituted 0.06% and 0.29% by weight respectively. The relatively higher carbon and manganese contents in the imported steels as compared to those in locally-made steel accounted for the high Ultimate Tensile Stress (UTS) of 689.00 ± 7.72 MPa, Yield Strength (541.60 ± 6.15 MPa), Moduli of Elasticity (244.00 ± 11.44 GPa) and Impact Strength (214.50 ± 5.57 J), and lower ductility (23.66 ± 0.67%) of the imported steel. This also confirmed the large proportions of perlites in the imported steel as compared to those in the local steel from their optical micrographs. Local steel had lower UTS (528.25 ± 13.66 MPa), Yield strength (381.75 ± 5.88 MPa), Moduli of Elasticity (240.25 ± 3.66 GPa) and Impact strength (160.67 ± 7.23 J) and higher ductility (28.03 ± 1.33%). When the steels were welded there were significant drops in the mechanical properties. The heat-treatment improved the Ductility and Impact strength at the expense of UTS, Yield Strength and Young's Modulus. The ductility and impact strengths of welded local steels through heat-treatment increased by 42.00% and 100.50% respectively over the welded samples. With imported steel ductility and impact strengths increased by 47.30% and 125.10% respectively over the welded samples. It was concluded heat-treatment lowered the level of internal stresses at the joints thereby improving the ductility and impact toughness.

CHAPTER ONE

INTRODUCTION

1.1 General Introduction and Historical Development of Welding

The process of welding denotes the joining of metal pieces by heating to a plastic or fluid state, with or without pressure. In its simplest form, “welding” has been known and used for several thousand years. Historians have speculated that the early Egyptians may have first used pressure welding about 5500 BC in making copper pipes from sheets by overlapping the edges and hammering. This type of welding, called forge welding was man’s first process to join pieces of metal together[1]. A well-known early example of forge welding is the Damascus sword which was made by forging layers of iron with different properties. Interestingly, forge welding was sufficiently well developed and important enough to the early Romans that they named one of their gods Vulcan (the god of fire and metal working) to represent the art[1]. Today, forge welding is practically a forgotten art in which the village blacksmith is the last major practitioner.

The practice of connecting steel plates by welding started when it was recognized that inconveniences associated with the use of rivets as well as weakening by bolt holes could be avoided if the parts were monolithically joined after local melting. Technology has led to the development of many other welding procedures. Automation has added to them; welding arcs and cutting flames, electronically guided arc, gas combined with electricity in hydrogen, helium and argon arcs. This has become necessary due to the nature of the pieces to be joined and to the use for which they are intended.

Welding offers many advantages, which may be briefly outlined as follows:

i. Simplicity of design details, efficiency, and minimum weight are achieved because welding provides the most direct transfer of stress from one member to another.
ii. Fabrication costs are reduced because fewer parts are handled and operations such as punching, reaming, and drilling are eliminated.
iii. There is a saving in weight in main tension members since there is no reduction in area due to rivet and bolt holes. Additional saving is also achieved because of the fewer connecting parts required.
iv. Welding provides the only plates-joining procedure that is inherently air-and water-tight and hence is ideal for water and oil storage tanks, ships, and so forth.
v. Simple fabrication becomes practicable for those joints in which a member is joined to a curved or sloping surface, such as structural pipe connections.
vi. Welding simplifies the strengthening and repair of existing riveted or welded structures[2].

Welding processes are employed extensively in the manufacture of automobile bodies, machine frames, sandcrete block machines, structural work, aircraft, tanks and general machine repair. In oil industries, welding is extensively used in refineries and in pipe-line fabrication. The largest single use of welding during war has been in shipbuilding; in peacetime it is the fabrication of metal structures. Competition of welding has also been felt in the casting industry because many machine parts which were formally cast are now made of steel members welded together. Such construction has the advantages of being lighter and stronger than cast iron[3].

1.2 Classification of Welding Processes

Welding is a process of joining pieces of metal together by the application of heat with or without pressure. There are numerous welding processes involving various techniques and procedures. They are markedly different in their process details and in the equipment required to achieve the joint. They can be classified into two basic categories based on the response of the metal in the welded joint.

i. ***Pressure welding process***: A non-fusion process which consists of simply heating the pieces above a certain temperature and hammering them together on an anvil.

ii. ***Fusion Welding Process:*** The most common type of welding in structural steel work which is a method of connecting pieces by molten metal. A special wire or rod is subjected to intense heat at its tip, which melts and deposits molten metal at the point where a connection is desired. The base metal also melts locally and unites with the deposited metal to form a welded connection.

In structural steel work, metal-arc welding is used almost exclusively. For special structures such as sheet-steel structures and materials that are unable to withstand higher temperatures, gas welding may be used[4]. Examples of each category of welding are given in Table 1.1

Table 1.1 Welding Processes.

Pressure Welding	***Fusion Welding***
Forge welding Pressure Thermit welding Resistance welding (ac) Resistance welding (dc)—seam and spot welding	Metal-arc welding (ac and dc) – shielded, unshielded, submerged. Carbon-arc welding – shielded and unshielded Inert- gas arc welding Atomic hydrogen arc welding Gas welding (air or oxyacetylene) Thermit welding

In order to use welding in structural design to its fullest advantage, a thorough familiarity with the various processes is desirable. However, for purposes of this research, only the essential features of the methods most commonly used in Ghana (gas and shielded –metal-arc welding) are described.

1.2.1 Gas Welding

This is a fusion–welding process which utilizes oxy-acetylene flame produced by the combustion of acetylene with oxygen. Oxy – fuel gas welding can be done with propane or butane, but acetylene has advantages over those gases because it provides a higher flame temperature, about 3100 ^{o}C and uses less oxygen, only one third that required for propane[5]. The two gases, oxygen and acetylene are fed to the torch separately, mixed together inside and emerge at its tip where the combustion takes place. Extreme heat is concentrated on the edges or on the edge and the surface of the pieces of the metal being joined. The filler metal in the form of a wire or a rod together with part of the parent materials are melted and allowed to fuse, thus uniting the two metal components. The flame formed also produces reducing gases (CO and H_2) which protect the pool.

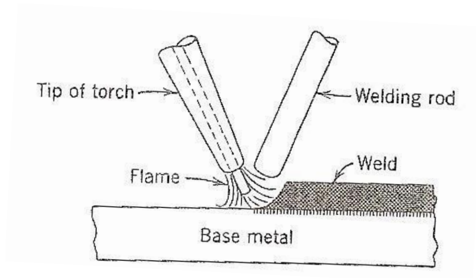


Fig 1.1 Gas welding[5]

By adjusting the supply of oxygen or acetylene from the gas cylinders, the type of flame can be regulated according to the requirements of the metal. Some metals, for example brass, weld better if the amount of oxygen is in excess of that required to burn acetylene while cast iron welds better in a reducing flame in which surplus acetylene is present[5].

1.2.2 Shielded Metal Arc Welding (SMAW)

Shielded metal arc welding is a fusion-welding process which uses heat generated by an electric arc. An electric arc is an electric discharge in gases, accompanied by high heat and a bright glow. The arc column is characterized by a nearly constant temperature of the order of 6000 ^{o}C throughout the length and diameter of the arc column. It is a particularly suitable source of energy for welding since its heat is effectively concentrated[6].

During the welding process, the arc heat melts the base metal and the consumable flux-coated electrode simultaneously, and the electromagnetic field carries the molten metal (electrode) toward the base metal, while the operator moves the welding rod manually along the length of the weld with proper speed to deposit the necessary amount of weld metal. The electrode wire becomes filler material and the coating is converted partly into a shielding gas, partly into slag, and some part is absorbed by the weld metal. The molten slag, having lower density than the molten metal, rises to the top, retards the rate of cooling of weld metal, and also protects it from undesirable exposure to atmospheric gases. The shielding of the arc prevents atmospheric contamination of the molten metal in the arc stream and in the arc pool. It prevents nitrogen and oxygen from being picked up and forming nitrides and oxides which may cause embrittlement[4].

Shielded metal arc welding is commonly done in four positions; flat, horizontal, vertical and overhead. Vertical and overhead welds are possible because molten metal is carried from the rod to the connection by the electromagnetic field of the arc and not by gravity.

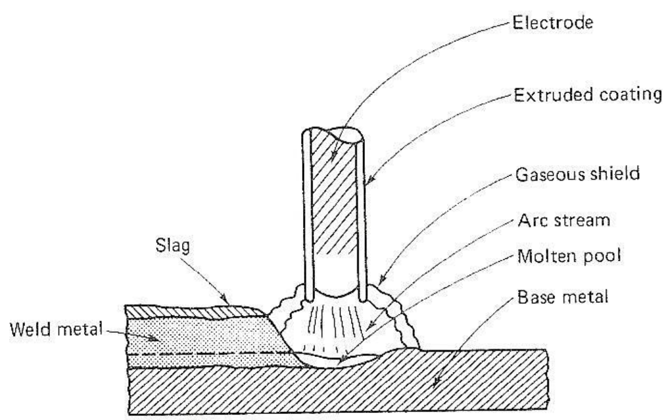


Fig 1.2 Shielded metal arc welding process[2]

1.3 Types of joints and welds

The type of joint depends on factors such as the size and shape of the members coming into the joint, the type of loading, amount of joint area available for welding, and the relative costs for various types of welds. There are five basic types of welded joints, although many variations and combinations are found in practice. These are the butt, lap, tee, corner, and edge joints as shown in figure 1.3

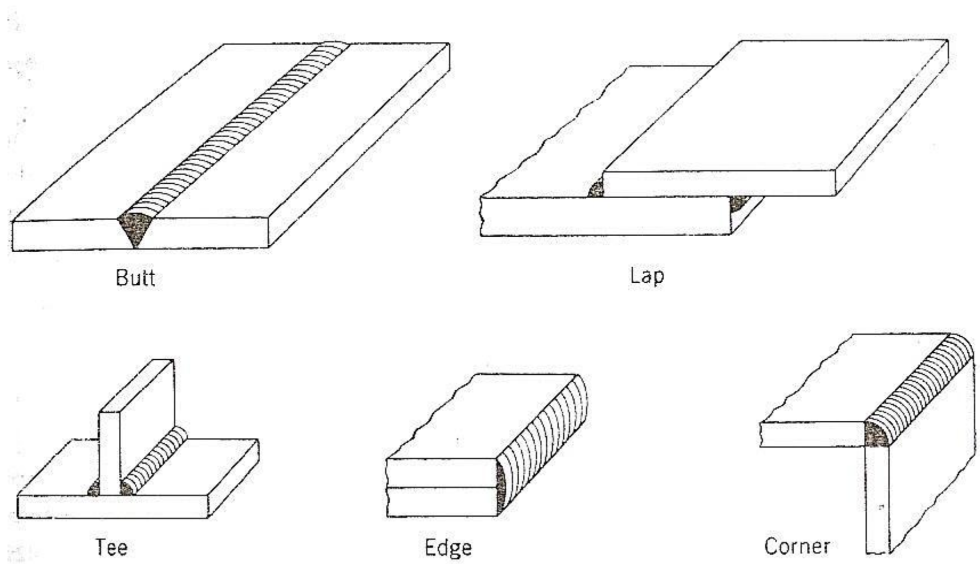


Fig 1.3 Types of joints [4]

Four basic types of welds are the groove, fillet, plug and slot. The most common types are groove and fillet welds.

1.3.1 Groove Welds

The principal use of groove welds is to connect structural members that are aligned in the same plane. Since groove welds are usually intended to transmit the full load of the members they join, the weld should have the same strength as the pieces joined.

There are many variations of groove welds and each is classified according to its particular shape. The selection of a proper type of groove weld for a butt joint is determined by the requirement of minimum cost of edge preparation and welding of the connection, provided that other requirements such as strength, minimum distortion, and minimum residual stress are satisfied. Fig 1.4 shows several types of groove welds and indicates typical edge preparations required for each.

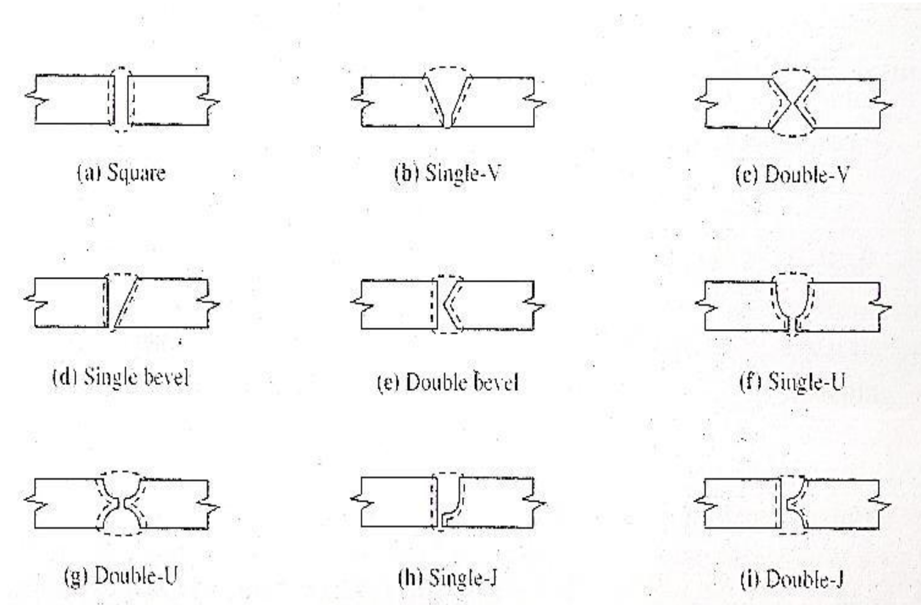


Fig 1.4 Edge preparations for groove-welded butt joints[7]

1.3.2 Fillet Welds

Fillet welds, owing to their overall economy, ease of fabrication, and adaptability, are the most widely used. They generally require less precision in the "fitting up" because of the overlapping pieces, unlike the groove welds that require careful alignment with specified gap (root opening) between pieces. The fillet weld is particularly advantageous to welding in the field or in realigning members, or connections that were fabricated within accepted tolerances but which may not fit as accurately as desired. In addition, the edges of pieces seldom need special preparation such as beveling or squaring[7].

1.4 Determinants of Weld Quality

Design of a welded connection consists of selecting the type of weld most favorable for the loads to be transmitted by the particular size and arrangement of members, and it involves the determination of arrangement and size of welds. A good design on paper cannot assure a good welded connection without good workmanship in the shop and field. Some of the factors that determine quality workmanship and therefore the quality of the weld include the following:

i. The properties of the base materials.

ii. Right size and chemical composition of electrode.

iii. Proper speed, voltage and current for particular weld.

iv. Proper edge preparation of the connection before welding.

v. The sequence and number of passes in welding.

vi. Judicious uses of jigs[4].

1.4.1 Material properties

The wide adoption of welding in recent years has required improved control of steel chemistry in order to provide steels that are "weldable", that is steels that can be joined together with sound metal, of adequate strength and ductility, and with minimal metallurgical damage to adjacent parent metal.

The relative economy and degree of ease of welding on particular steel is generally termed 'weldability'. In ordinary structural steel, the carbon content is the most important factor determining weldability. Steels with carbon content below 0.1% have a high gas absorption which is a common cause of porous welds. Steels with carbon content 0.3% and more become brittle when cooled rapidly and for a given rate of cooling, brittleness increases with increase in carbon content. Because rapid cooling is prevalent in welding of thick parts, carbon content is particularly important for shapes and plates where thickness in excess of 25.4 mm or 1 38.1 mm can occur[8].

To secure good quality of welding connections, the design engineer must have some knowledge of the basic principles of welding metallurgy, the thermal effects of welding on base metal and the properties of materials and techniques used in the process.

1.4.1.1 Metallurgy.

Three metallurgical factors are of interest in metal-arc welding: crystalline structure, gas solubility, and oxidation. When steel is heated to a critical temperature of approximately 815.6 ^{0}C, it has an almost uniform crystalline structure (austenite). When it is cooled slowly from this temperature, the grain structure changes to a ductile material called pearlite. When cooled very rapidly, austenite changes to a brittle material with little pearlite and mostly martensite. The critical temperatures and the rates of cooling which determine whether the steel will be ductile or brittle after welding vary with the chemical composition of steel, particularly with its carbon content. Therefore, the chemical composition of base metal and filler metal must be carefully considered in design of welded connections. The most critical factor, however, is the rate of cooling: slow cooling usually results in ductile steel; rapid cooling results in hard brittle steel[8].

1.4.1.2 Thermal Effects.

Two effects of welding temperatures are of primary interest: one is expansion and contraction of metals with change in temperature and the other is the rate of cooling. Expansion and contraction are largely responsible for the development of the residual stresses and distortions in welded connections; the rate of cooling is primarily important in its effect on the crystalline structure of the welded part.

1.4.2 Electrodes

There are many specialized welding electrodes used for specific alloys and types of metals such as cast malleable iron, stainless or chromolly steel, aluminum and tempered or high carbon steels. A typical electrode consists of a wire rod in the center covered with a special coating (flux) which burns as the arc is maintained, consuming oxygen and producing carbon dioxide in the weld area to prevent the base from oxidizing or burning away in the arc flame during the welding process. The materials of components and electrode must be compatible from the point of view of strength, ductility and metallurgy - this last being most important in view of thermal effects arising from the usual uncontrolled localized cooling. When "matching" electrode material is used, the weld material is somewhat stronger than the base material; thus the strength of the welded joint is controlled by the base material properties.

Below are codes for identifying electrodes which are used for given steels.

i. E6010 electrodes are a reverse polarity electrode. The first two numbers in the electrode identification is the tensile strength, measured in pounds per square inch times 1,000. Thus, the yield of the electrode would be 60,000 PSI. They are commonly used for welding steam and water pipes, and are particularly useful for overhead welding, since the metal holds its position while in a liquid state, being drawn into the molten weld pool by the flow of the direct current from the electrode to the workpiece.

ii. E6011 electrodes are a mild steel electrode with a cellulose fiber coating. The yield of this electrode would also be 60,000 PSI.

iii. E7018 electrodes are *low hydrogen*flux coated steel rods, with a high yield tensile strength of 70,000 PSI. These are often used in assembling structural steel used in the construction industry, and in other applications where a strong filler material and higher strength weld is required. Note that, although these rods provide greater strength, they are less forgiving in respect to achieving a clean, high-grade weld at incorrect amperages and with *dirty* (rusted, painted, or galvanized) steels. These electrodes are called low hydrogen due to every attempt to lower the hydrogen content[9].

1.5 Research Objectives

The objective of this research is to

- Carry out chemical analysis of locally-produced and imported low-carbon steels.
- Determine the tensile, yield and impact strengths and ductility of the “as-received” local and imported steels.
- Determine the tensile, yield and impact strengths and ductility of welded joints.
- Study the effect of pre- and post-weld heat-treatment on the mechanical properties of the joints.
- Use the micrographs of the joints to confirm their mechanical properties.

1.6 Justification of Study

Welding is the most economical and efficient way to join metals permanently. It is applied on a very wide scale, especially for building up structures and offers many structural design options that cannot be simply realized with other production techniques. Welded joints have different levels of strength and ductility. These mechanical properties depend partly on the grades of steel used. In Ghana, artisans use both the locally-produced and imported low carbon steels for welding. The project aims at investigating the quality of welded joints produced with these two types of steels.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Welding is a metal joining process which involves coalescence of two or more clean metal surfaces by the application of heat with or without pressure. Shielded Metal Arc Welding is one of the major welding techniques in industry. It is extensively employed in the finishing stage of steel casting production and in fabricating larger components by joining castings or by joining castings to wrought steel components.

During the welding process, discontinuities such as cracks, undercuts, slag inclusions, blowholes, inadequate joint penetration among others normally occur at the joints. Most of these defects result in stress concentrations under load and thus reduce the strength of the weld, particularly under dynamic or repeated loads. To eliminate these defects or to minimize those to acceptable levels, it is necessary to know their causes.

Cracks are breaks in the weld metal, either longitudinal or transverse to the line of weld, that result from internal stress. Cracks may also extend from the weld metal into the base metal or may be entirely in the base metal in the vicinity of the weld. Cracks are perhaps the most harmful of weld defects. Some cracks form as the weld begins to solidify, generally caused by brittle constituents, either brittle states of iron or alloying elements, forming along the grain boundaries. More uniform heating and slower cooling will prevent the "hot" cracks from forming. Tsay et al. conducted fatigue crack growth rate tests for 304 stainless steel base metal and weld metal (in the as-welded condition and after stress-relief) in both air and hydrogen gas with a partial pressure of 0.2 MPa and at a loading frequency of 20 Hz. It was found that the fatigue crack growth rates were clearly enhanced by gaseous hydrogen in all three materials. They concluded that the crack growth resistance in hydrogen gas was found to be highest in the as-welded specimen due to tortuous crack growth path[10].

Undercut denotes depressions along the edges of a weld, and parallel to its length. They form as intermittent or continuous grooves which vary in depth and width. Undercut occurs when surface tension forces draw the metal away from the sides of the weld groove. It results from the use of excessive current or an excessively long arc which burns or digs away a portion of the base metal. This defect is easily detected visually and can be corrected by depositing additional weld material after the surface is properly cleaned.

Slag discontinuities occur mainly in welds made with the shielded metal-arc and submerged-arc processes that utilize a welding flux. It is formed during the welding process as a result of chemical reactions among the metal, the air, and the electrode coating during deposition and solidification of weld metal and consists of metal oxides and other compounds. These oxide films occur with improper shielding during welding. Having a lower density than the molten weld metal, the slag normally floats to the surface where, upon cooling, it is easily removed by the welder. However, too rapid a cooling of the joint may trap the slag before it can rise to the surface. When several passes are necessary to obtain the desired weld size, the welder must remove slag between each pass. Slag inclusions present a problem if they are large enough, even though they are usually globular in shape. If they are large relative to the weld section, they can act as significant stress raisers, thereby causing the degradation in fatigue strength and mechanical properties

Porosity consists of numerous gas pockets in the weld resulting from the evolution and entrapment of gas from molten metal during solidification. Carbonates and other materials commonly employed in electrode coverings can dissociate when heated to high temperatures which results in the formation of gas. Gas may be trapped in the weld as a result of gas formed by chemical reactions such as the reaction of the hydrogen with sulphide inclusions present in the base metal. Moisture on the workpiece or present in the electrode coating, may serve as a source of hydrogen. Porosity may also result from using excessively high current or too long an arc length. It may occur uniformly dispersed through the weld, or it may be a large pocket concentrated at the root of a fillet weld or at the root adjacent to a backup plate in a groove weld. In simple terms, porosity is an indicator that welding parameter, consumables, or joint fitup were not properly controlled for the welding process selected or that the base metal is contaminated or of a composition incompatible with the weld filler metal being used. Tsay et al. explored the influence of porosity on the fatigue crack growth behavior of Ti-6Al-4V alloy laser welds and concluded that the effect of porosity against fatigue crack growth resistance was less at lower stress ratio compared to higher stress ratio.[11]

Incomplete penetration is defined as the failure of the base metal and weld metal to fuse at the root. The vertex of a V-shaped or X-shaped or any other setting is always that part at which the edges to be welded are closest and it is not so easy to obtain a regular and complete melting of the shaped edge by the first weld pass. This defect, relating primarily to groove welds, may be due to faulty design of the groove such as excessive root – face dimension, insufficient root gab or groove angle, or it may be due to faulty technique such as use of an excessively large size electrode, excessive speed, or insufficient welding current. Incomplete penetration is particularly undesirable since it causes stress concentration under load and may be the cause of cracks due to shrinkage. The defect can be eliminated if it is possible to back gouge and apply a sealing pass.

Incomplete fusion refers to a condition in which the interface between adjacent welds or between the weld and base metal has not achieved coalescence yet has resulted in a metallurgical bond. This may be caused by an insufficient application of heat to raise the temperature of the base metal to the melting point, by the presence of heavy oxides or other foreign material on the base metal. Too rapid a rate of welding will also have the same effect. If surfaces are properly cleaned and the electrode size, speed, and current are properly selected, complete fusion will be assured.

2.2 Mechanical Testing

Samples of engineering materials are subjected to a wide variety of mechanical tests to measure their strength or other properties of interest. Such samples, called specimens, are often broken or grossly deformed in testing. Among the various mechanical tests conducted are tensile and notch-impact tests.

2.2.1 Tensile Tests

The tensile test is used to access some key mechanical properties such as yield stress, ultimate tensile stress, modulus of elasticity and ductility of structural materials. It consists of slowly pulling a sample of material uni-axially along its axis with a tensile load until fracture.

Two specimen geometries, cylindrical and flat, are recommended by the American Society for Testing and Materials (ASTM) for tensile testing of metals. The choice of specimen geometry and size often depends on the product form in which the materials is to be used or the amount of material available for samples. Flat specimen geometry is preferred when the end product is a thin plate or sheet. Round cross-section specimens are preferred for products such as extruded bars, forgings and castings.[12]

In a tensile test, an increasing tensile stress is applied to a specimen and the resulting changes in length are monitored. This continues until the specimen fractures. A stress-strain curve is obtained for each sample from their original cross-sectional areas and gauge lengths – a relationship which depends on the chemical composition, heat treatment and the method of manufacture.

Fig.2.1 is a stress-strain curve of a low carbon steel sample. Stress-strain curves from tension tests exhibit a variety of different behaviours. At the beginning of the test the material extends elastically, the strain being directly proportional to the stress and the specimen returns to its original length on removal of the stress. Here, Hooke's law is obeyed. The Young modulus of elasticity for the steel is determined within this regime. Beyond the elastic limit the applied stress produces plastic deformation so that a permanent extension remains after removal of the applied load. The ratio applied load to original cross-sectional area is termed the engineering stress and this continues to increase with elongation due to work-hardening until the ultimate tensile stress (maximum load/original cross-sectional area) is reached. At this point a neck begins to develop within the gauge length of the specimen and further plastic deformation is localized within the neck. After necking has begun the nominal stress decreases until the material fractures at the point of minimum cross-sectional area within the neck. The stress at fracture is the breaking stress.

It is worth noting that a curve of engineering stress versus engineering strain will have the same shape as the original load-extension curve obtained directly from the tensile testing machine.

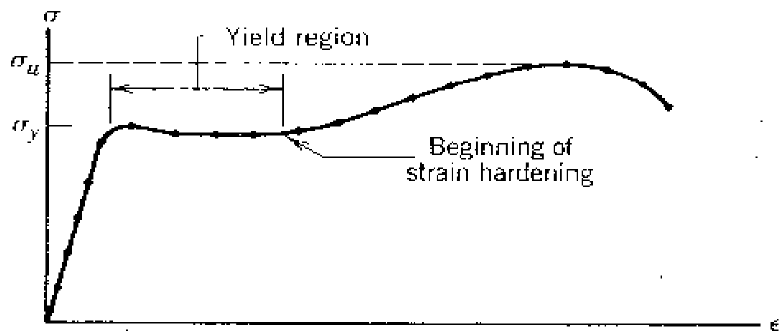


Fig 2.1 Stress-strain curve of low-carbon steel[13]

2.2.2 Impact Testing

Various standard impact tests are widely employed in which notched beams are broken by a swinging pendulum or a falling weight. The most common test of this type is the Charpy V-notch tests.

Charpy V-notch testing is used to measure the impact energy which is sometimes termed the notch toughness. It provides information on the resistance of a material to a sudden fracture where a sharp stress raiser or flaw is present in the material. In notch-impact tests, the energies obtained depend on the details of the specimen size and geometry, including the notch-tip radius. Specimens and loading configurations for these are shown in fig 2.2. The flaw is a standard V-notch cut into the test specimen of rectangular shape. A swinging pendulum arrangement is used for applying the impact load. The weight is released from a known height to strike the specimen on the side opposite the notch. After breaking the sample, the pendulum swings on and the energy expended in breaking it is determined from an indicator that measures how high the pendulum swings.

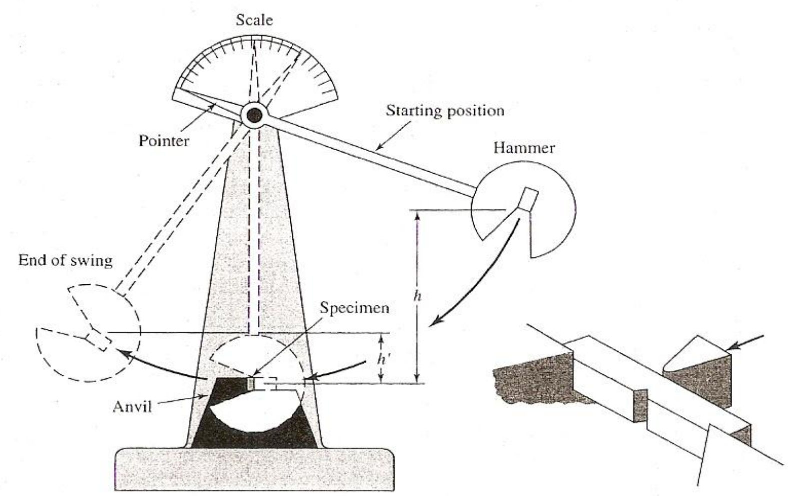


Fig.2.2. An illustration of a Charpy impact test setup[14]

CHAPTER THREE

METHODOLOGY

This chapter outlines the procedures for the chemical analysis of the steel rods, preparation of samples from the rods and their characterization in terms of tensile tests, impact tests and microstructural behaviour.

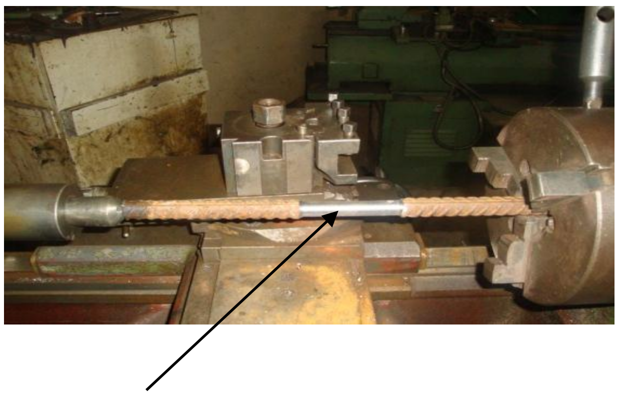
3.1 Chemical Analysis of Steel Samples

Chemical compositional analyses of the iron rods were performed using optical emission spectroscopy at Tema Steel Limited. Sample material was vaporized on the spark stand by an arc or spark discharge. The atoms and ions contained in the atomic vapour were excited into emission of radiation. The radiation emitted was passed to the spectrometer via an optical fibre, where it was dispersed into its spectral components. From the wavelengths emitted by each element, the most suitable line for the application was measured by means of a photomultiplier. The radiation intensity, which was proportional to the concentration of the element in the sample, was recalculated internally from a stored set of calibration curves and could be shown directly as percent concentration.

3.2 Mechanical Test Samples Preparation

3.2.1 Tensile Test Samples

The tensile test samples prepared from both local and imported low carbon steels were of two main types: un-welded and welded samples. The un-welded samples were further grouped into: “as-received” and heat-treated samples whereas the welded samples also had the divisions “as-welded” and welded heat-treated samples. All types were machined longitudinally using the Centre Lathe Machine into a ‘dog-bone’ shape of circular cross-section with a diameter range of 12.10 – 12.95 mm and gauge length 48 mm.



Mid-portion of sample being machined

Fig. 3.1 Picture of the Lathe machine holding sample

Fig.3.2 Picture of machined sample for tensile test

The gauge length and diameter of the machined samples conformed to the ASTM standards, that is, the gauge length should be four times the cross-sectional diameter of the specimen.

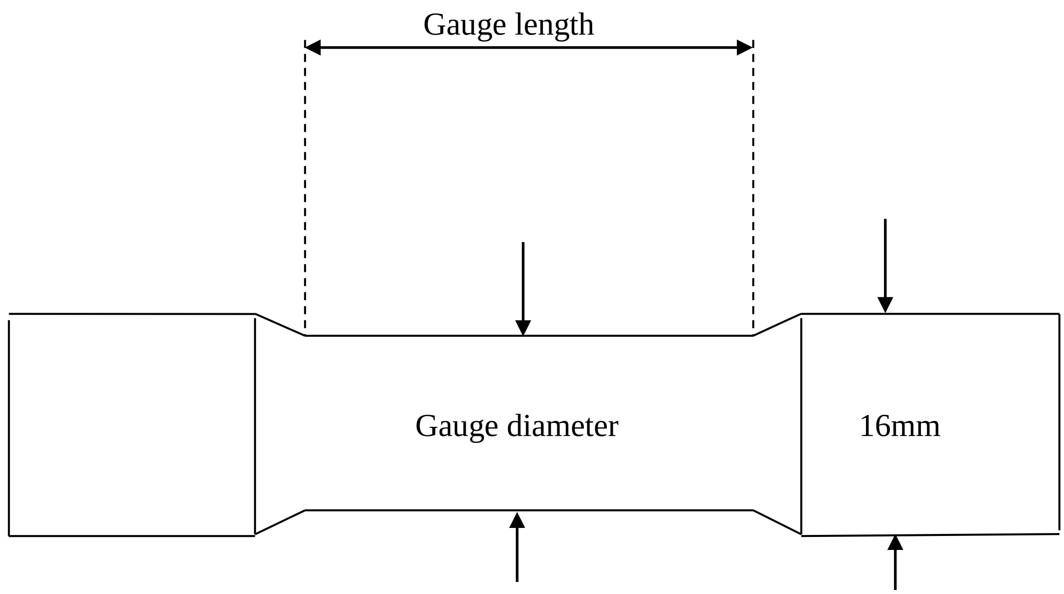


Fig. 3.3 Schematic diagram of a prepared tensile test sample

3.2.1.1 Un-welded Samples

Locally-made and imported low carbon steel rods of diameter 16mm were cut slowly using the hacksaw into lengths of 30cm; this length resulting from the constraint in the space in the furnace for heat-treatments. A hole was made at one end of each sample using the centre drill in order to enhance firm positioning in the Lathe machine. The mid-portions of the samples were machined into a “dog-bone shape” having dimensions as given by the ASTM standards.

3.2.1.2 Welded Samples

Locally-made and imported low carbon steel rods of diameter 16 mm were cut slowly using the hacksaw into lengths of 15 cm. One end of each piece was chamfered so that when two such ends were brought together they formed a double V – shape. This would ensure complete penetration of the filler metal into the joint.

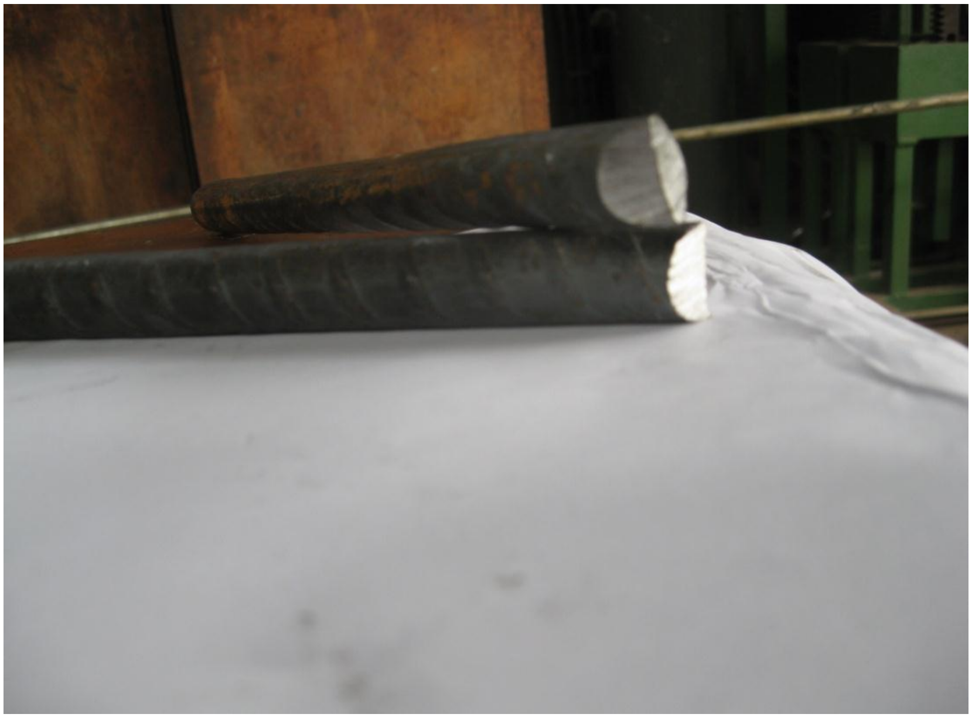


Fig.3.4 Picture of steel rods with chamfered ends

Employing the Shielded Metal Arc Welding (SMAW) technique, the two pieces were fused by complete-penetration groove welding using E-7018 high strength steel welding electrodes and cooled slowly in sand bag. Sand-cooling was chosen as a means to lower the rather fast cooling rates after welding which could lead to cracking of the joint. Slags were chipped off following each pass of the weld metal to ensure sound weldment.

Fig.3.5. Picture of welded sample just before sand-cooling

3.2.1.3 Heat-treated Samples

Two sets of samples for the tensile tests (un-welded and welded), after being machined on the Lathe Machine, were placed in a furnace, one batch at a time. After the samples have been heated slowly from room temperature to a predetermined temperature, they were soaked for one hour and then air-cooled. The predetermined temperatures were 450 ^{0}C, 550 ^{0}C and 650 ^{0}C.

3.2.2 Charpy Impact Tests samples

The impact tests samples comprised un-welded and welded samples prepared from local low carbon steels and imported low carbon steels. The two batches were produced by shaping the ribbed steel rods ("as-received" and welded) into a square prism using the shaping machine. The dimensions of the square prism as given by the ASTM Standards are 10 mm x 10 mm x 55 mm. A standard V-notch 2 mm deep, radius 0.25 mm and angle opening 45^{0} was cut into the specimens at the mid-section of their lengths. The welded samples were notched in the weld metal centre perpendicular to the welding direction.

The heat-treatment of the impact tests samples was done the same way as the samples for tensile tests.

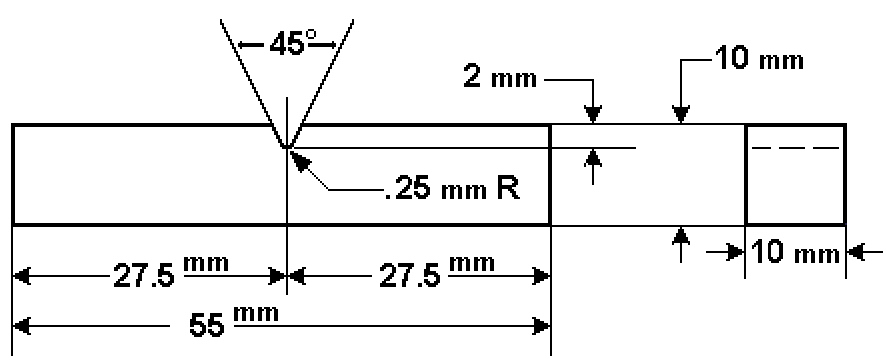


Fig.3.6 Diagram showing the dimensions of impact test sample

Table 3.1 Coding of Samples

Code	Interpretation
$LC_{(1)}$	“As-received” Local steel sample 1, with no heat treatment
$LC^{450}_{(1)}$	“As-received” Local steel sample 1, heat-treated at 450 ^{0}C
$LC^{550}_{(1)}$	“As-received” Local steel sample 1, heat-treated at 550 ^{0}C
$LC^{650}_{(1)}$	“As-received” Local steel sample 1, heat-treated at 650 ^{0}C
$IC_{(1)}$	“As-received” Imported steel sample 1, with no heat treatment
$IC^{450}_{(1)}$	“As-received” Imported steel sample 1, heat-treated at 450 ^{0}C
$IC^{550}_{(1)}$	“As-received” Imported steel sample 1, heat-treated at 550 ^{0}C
$IC^{650}_{(1)}$	“As-received” Imported steel sample 1, heat-treated at 650 ^{0}C
$LW_{(1)}$	Local steel welded sample 1, with no heat treatment
$LW^{450}_{(1)}$	Local steel welded sample 1, heat- treated at 450 ^{0}C
$LW^{550}_{(1)}$	Local steel welded sample 1, heat- treated at 550 ^{0}C
$LW^{650}_{(1)}$	Local steel welded sample 1, heat- treated at 650 ^{0}C
$IW_{(1)}$	Imported steel welded sample 1, with no heat treatment
$IW^{450}_{(1)}$	Imported steel welded sample 1, heat- treated at 450 ^{0}C
$IW^{550}_{(1)}$	Imported steel welded sample 1, heat- treated at 550 ^{0}C
$IW^{650}_{(1)}$	Imported steel welded sample 1, heat- treated at 650 ^{0}C
$LW^{450\,*}_{(1)}$	Local steel heat-treated at 450^{0}C before and after welding 1
$LW^{550\,*}_{(1)}$	Local steel heat-treated at 550^{0}C before and after welding 1
$LW^{650\,*}_{(1)}$	Local steel heat-treated at 650^{0}C before and after welding 1
$IW^{450\,*}_{(1)}$	Imported steel heat-treated at 450^{0}C before and after welding1
$IW^{550\,*}_{(1)}$	Imported steel heat-treated at 550^{0}C before and after welding1

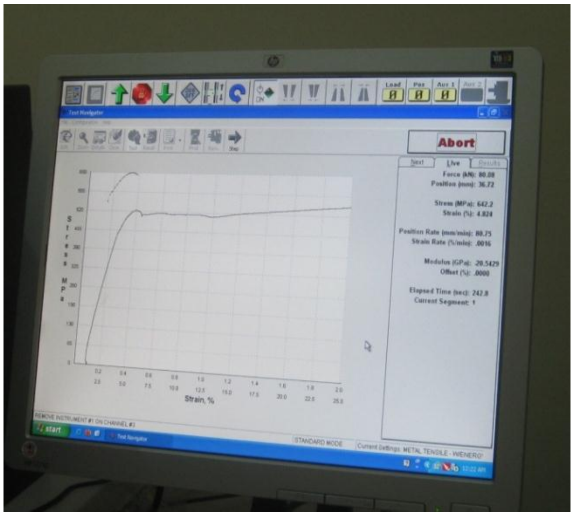
3.3. Mechanical Testing

3.3.1. Tensile Tests

The test specimen was placed in a computer-interfaced universal tensile testing machine (Tinius Olsen) fitted with an electronic extensometer. One end of the specimen was gripped in a fixture attached to the stationary cross-head while the other end was gripped in a fixture attached to the movable cross-head (actuator) of the testing machine. The actuator moved at a fixed rate of displacement which applied increasing load, measured by a transducer called load cell, to the specimen. The increasing stress applied and the resulting changes in length measured by the extensometer were monitored electronically. The test continued until the specimen fractured. Thereafter, a stress-strain curve for the sample was drawn by the computer.

(a)

(b)



(c)

Fig.3.7 Pictures showing (a) universal tensile testing machine with interfaced computer, (b) extensometer on gripped sample, and (c) monitor.

3.3.2. Impact Tests

The specimen in the form of a square prism was clamped in the impact machine and the hammer released from a preset height as to strike the specimen on the side opposite the notch. After breaking it, the pendulum swung on and the energy absorbed in breaking the bar was read off from a scale fitted on the machine.

Sample held in the impact testing machine.

(a) (b)

Fig. 3.8 Pictures showing (a) a Charpy impact testing machine (Tinius Olsen) and (b) sample loading

3.4. Microstructural Examination

3.4.1. Specimen Preparation

Both welded and un-welded samples were prepared for metallographic observations. Samples taken from the welded joints contained portions of the base metal on either side of the weld. Proper preparation of metallographic specimens to determine microstructure required that a rigid step-by-step process be followed. In sequence, the steps included sectioning, mounting, course grinding, fine grinding, polishing and etching.

The sectioning of the samples was done slowly using the hack-saw to minimize the heat associated with the cutting which could alter the microstructure. Subsequent to cold-mounting using epoxy resin, wet grinding of the samples was done using the 240 grit, 400 grit, 600 grit and 1000 grit SiC waterproof abrasive paper in succession on electrically powered disks. The size of the abrasive particles determines the grit size. The higher the number, the finer the abrasive. The samples were washed thoroughly before proceeding from one grinding stage to the next. This prevented the transfer of abrasive particles between stages.

Following the final 1000 grit fine-grinding stage, the sample were washed thoroughly and carefully dried before proceeding to the first polishing stage on a nylon-cloth- covered electrically powered disk. Beginning polishing with 25-micron aluminum oxide particles suspended in water, the final fine-grinding surface layer was completely removed. This was followed by the 5-micron stage and then the final polishing stage with 1-micron aluminum oxide suspension which resulted in a mirror-like surface free of scratches. A new nylon-cloth was used for each polishing stage. The specimens were etched with 4% nital (4% nitric acid + 96% alcohol) for 20 s. This was done by agitating the samples in the etchant for the 20 s, immediately washing under running water, rinsed with alcohol and dried in an air blast.

3.4.2. Microscopic Examination

Each specimen was placed on the stage of the Leica DM 2500 M optical microscope capable of producing magnifications (25X to 1000X) so that the specimen’s surface was perpendicular to the optical axis. For the welded specimens, the micrographs of the base, heat affected zone and the weld were taken.

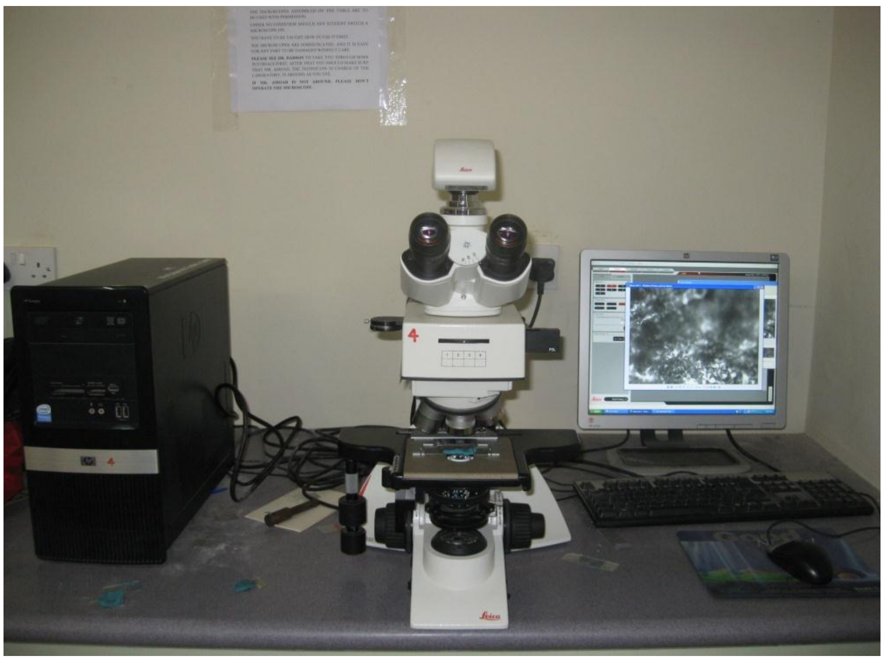


Fig 3.9 Picture of optical microscope with interfaced computer.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Chemical Analysis of Local and Imported Low Carbon Steels

Table 4.1 Elemental Compositions in Locally-produced Low Carbon Steel in wt. %

Fe	C	Mn	P	S	Si	Cu	Ni	Cr
98.814	0.059	0.295	0.071	0.037	0.197	0.191	0.120	0.073
V	Mo	Ti	Al	Nb	Co	Sn	B	Pb
0.000	0.094	0.002	0.009	0.000	0.008	0.026	0.003	0.000

Table 4.2 Elemental Compositions in Imported Low Carbon Steel in wt. %

Fe	C	Mn	P	S	Si	Cu	Ni	Cr
98.999	0.186	0.543	0.027	0.022	0.020	0.015	0.039	0.051
V	Mo	Ti	Al	Nb	Co	Sn	B	Pb
0.000	0.082	0.002	0.009	0.000	0.000	0.004	0.002	0.000

The data in tables 4.1 and 4.2 are the results of the chemical analyses carried out at Tema Steel Limited. The main alloying element that determines the strength and hardness of steels is carbon. As carbon dissolves in the interstices, it distorts the original crystal lattice of iron.

This mechanical distortion interferes with an external applied stress to the crystal lattice by mechanically blocking the dislocation of the crystal lattice. This provides mechanical strength. Adding more carbon to iron (up to solubility of iron) results in more and more distortions of the crystal lattice, hence providing increased mechanical strength. However, solubility of more carbon negatively affects another important property, that is, the ductility. This is because the content of the ductile phase (ferrite) which flows plastically decreases while that of the hard phase (pearlite) increases with increasing carbon content. Manganese also contributes greatly towards increasing strength and hardness, but to a lesser extent than carbon. These two elements are in greater proportions in the imported steels (Table 4.2) than in the locally-produced ones (Table 4.1). Hence the relatively higher UTS, Yield Strengths and Moduli of Elasticity and lower ductility (percent elongations) for imported steels than for the local steels as seen in Fig 4.2.

4.2 Tensile Testing

Figures 4.1(a) and 4.1(b) show the stress-strain curves of a welded low-carbon steel (local) sample. Some key mechanical properties such as yield strength, ultimate tensile strength and ductility (measured in terms of percent elongation) were determined from the curves. The data have been presented in bar charts in section 4.1.2

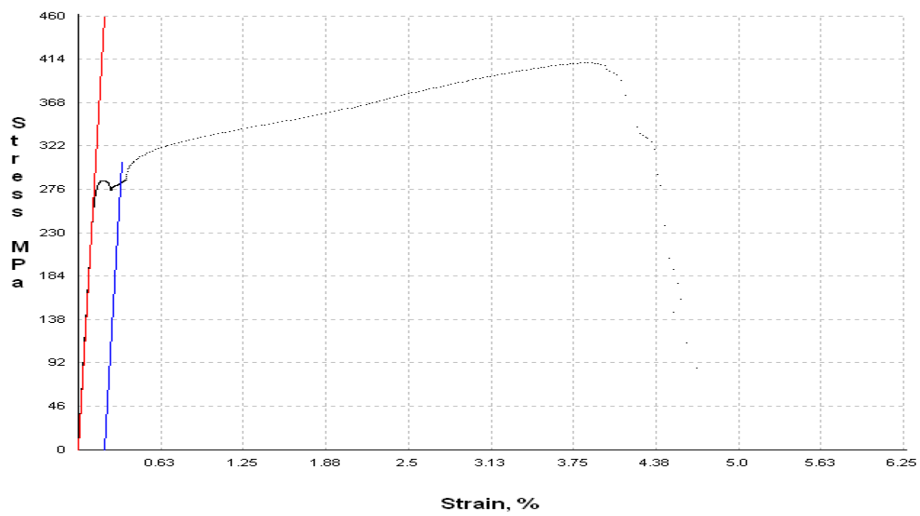


Fig 4.1(a). Stress-strain curve of welded low carbon steel (local) sample, showing the stresses in the full range of the strain. The slope of the red line is the Young Modulus while the intersection of the blue line with the curve defines the 0.2% proof stress

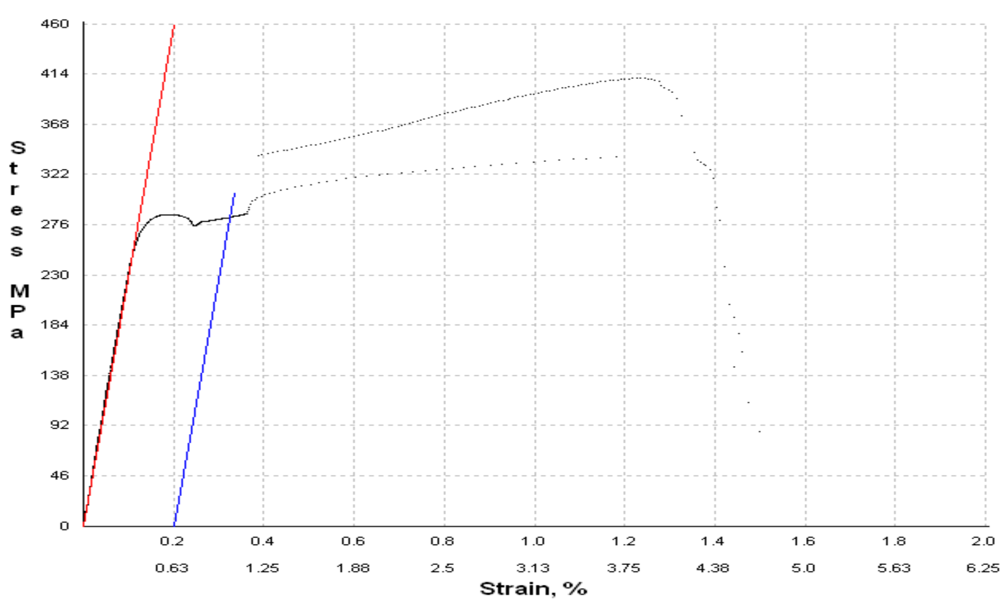


Fig 4.1(b) Stress-strain curve of welded low-carbon steel (local) sample, showing a magnified linear section (in red) and the 0.2% proof stress (in blue).

4.2.1. Un-welded samples

Fig 4.2 is a composite stress-strain plot of "as-received" local and imported steel samples. From the plots, the imported steel samples showed higher UTS and yield stress and lower percent elongation as compared to the locally-made samples. This was due to the higher proportion of pearlites than ferrites in the imported steels as compared to the high proportion of ferrites in the locally-made steels as shown in their optical micrographs (Fig 4.6). The higher proportion of pearlites in the imported steel samples was confirmed by the relatively high carbon content as chemical analysis revealed (Table 4.2).

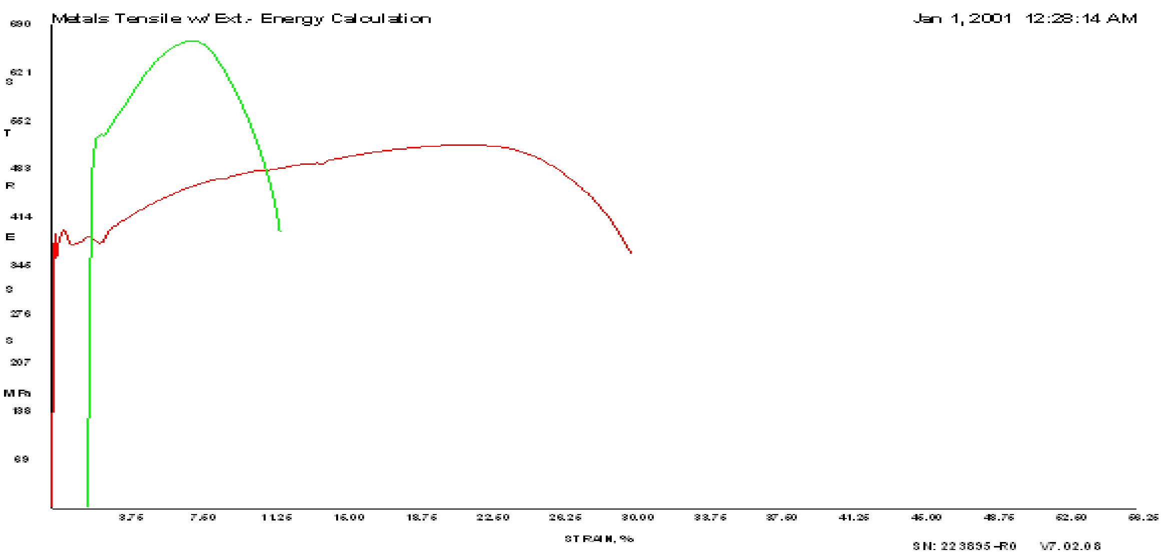


Fig 4.2. Composite stress-strain plot of "as-received" local and imported steel samples.

Key: Green plot - Imported steel sample "as-received"

Red plot – Local steel sample "as-received"

Heat-treatment altered the mechanical properties of both sets of samples. This can be seen from Fig 4.3 and Fig 4.4. The bar charts in Fig 4.5 show quantitatively the effect of the heat-treatment on the strengths, Young's modulus and percent elongation of locally-made and imported low-carbon steels. Since heat-treatment reduces the level of internal stresses that remain locked in the metal rods as a consequence of manufacturing processes, it generally lowered the Tensile Strength, Yield Strengths and Young's modulus and raised the percent elongation when the heat-treated samples are compared with the "as-received" samples for both types of steels (Fig 4.3 and Fig 4.4). The removal of residual stresses took place due to the fact that the thermal energy received by the metal allowed for grain boundary sliding and removal of metallurgical defects like dislocations, vacancies and slip planes.

Considering the heat-treated samples, raising the heat-treatment temperature led to decreases in the tensile strength (Fig 4.5(a)), the yield strengths (Fig 4.5(c)) and Young's moduli (Fig 4.5(d)), but an increase in percent elongation (Fig 4.5(b)). This was due to the fact that the closer the heat-treatment temperature is to the critical or re-crystallization temperature, the more effective it is in the removal of residual stresses. At the temperature of 650^0C, closest to the lower critical temperature of 723 ^{0}C, the UTS, Yield Strength and Young's modulus decreased by 9.18%, 11.39% and 10.61% respectively while Ductility improved by 24.42% for locally-made low carbon steel samples. For the imported steel samples, there were 27.83%, 22.54% and 5.94% drops in UTS, Yield Strength and Young's modulus respectively. Ductility, however, improved by 48.35% over the non-heat treated "as-received" samples.

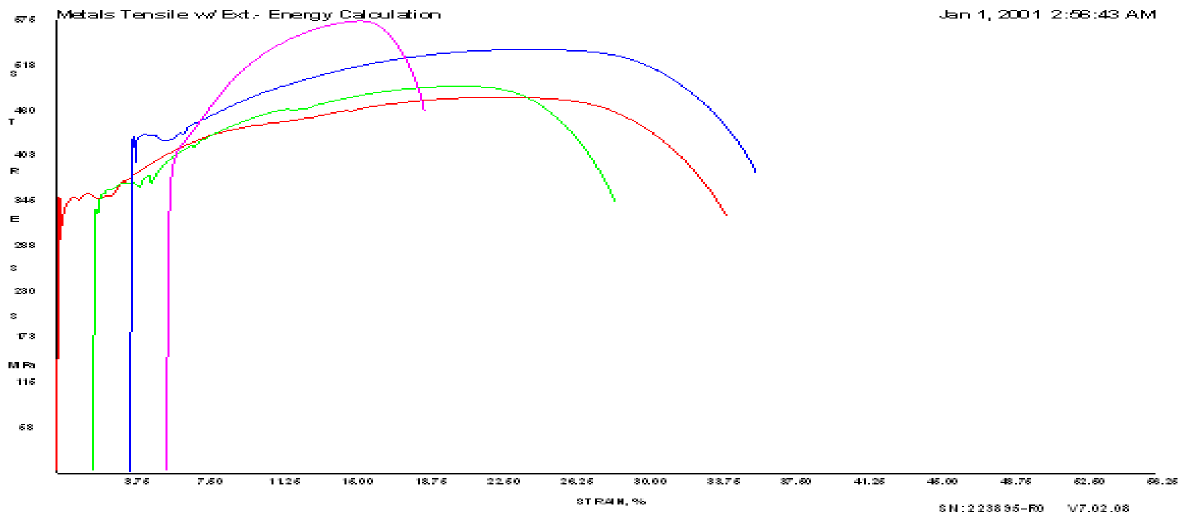


Fig 4.3 Composite stress-strain plots of “as-received” and heat-treated local steel samples.

Key: Pink plot – LC, blue plot – LC^{450}, green plot– LC^{550}, red plot– LC^{650}.

LC ------ Un-welded local steel sample with no heat-treatment

LC^{450} --- Un-welded local steel sample heat-treated at 450 ^{0}C

LC^{550} -- Un-welded local steel sample heat-treated at 550 ^{0}C

LC^{650} -- Un-welded local steel sample heat-treated at 650 ^{0}C

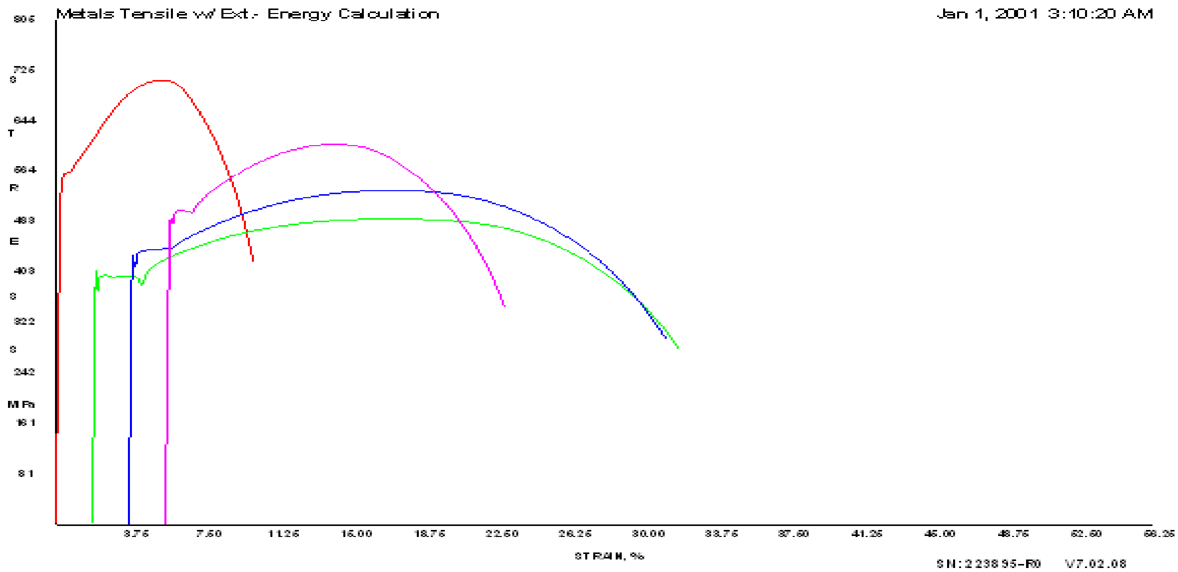


Fig 4.4 Composite stress-strain plots of "as-received" and heat-treated imported steel samples.

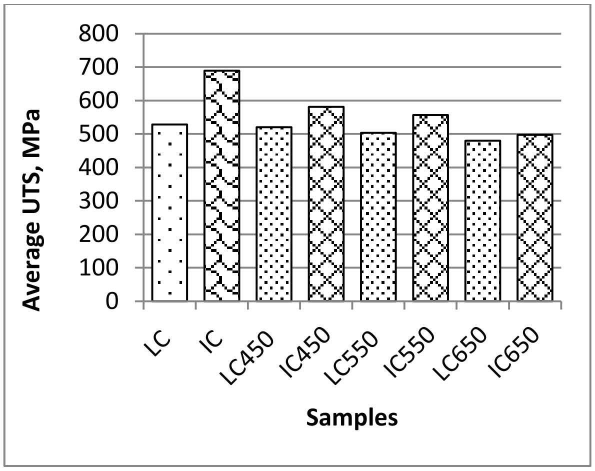
Key: Red plot- IC, pink plot – IC^{450}, blue plot – IC^{550}, green plot – IC^{650}

IC ---- Un-welded imported steel sample with no heat-treatment

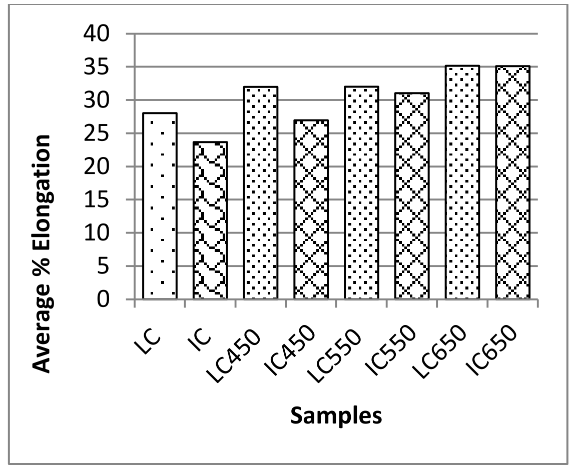
IC^{450} -- Un-welded imported steel sample heat-treated at 450 ^{0}C

IC^{550} -- Un-welded imported steel sample heat-treated at 550 ^{0}C

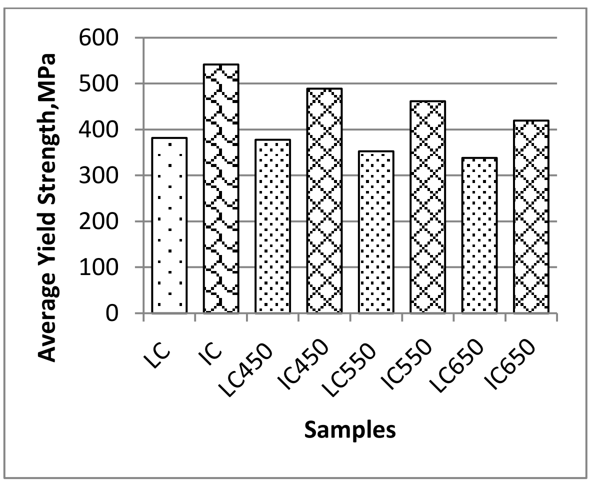
IC^{650} --- Un-welded imported steel sample heat-treated at 650 ^{0}C



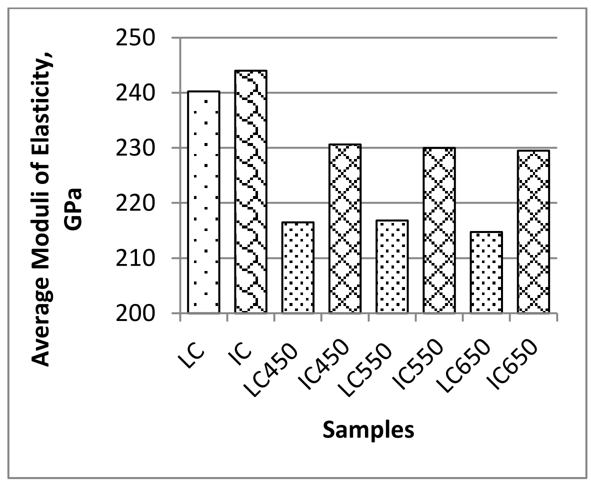
(a)



(b)



(c)



(d)

Fig.4.5. Bar charts comparing the mechanical properties of the local and imported low-carbon steels showing the (a) average UTS, (b) average Elongation, (c) average Yield Strength, and (d) average Moduli of Elasticity of the two different materials.

Key:

LC ------ Un-welded local steel sample with no heat-treatment

LC^{450} --- Un-welded local steel sample heat-treated at 450 ^{0}C

LC^{550} -- Un-welded local steel sample heat-treated at 550 ^0C

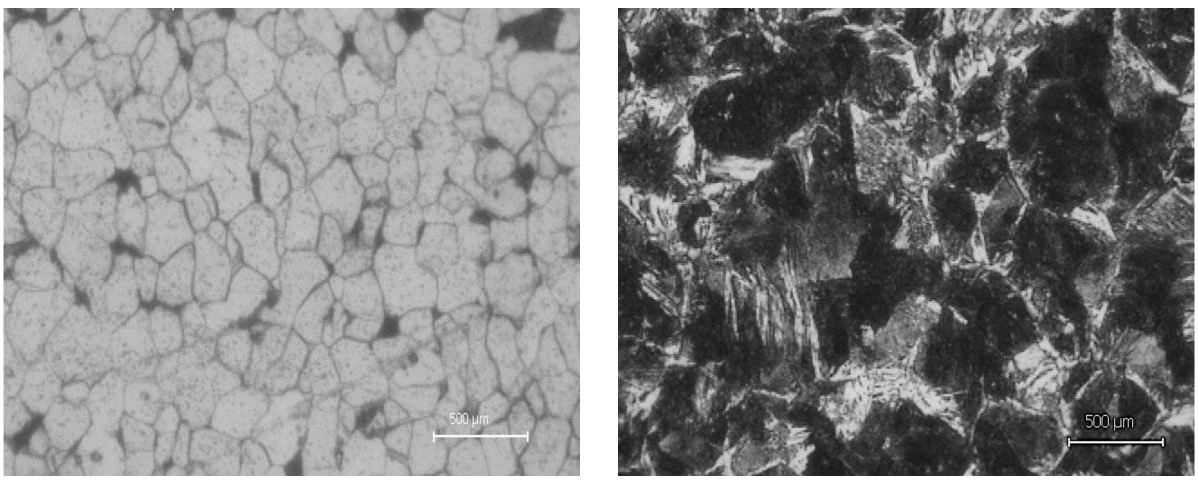
LC^{650} -- Un-welded local steel sample heat-treated at 650 ^0C

IC ---- Un-welded imported steel sample with no heat-treatment

IC^{450} -- Un-welded imported steel sample heat-treated at 450 ^0C

IC^{550} -- Un-welded imported steel sample heat-treated at 550 ^0C

IC^{650} --- Un-welded imported steel sample heat-treated at 650 ^0C



(a) (b)

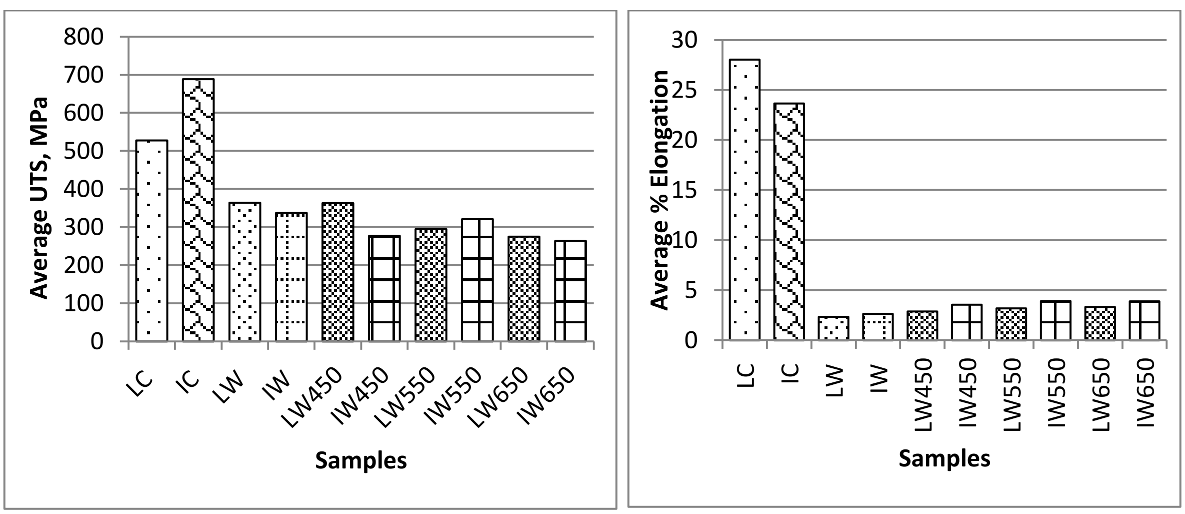
Fig.4.6. Optical micrograph of (a) local, and (b) imported steels at 500X nominal magnification. The dark portions are the pearlites while the grey portions are the ferrites.

4.2.2 Welded and Welded-Heat-treated Samples

The bar charts in Fig 4.7 show the effect of the heat-treatment temperature on the strengths, Young's moduli and percent elongations of welded samples of both locally-made and imported low-carbon steels. High level residual tensile stresses occurred in weldment due to restraint by the relatively cold parent metal during weld solidification. The post-weld heat-treatment relieved the residual tensile stresses at the weld interface.

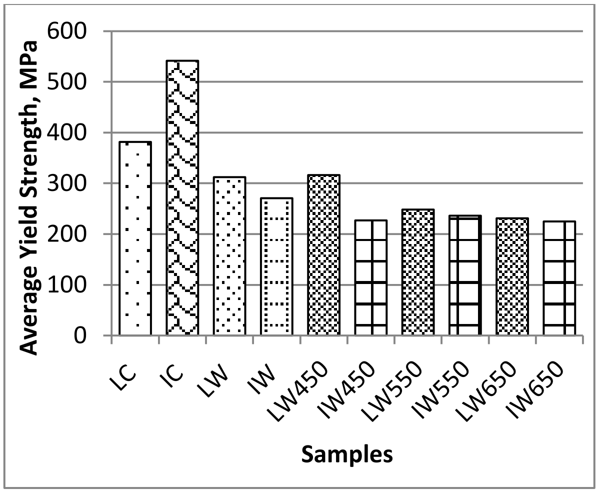
Increasing the heat-treatment temperature to 650 ^{0}C, closer to the recrystallization temperature (723 ^{0}C), had greater effect on the mechanical properties. It enhanced the removal of more metallurgical defects such as dislocations and grain boundaries which are meant to strengthen the metal. This reflected a 24.5% decrease in the UTS, 26.0% decrease in Yield Strengths and a 42.0% increase in the Elongation for welded samples made from local steel. Welded samples made from imported steel recorded a 21.8% drop in UTS, a 16.9% drop in the Yield Strength, and a 47.3% rise in Percent Elongation through the heat-treatment. Comparing the mechanical properties of the joints, those fabricated from local steel generally had higher UTS and Yield Stresses but lower Percent Elongations and Young modulus as compared to their imported steel counterparts for similar heat-treatments. The relatively higher strength in the joints of local steel was as a result of the formation of finer grains in the weld microstructure during solidification. The finer the grains the larger the area of grain boundaries that impedes dislocation motion. A reduction in dislocation mobility implies larger stresses required for deformation, hence its strength. The slight deviations from the trends of the mechanical properties could result from welding defects such as blow holes and slag inclusions at the joints.

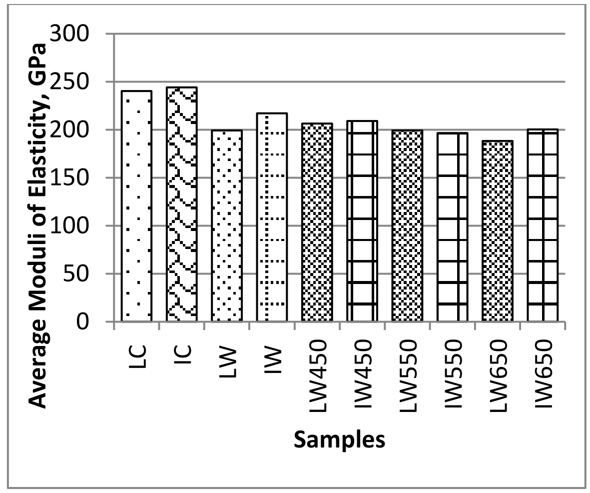
Comparing the welded with the un-welded samples (Fig 4.7), there were losses of 30.0%, 18.2% and 17.11% in UTS, yield strength and Young’s modulus respectively and a drastic loss of 91.6% in Percent Elongation in the local steels when welded. With the imported steels, there were losses of 51.0%, 50.0%, 11.07% and 88.0% in the UTS, Yield Strength, Young’s modulus and Percent Elongation respectively. On heat-treating the welded samples, there were further losses in UTS and yield strength of 24.5% and 26.0% respectively for local steels and 21.8% and 16.9% respectively for the imported steels. However, the ductility improved greatly by 100.5% for local steel and 125.1% for the imported steels over those of the welded samples with no heat-treatment. There were no appreciable changes in the Moduli of Elasticity for both steel types.



(a) (b)

Fig.4.7. Bar charts comparing the mechanical properties of the welded joints in local and imported low-carbon steels showing the (a) average UTS, and (b) average Percent Elongation. See continuation of Fig 4.7 on page 56.





(c) (d)

Fig.4.7. Bar charts comparing the mechanical properties of the welded joints in local and imported low-carbon steels showing the (c) average Yield Strength and (d) average Moduli of Elasticity, of the two different materials.

Key:

LW ------ Welded local steel sample with no heat-treatment

LW^{450} --- Welded local steel sample heat-treated at 450 ^{0}C

LW^{550} -- Welded local steel sample heat-treated at 550 ^{0}C

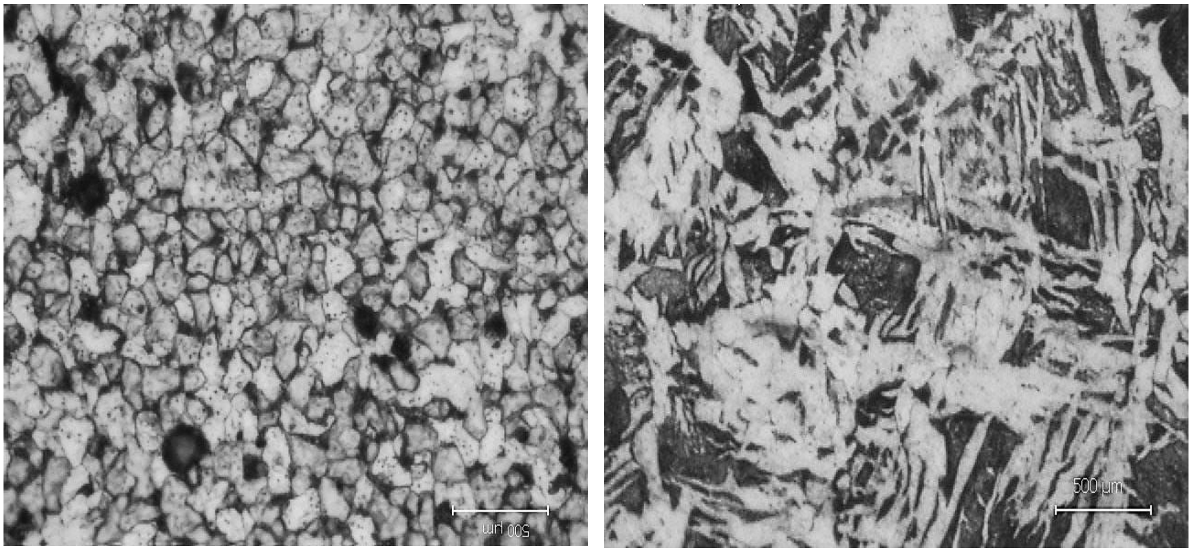
LW^{650} -- Welded local steel sample heat-treated at 650 ^{0}C

IW ----- Welded imported steel sample with no heat-treatment

IW^{450} -- Welded imported steel sample heat-treated at 450 ^{0}C

IW^{550} -- Welded imported steel sample heat-treated at 550 ^{0}C

IW^{650}-- Welded imported steel sample heat-treated at 650 ^{0}C



(a) (b)

Fig.4.8. Optical micrographs of the weld in (a) local and (b) imported low-carbon steels at 500X nominal magnification

Fig 4.9, Fig 4.10, Fig 4.11 and Fig 4.12 show the changes in the mechanical properties of welded and un-welded samples with heat-treatment temperature. Generally, heat-treatment reduced the UTS, Yield Strengths and Moduli of Elasticity, and raised the Ductility for both sets of samples. There were significant deteriorations in the mechanical properties of the steels when welded especially, in the UTS, Yield Strengths and Percent Elongations. The percentage reductions in UTS and Yield Strength and increases in Ductility as samples were taken through heat-treatments at the temperatures 450 ^{0}C, 550 ^{0}C and 650 ^{0}C are summarized in Table 4.3.

Table 4.3 Percentage changes in mechanical properties of (a) Un-welded local steel, (b) Welded local steel, (c) Un-welded imported steel, and (d) Welded imported steel, when heat-treated at some designated temperatures

Key: ↓ - drop, ↑ - rise

(a) Un-welded local steel.

	$450\ ^0C$	$550\ ^0C$	$650\ ^0C$
UTS	1.51% ↓	4.72% ↓	9.18% ↓
Yield Strength	1.05% ↓	7.62% ↓	11.39% ↓
Ductility	14.04% ↑	14.18% ↑	25.42% ↑

(b) Welded local steel

	$450\ ^0C$	$550\ ^0C$	$650\ ^0C$
UTS	0.33% ↓	19.07% ↓	24.47% ↓
Yield Strength	0.29% ↓	20.47% ↓	25.97% ↓
Ductility	18.63% ↑	36.03% ↑	42.03% ↑

(c) Un-welded imported steel

	450 ^{0}C	550 ^{0}C	650 ^{0}C
UTS	15.67% ↓	19.21% ↓	27.83% ↓
Yield Strength	9.71% ↓	14.76% ↓	22.54% ↓
Ductility	13.91% ↑	31.16% ↑	48.35% ↑

(d) Welded imported steel

	450 ^{0}C	550 ^{0}C	650 ^{0}C
UTS	17.78% ↓	4.81% ↓	21.78% ↓
Yield Strength	16.16% ↓	12.74% ↓	16.92% ↓
Ductility	34.66% ↑	48.14% ↑	47.31% ↑

From Table 4.3, it was observed that the effect of heat-treatment was more prominent at the highest temperature of 650 ^{0}C. However, there were no appreciable changes in the Moduli of Elasticity when the heat-treatment temperature was raised from 450 ^{0}C through 550 ^{0}C to 650 ^{0}C (fig 4.12).

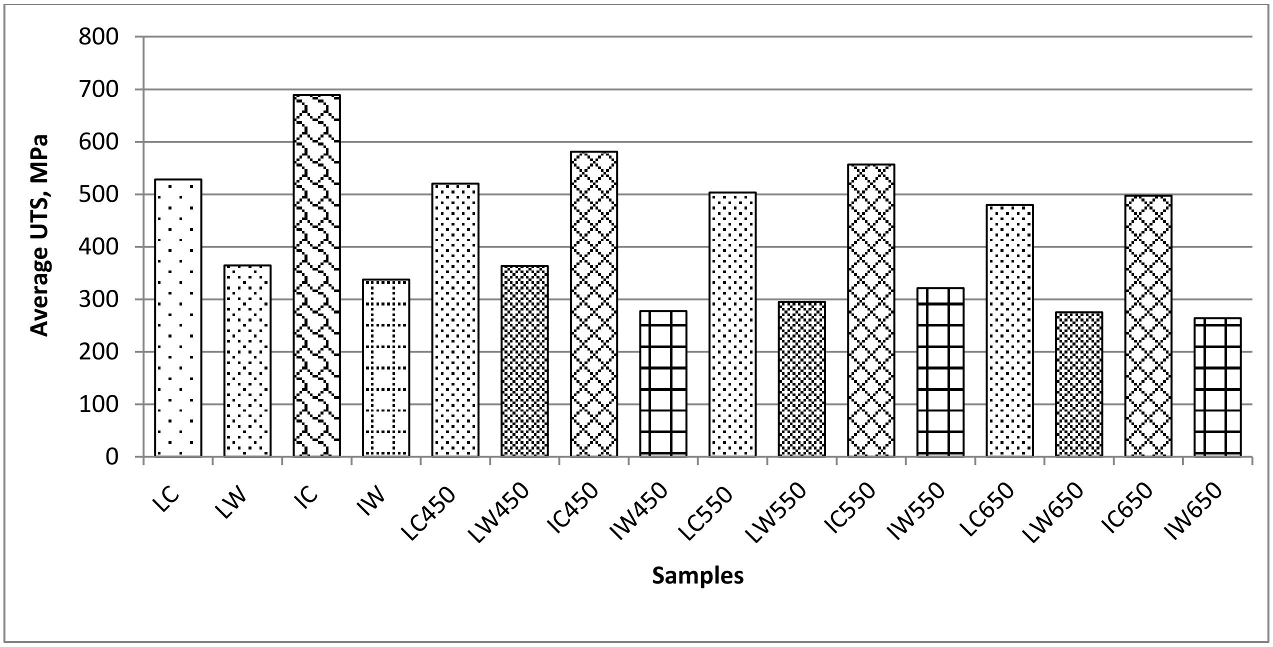


Fig.4.9. Bar charts showing a comparison between the average UTS for the “as-received” samples and welded samples of local and imported low-carbon steels. The symbols have been explained in the key to caption of Fig 4.7.

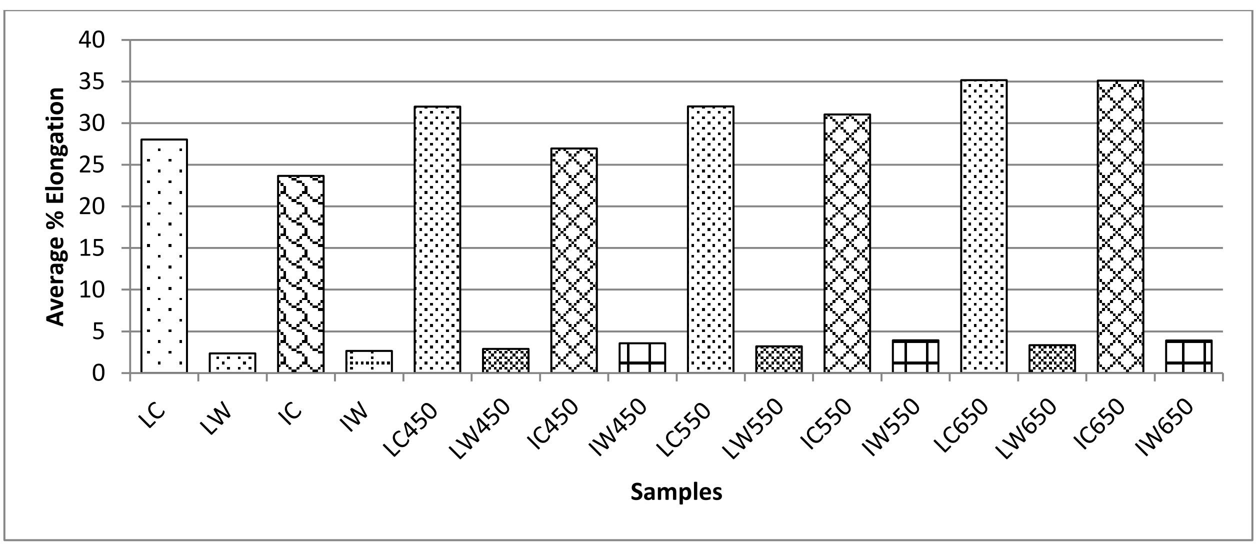


Fig.4.10. Bar charts showing a comparison between the average Percent Elongation for the “as-received” samples and welded samples of the local and imported low-carbon steels. The symbols have been explained in the key to caption of Fig 4.7.

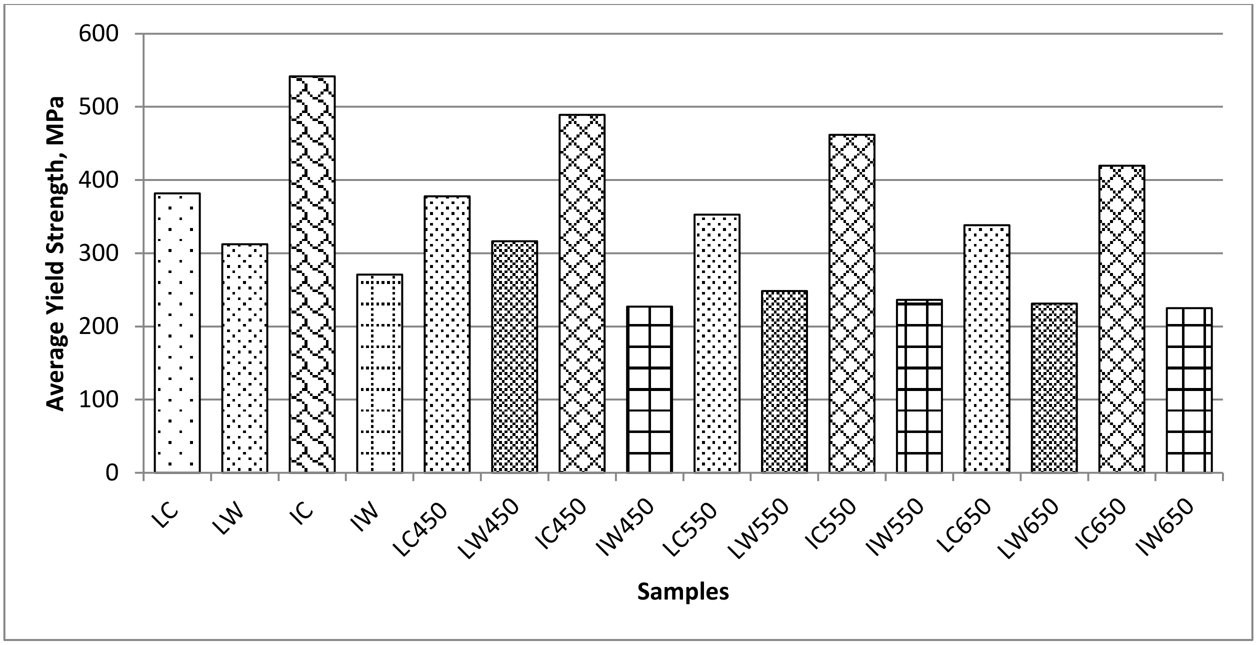


Fig.4.11. Bar charts showing a comparison between the average Yield Strength for the "as-received" samples and welded samples of the local and imported low-carbon steels.

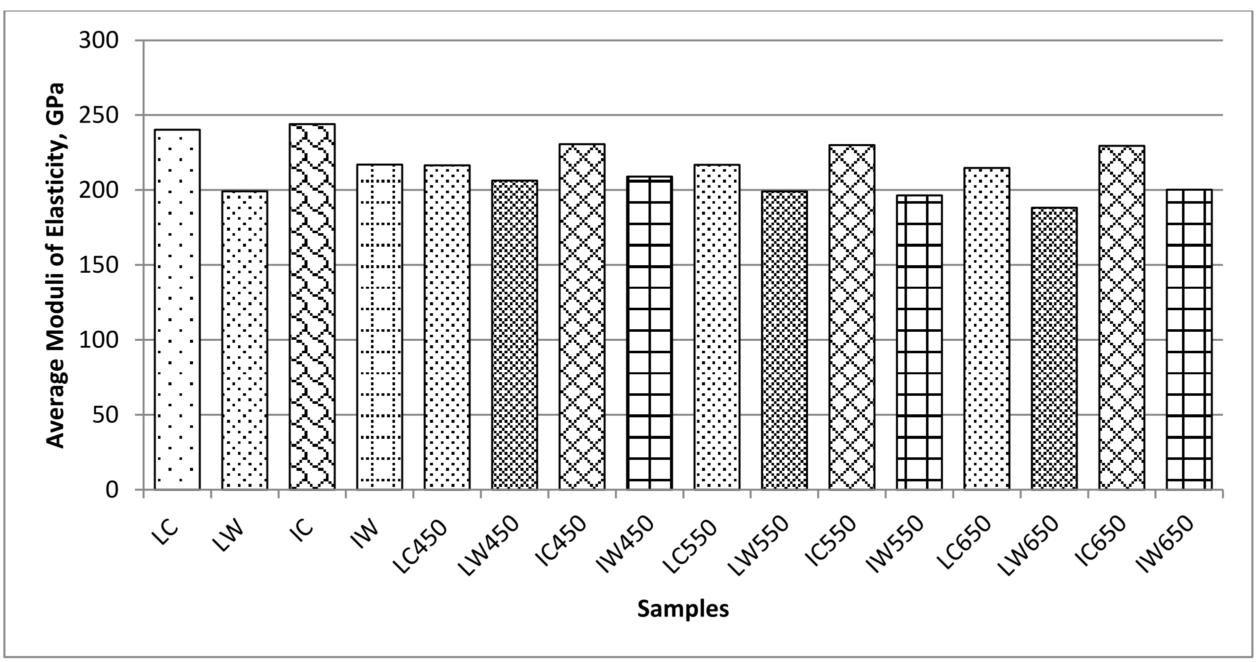
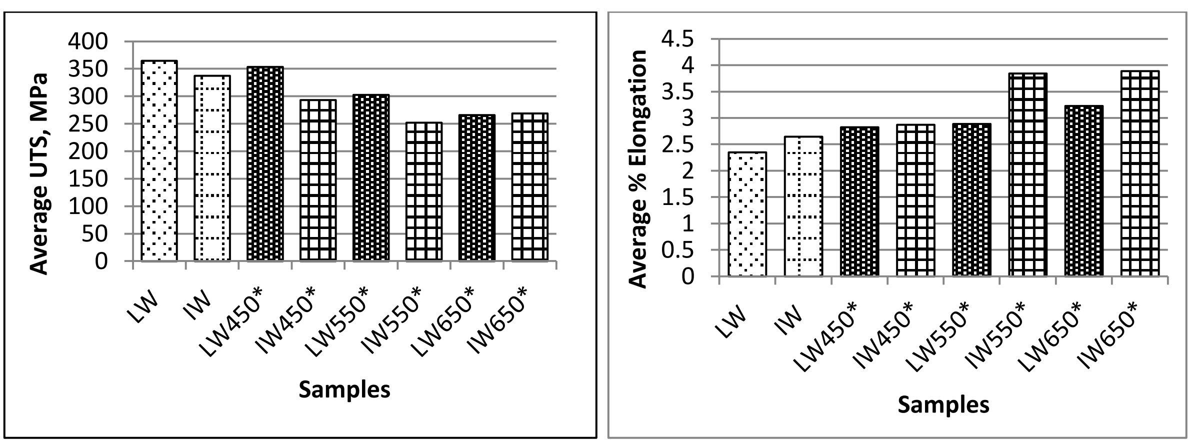


Fig.4.12. Bar charts showing a comparison between the average Moduli of Elasticity for the "as-received" samples and welded samples of the local and imported low-carbon steels

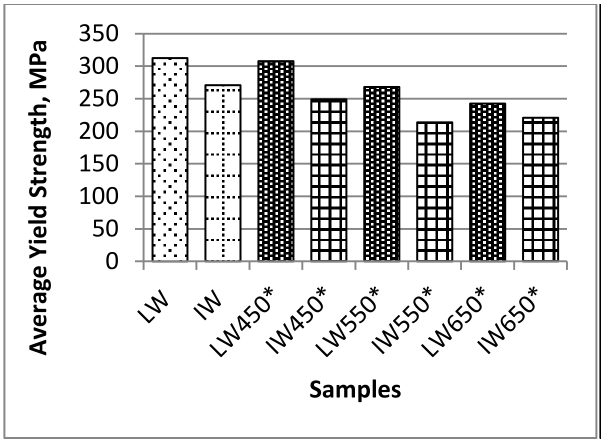
4.2.3 Samples Heat-treated, Welded and Heat-treated

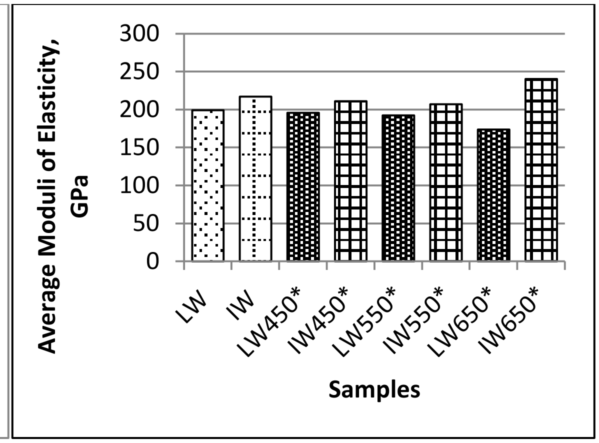
The heat-treatment generally altered the Tensile and Yield Stresses, Percent elongations and Young's Moduli of the welded samples. It caused a redistribution of the high residual stresses resulting from weld shrinkage locked into the welded joint. This redistribution took place due to the fact that the thermal energy received by the metals allowed for grain boundary sliding and removal of metallurgical defects like dislocations, vacancies and slip planes. Increasing the heat-treatment temperature generally led to a decrease in the Tensile Stress, Yield Stresses and Young's Modulus, and an increase in the Percent Elongation for welded samples prepared from both local and imported steels (Fig 4.13). Welding defects at the joints such as blow holes and slag inclusions could account for the slight deviations from the general trend of the mechanical properties.



(a) (b)

Fig 4.13 Bar charts comparing the mechanical properties of the welded joints in local and imported low-carbon steels showing the (a) average UTS and (b) average Percent Elongation. See continuation of Fig 4.13 on page 63.





(c) (d)

Fig 4.13 Bar charts comparing the mechanical properties of the welded joints in local and imported low-carbon steels showing the (c) average Yield Strength and (d) average Moduli of Elasticity, of the two different materials.

Key:

LW^{450*} -- Locally-made low-carbon steel sample heat-treated at 450 ^{0}C before and after welding

LW^{550*} -- Locally-made low-carbon steel sample heat-treated at 550 ^{0}C before and after welding

LW^{650*} -- Locally-made low-carbon steel sample heat-treated at 650 ^{0}C before and after welding

IW^{450*} -- Imported low-carbon steel sample heat-treated at 450 ^{0}C before and after welding

IW^{550*} -- Imported low-carbon steel sample heat-treated at 550 ^{0}C before and after welding

IW^{650*} -- Imported low-carbon steel sample heat-treated at 650 ^{0}C before and after welding

The heat-treatment before welding did not cause any appreciable change in the mechanical properties of the samples concerned when they were compared with those samples first welded and then followed by heat-treatment (Fig 4.14, Fig 4.15, Fig 4.16 and Fig 4.17).

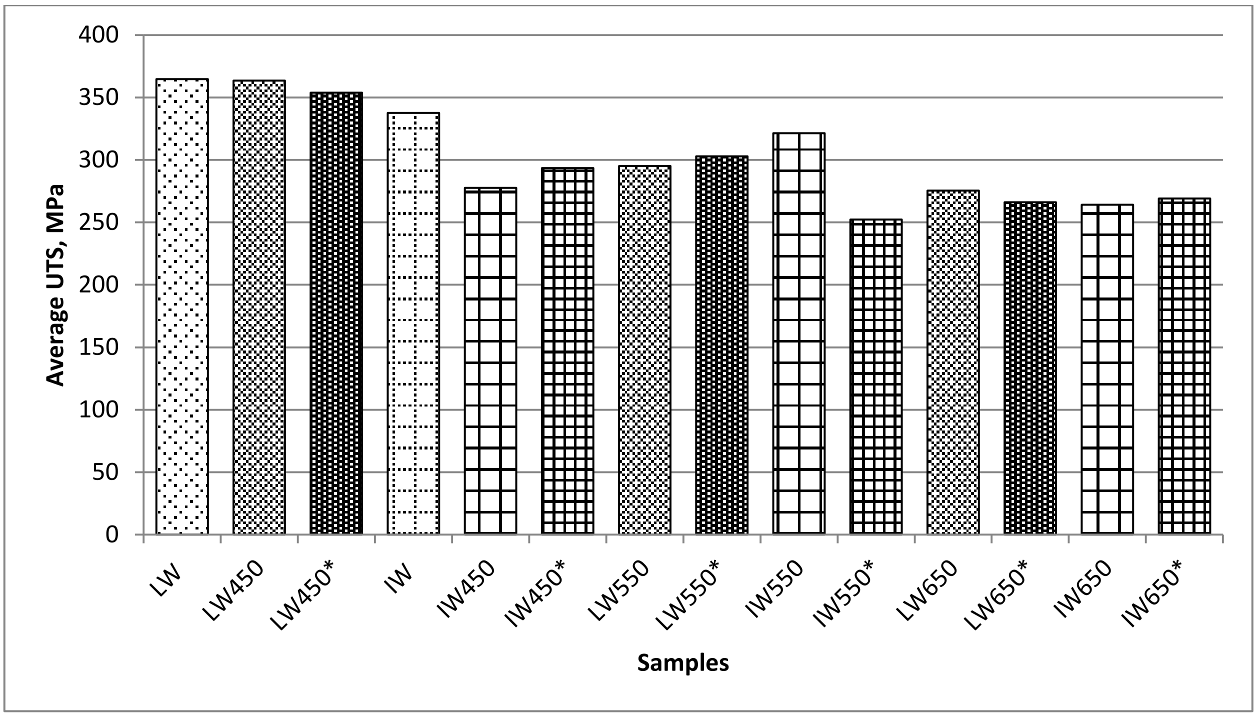


Fig.4.14 Bar charts showing a comparison between the average UTS for the welded, welded-heat-treated and heat-treated-welded-heat-treated local and imported low-carbon steels. The symbols have been explained in the key to caption of Fig 4.13.

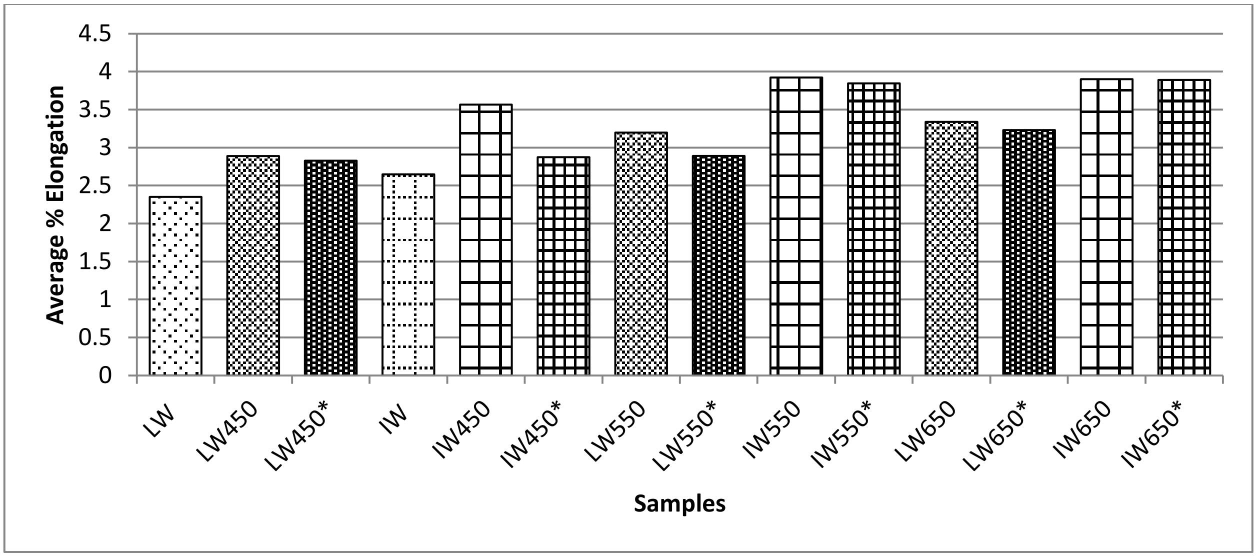


Fig.4.15. Bar charts showing a comparison between the average % elongation for the welded, welded-heat-treated and heat-treated-welded-heat-treated local and imported low-carbon steels

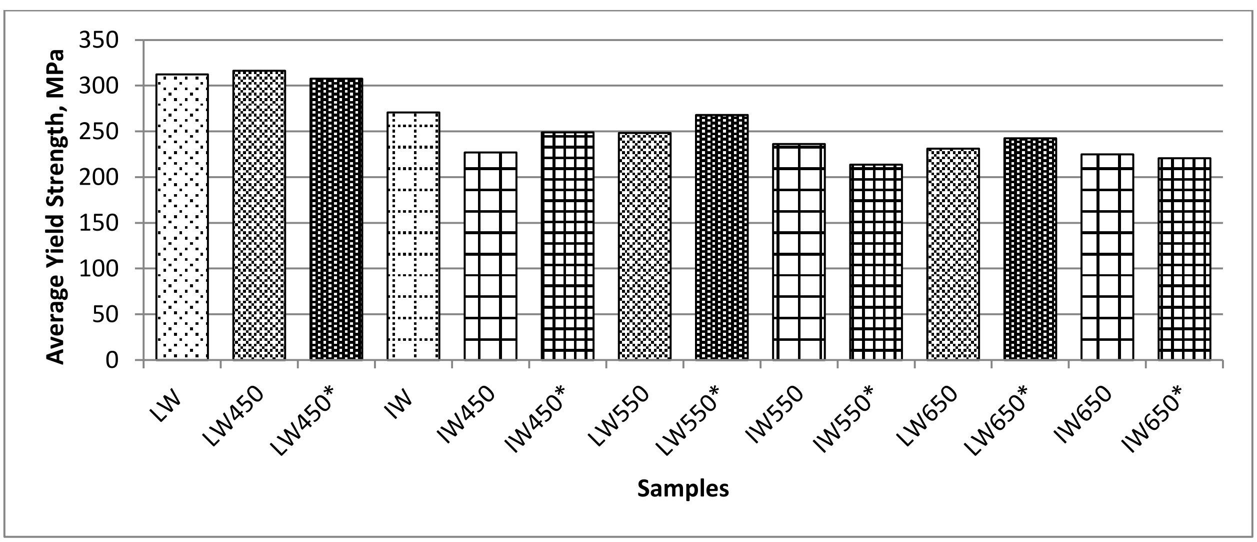


Fig.4.16. Bar charts showing a comparison between the average Yield strength for the welded, welded-heat-treated and heat-treated-welded-heat-treated local and imported low-carbon steels

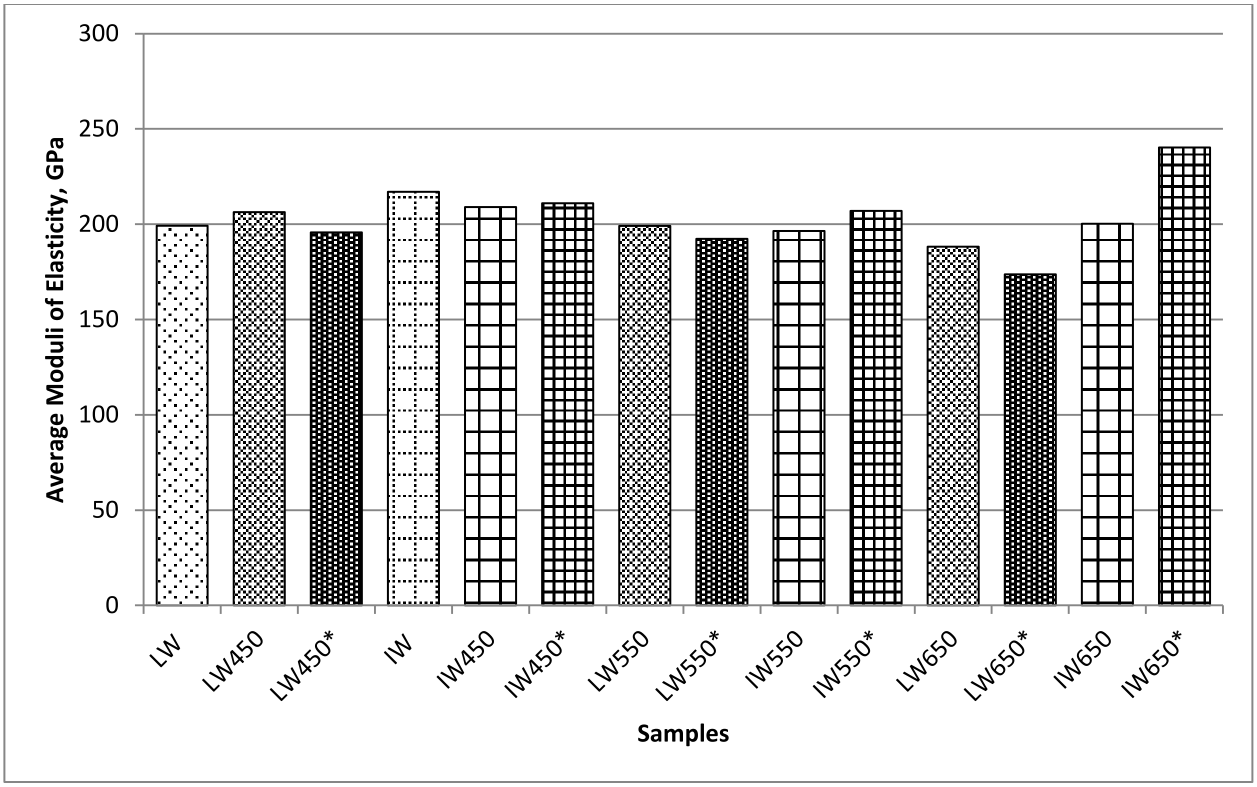


Fig.4.17. Bar charts showing a comparison between the average Moduli of elasticity for the welded, welded-heat-treated and heat-treated-welded-heat-treated local and imported low-carbon steels

4.3 IMPACT TESTING

4.3.1 Un-welded Sample

Fig 4.15 shows the effect of heat-treatment temperature on the impact strengths of locally-made and imported steels. Even though some level of strength (UTS) which complements ductility in determining impact strength was sacrificed through heat-treatment, due to the tremendous improvement in ductility there was an overall increase in the impact strength with increasing temperature. Details are given in Table 4.4.

Table 4.4 Percentage changes in mechanical properties of (a) un-welded local steel, and (b) un-welded imported steel samples when heat-treated at some designated temperatures.

Key: ↓ - drop, ↑ - rise

(a) Un-welded local steel

	450 ^{0}C	550 ^{0}C	650 ^{0}C
UTS	1.51% ↓	4.72% ↓	9.18% ↓
Ductility	14.04% ↑	14.18% ↑	25.42% ↑
Impact strength	34.43% ↑	35.68% ↑	95.64% ↑

(b) Un-welded imported steel

	450 ^{0}C	550 ^{0}C	650 ^{0}C
UTS	15.67% ↓	19.21% ↓	27.83% ↓
Ductility	13.91% ↑	31.16% ↑	48.35% ↑
Impact strength	40.56% ↑	52.68% ↑	73.75% ↑

For similar heat-treatments, the imported steel samples had higher impact strengths than their locally-made counterparts (Fig 4.18) which implied a better UTS-Percent Elongation combination for the imported steels.

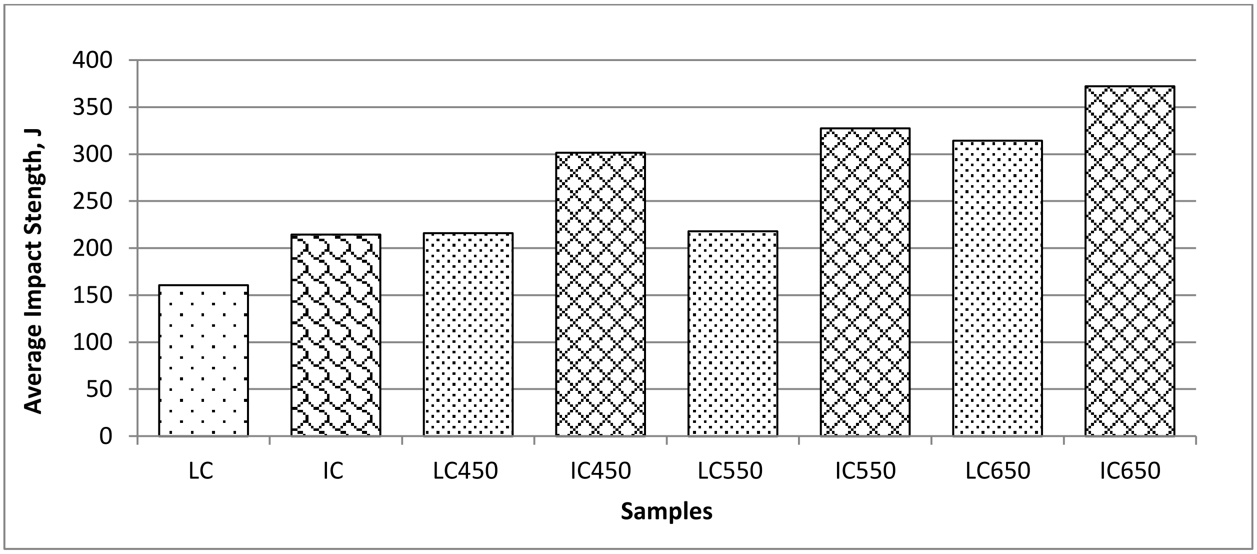


Fig.4.18. Bar charts showing a comparison between the average impact strengths of the “as-received and heat-treated local and imported low-carbon steels.

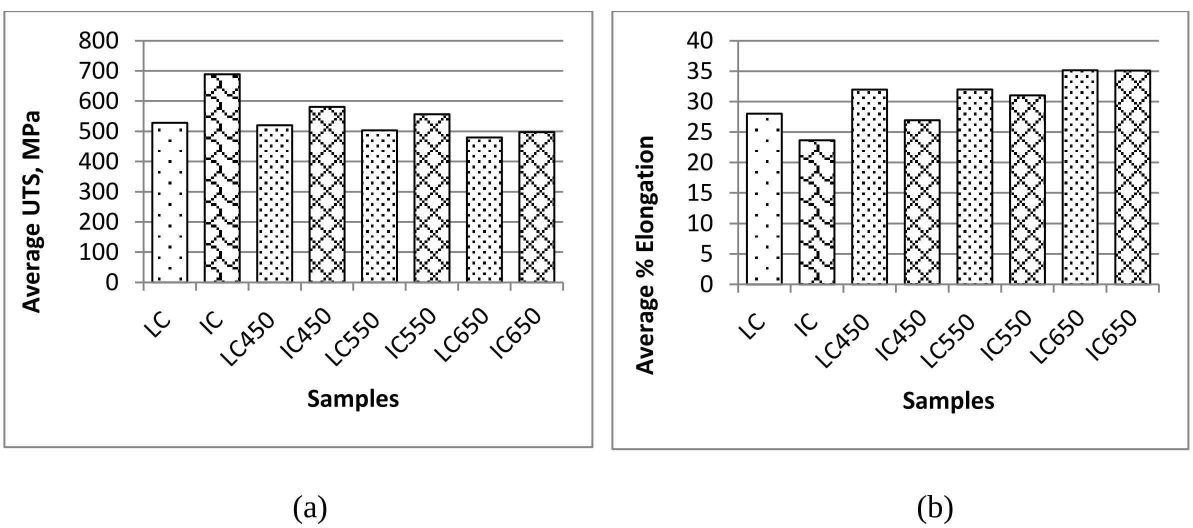


Fig.4.19. Bar charts comparing the mechanical properties of un-welded local and imported low-carbon steels showing the (a) average UTS and (b) average Percent Elongation, of the two different materials.

4.3.2 Welded and Welded-Heat-treated samples

There was a general increase in the impact strength for both locally-made and imported steel samples as the heat-treatment temperature was raised. The post-weld heat-treatment tempered the martensite[15] in the weld metal and the heat-affected zone, reducing the hardness at the joint. Increasing the heat-treatment temperature, the level of internal stresses which is the driving force for crack propagation dropped, thereby enhancing the ability of the welded joint to absorb more shock. This led to an increase in the impact strength. Welded samples made from imported steels had higher impact strengths than those from locally-made steels. This was due to their higher Percent Elongations as compared with welded samples of local steel.

Comparing the welded with the un-welded samples (Fig 4.20), there were losses of 33.20% and 30.71% in the impact strengths of local and imported steels respectively when welded. On heat-treating the welded samples, some level of impact strength was regained as ductility was improved greatly even though the strength (UTS) was sacrificed. Details are given in table 4.5.

Table 4.5 Percentage changes in mechanical properties of (a) welded local steel, and (b) welded imported steel samples when heat-treated at some designated temperatures.

Key: ↓ **-** drop, ↑ **-** rise

(a) Welded local steel

	450 ^{0}C	550 ^{0}C	650 ^{0}C
UTS	0.33% ↓	19.07% ↓	24.47% ↓
Ductility	18.63% ↑	36.03% ↑	42.03% ↑
Impact Strength	7.41% ↑	33.80% ↑	100.46% ↑

(b) Welded imported steel

	450 ^{0}C	550 ^{0}C	650 ^{0}C
UTS	17.78% ↓	4.81% ↓	21.78% ↓
Ductility	34.66% ↑	48.14% ↑	47.31% ↑
Impact Strength	2.65% ↑	61.03% ↑	125.08% ↑

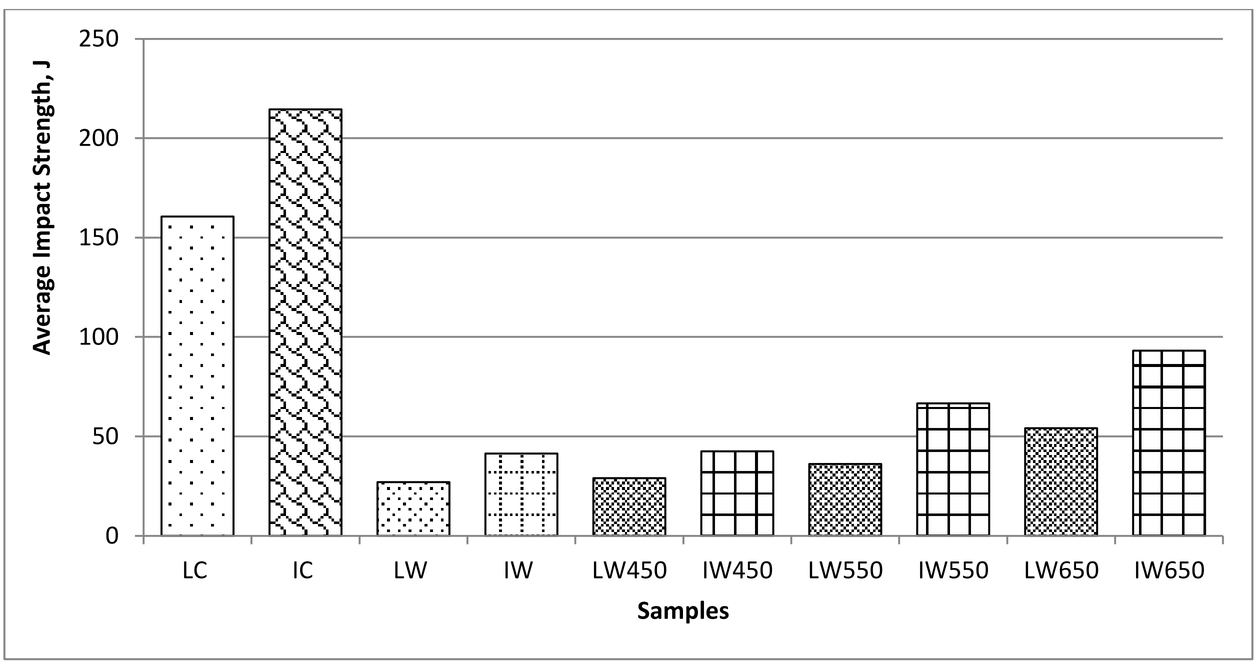


Fig.4.20. Bar charts showing a comparison between the impact strengths of “as-received”, welded and welded, heat-treated joints of local and imported low-carbon steels.

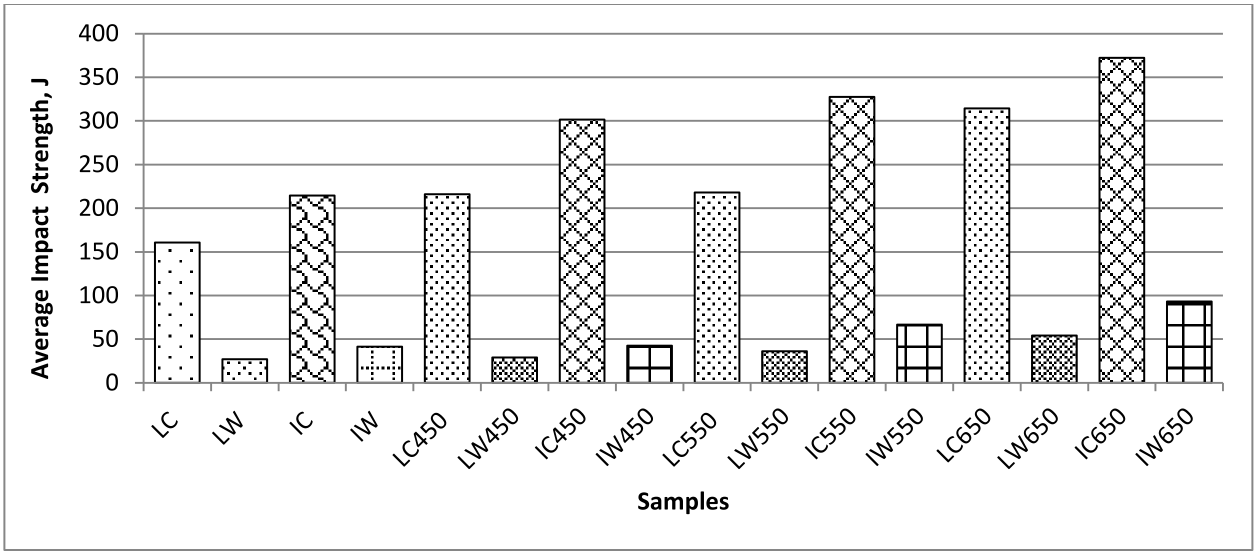


Fig.4.21. Bar charts showing a comparison between the impact strengths of un-welded and welded local and imported low-carbon steels at different heat-treatment temperatures.

4.3.3 Samples Heat-treated, Welded and Heat-treated

From the bar charts in Fig 4.22, welded samples made from imported steel had higher impact strengths than those made from locally-made steel. This is due to their high UTS values, even though their percent elongations, a parameter in the impact strength determination are low. The heat-treatment improved the impact strength through the redistribution of the internal stresses resulting from weld shrinkage at the joints.

Generally, the heat-treatment before welding did not cause any appreciable change in the impact strengths of the samples concerned when they were compared with those samples first welded and then followed by heat-treatment (Fig 4.23).

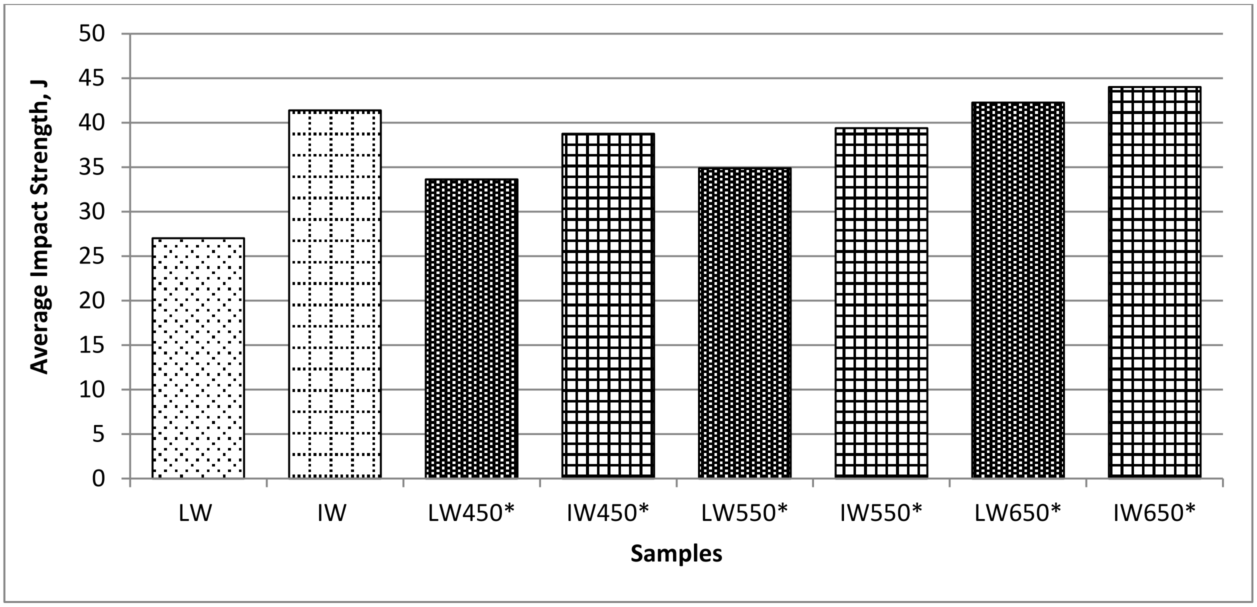


Fig.4.22. Bar charts showing a comparison between the impact strengths of welded and heat-treated-welded-heat-treated joints of local and imported low-carbon steels.

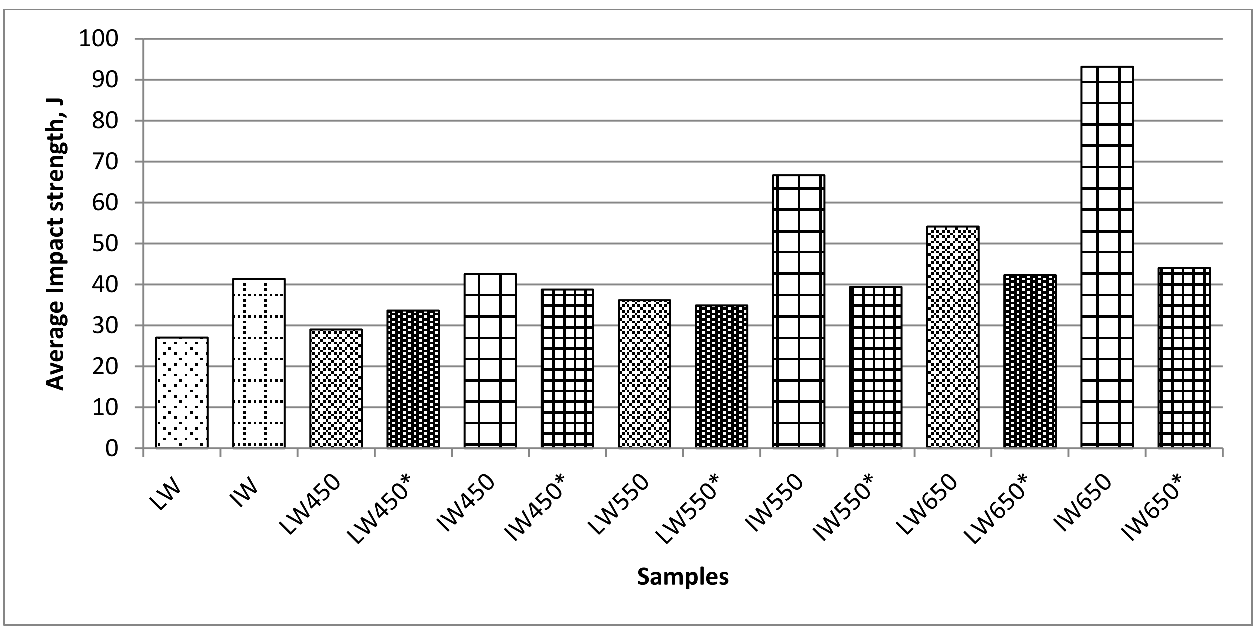


Fig.4.23. Bar charts showing a comparison between the Impact Strengths of welded and welded-heat-treated joints of local and imported low-carbon steels.

4.4 Summary of the Changes In Mechanical Properties of Welded Samples

Table 4.6 Percentage Changes In The Mechanical Properties Of Welded And Welded, Heat-treated Samples

Sample	UTS	Yield Strength	Elongation	Impact Strength
LW	30.0% ↓ w.r.t. as-received	18.2% ↓ w.r.t. as-received	91.6% ↓ w.r.t. as-received	83.2% ↓ w.r.t. as-received
LW^{650}	47.9% ↓ w.r.t. as-received	39.4% ↓ w.r.t. as-received	88.1% ↓ w.r.t. as-received	66.3% ↓ w.r.t. as-received
LW^{650}	24.5% ↓ w.r.t. welded	26.0% ↓ w.r.t. welded	42.0% ↑ over welded	100.5% ↑ over welded
IW	51.0% ↓ w.r.t. as-received	50.0% ↓ w.r.t. as-received	88.0% ↓ w.r.t. as-received	80.7% ↓ w.r.t. as-received
IW^{650}	61.7% ↓ w.r.t. as-received	58.5% ↓ w.r.t. as-received	83.5% ↓ w.r.t. as-received	56.6% ↓ w.r.t. as-received
IW^{650}	21.8% ↓ w.r.t. welded	16.9% ↓ w.r.t. welded	47.3% ↑ over welded	125.1% ↑ over welded

Key: ↓ - drop, ↑ - rise

Table 4.7 Percentage Changes In Mechanical Properties Of Welded Samples And Samples Heat-treated Before And After Welding

Sample	UTS	Yield Strength	Elongation	Impact Strength
LW	30.0% ↓ w.r.t. as-received	18.2% ↓ w.r.t. as-received	91.6% ↓ w.r.t. as-received	83.2% ↓ w.r.t. as-received
LW^{650*}	46.9% ↓ w.r.t. as-received	36.5% ↓ w.r.t. as-received	88.5% ↓ w.r.t. as-received	73.7% ↓ w.r.t. as-received
LW^{650*}	27.0% ↓ w.r.t. welded	28.8% ↓ w.r.t. welded	37.4% ↑ over welded	56.5% ↑ over welded
IW	51.0% ↓ w.r.t. as-received	50.0% ↓ w.r.t. as-received	88.0% ↓ w.r.t. as-received	80.7% ↓ w.r.t. as-received
IW^{650*}	61.0% ↓ w.r.t. as-received	59.3% ↓ w.r.t. as-received	72.3% ↓ w.r.t. as-received	79.5% ↓ w.r.t. as-received
IW^{650*}	20.3% ↓ w.r.t. welded	18.5% ↓ w.r.t. welded	46.9% ↑ over welded	6.3% ↑ over welded

4.5 Microstructure across the Weld Interfaces

4.5.1 Welded Local Steel Sample

The micrographs in this section show the microstructure of the un-affected base metal (region A), interface between base metal and heat-affected zone (region B), heat-affected zone (region C), interface between heat-affected zone and the weld (region D), and in the weld region(E). The sections A, B, C, D and E were pieced up to highlight the progression of the microstructural evolution.

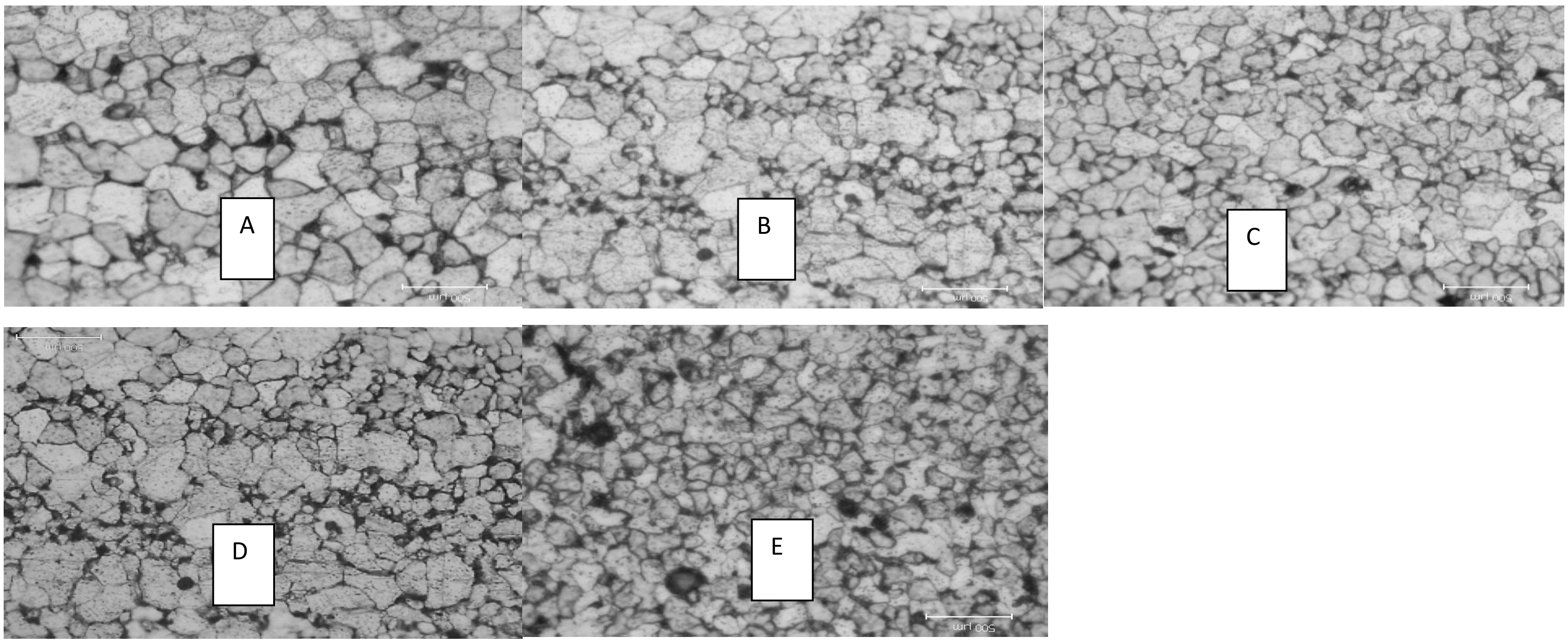


Fig. 4.24 Optical micrograph of welded sample of locally made low carbon steel. The regions A, B, C, D and E are microstructures of the un-affected base metal, interface between base metal and heat-affected zone, heat-affected zone, interface between heat-affected zone and the weld, and in the weld respectively.

4.5.2 Welded and Heat-treated Local Steel Sample

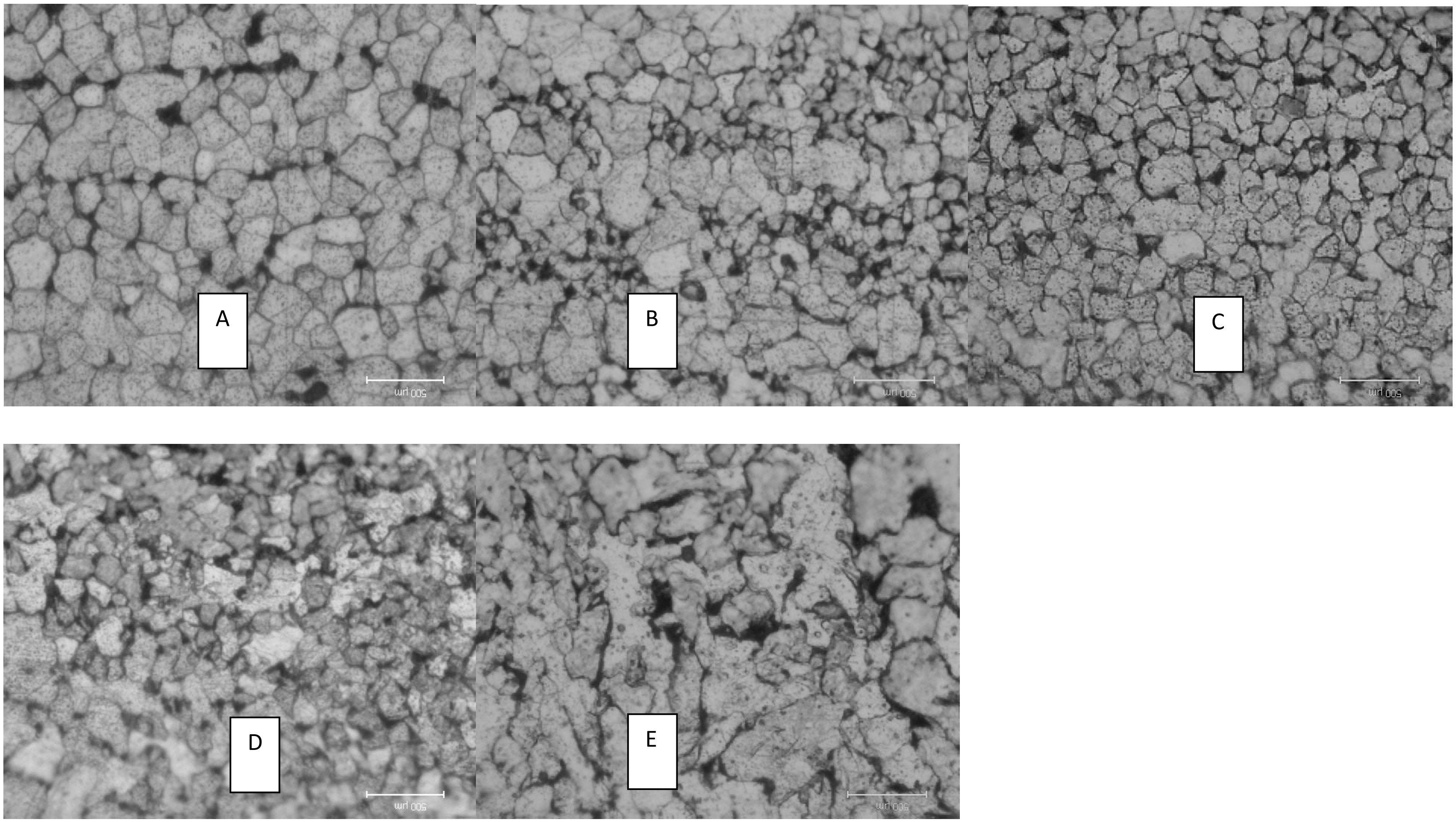


Fig. 4.25 Optical micrograph of welded and heat-treated sample of locally made low carbon steel. The regions A, B, C, D and E have been explained in the caption to Fig 4.24.

4.5.3 Welded Imported Steel Sample

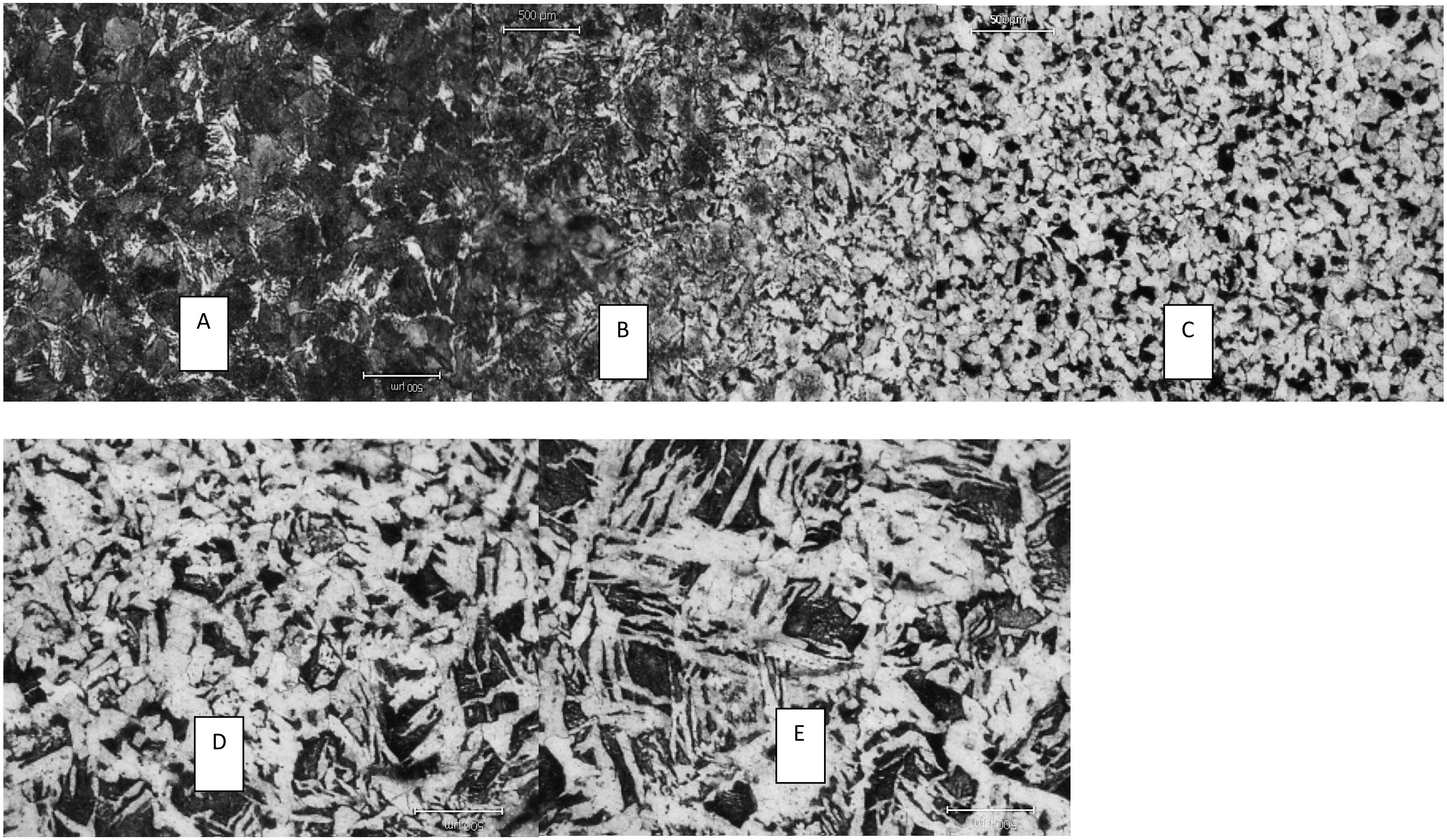


Fig 4.26. Optical micrograph of welded sample of imported low carbon steel. The regions A, B, C, D and E have been explained in the caption to Fig 4.24.

4.5.4 Welded and Heat-treated Imported Steel Sample

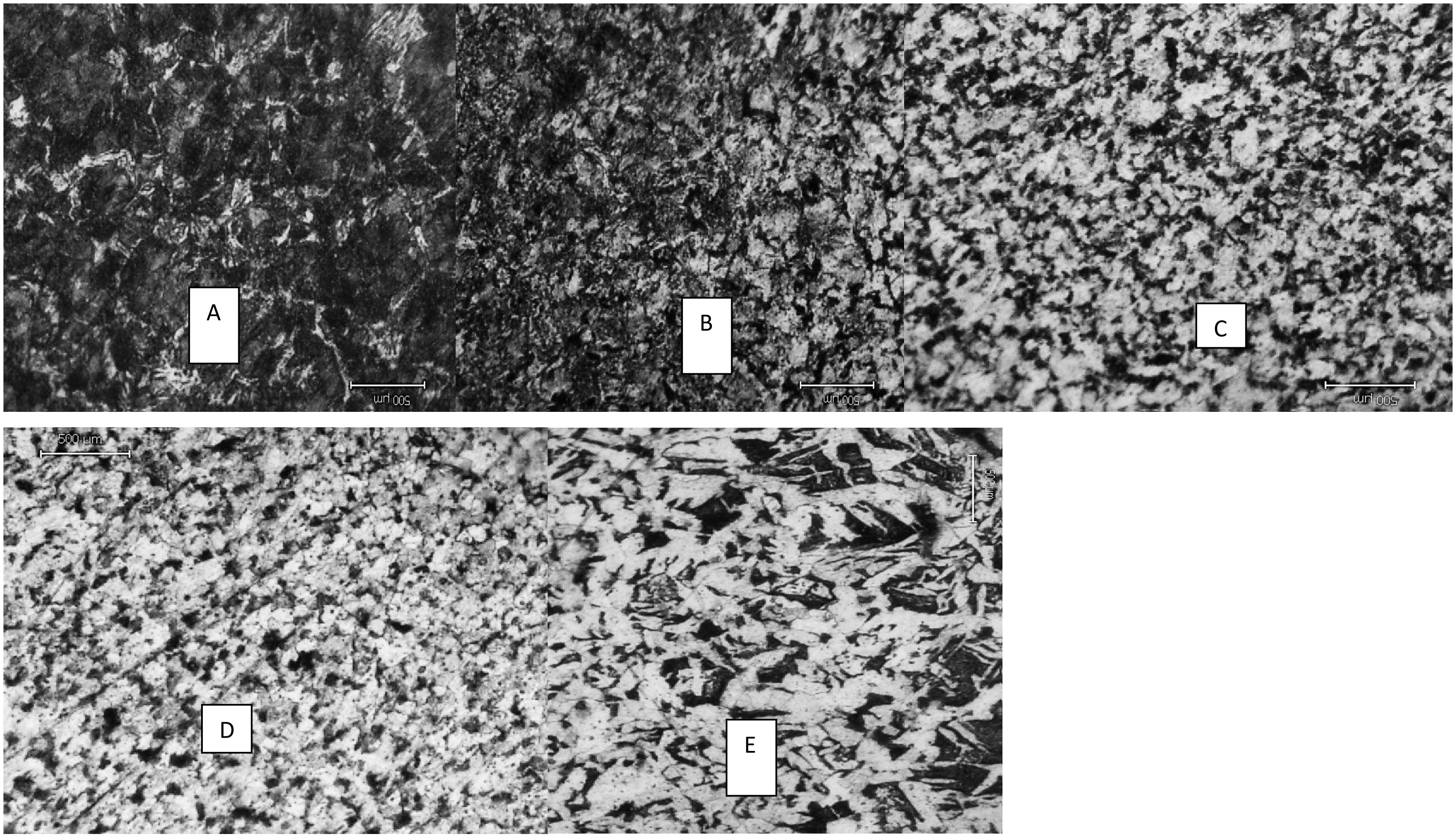


Fig 4.27 Optical micrograph of welded and heat-treated sample of imported low carbon steels. The regions A, B, C, D and E have been explained in the caption to Fig 4.24.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following are the conclusions of the research on the Metallurgical Studies of welded joints of local and imported low carbon steels on the Ghanaian market.

i. The contents of the main alloying elements, carbon and manganese, which determined strength and hardness of low carbon steels were higher in imported steels than in the locally produced steels. Average contents of 0.186% C and 0.543% Mn were recorded for imported steels; whereas locally produced steels contained 0.059% C and 0.295% Mn.

ii. The higher carbon and manganese contents in the imported steels accounted for their high UTS (689.00 ± 7.72 MPa), Yield Strength (541.60 ± 6.15 MPa), Moduli of Elasticity (244.00 ± 11.44 GPa) and Impact Strength (214.50 ± 5.57J), and lower ductility (23.66 ± 0.67%). Local steels had lower UTS (528.25 ± 13.66 MPa), Yield strength (381.75 ± 5.88 MPa), Moduli of Elasticity (240.25 ± 3.66 GPa) and Impact strength (160.67 ± 7.23 J) and higher ductility (28.03 ± 1.33%).

iii. When the steels were welded their UTS, Yield Strength, Moduli of elasticity, Ductility and Impact Strengths dropped significantly by 30.0%, 18.2%, 17.11%, 91.6% and 83.2% respectively for local steels. Imported steels recorded 51.0%, 50.0%, 11.07%, 88.0% and 80.7% drop in the UTS, yield strength, Young's modulus, percent elongation and impact strength respectively. On heat-treating the welded joints, only ductility and impact strengths were improved; 42.0% and 100.5%

respectively over welded for local steel and 47.3% and 125.1% for imported steel. Ultimate Tensile Strength, Yield Strength and Moduli of elasticity, however, deteriorated further. The effect of heat-treatment became more pronounced as the heat-treatment temperature approached the lower critical temperature.

iv. Welded joints of local steels rather had higher UTS and Yield Strength and lower ductility and impact strength than their imported steel counterparts unlike the un-welded samples where the reverse was the case.

v. All welded samples fractured at the joints. The fractured surfaces show ductile failure for un-welded samples and somewhat brittle failure for welded samples; the latter having some portions of smooth fractured surfaces.

5.2 Recommendations

Fatigue tests should be carried out on the welded joints since, mostly under service conditions, they are subjected to fluctuating loads. This kind of loading causes small cracks to grow during the life of the component and leads to fatigue failure. A detailed study of this crack growth measurement could prevent the failure with prediction. Also bend and hardness tests should be conducted for the welded joints to investigate a correlation between the two parameters. Microstructural examinations of the welded joints to confirm the surface hardness would be necessary.

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Appendix A

Tensile Test Results

Sample Id	Moduli of Elasticity, GPa	Yield Strength, MPa	UTS, MPa	% Elongation
$LC_{(1)}$	237.00	394.00	575.00	25.40
$LC_{(2)}$	231.00	393.00	519.00	30.10
$LC_{(3)}$	251.00	370.00	512.00	31.20
$LC_{(4)}$	242.00	370.00	507.00	25.40
$LC_{(Av)}$	240.25	381.75	528.25	28.03
$IC_{(1)}$	236.00	562.00	710.00	24.90
$IC_{(2)}$	238.00	523.00	677.00	23.40
$IC_{(3)}$	291.00	550.00	709.00	25.20
$IC_{(4)}$	213.00	531.00	668.00	21.00
$IC_{(5)}$	242.00	542.00	681.00	23.80
$IC_{(Av)}$	244.00	541.60	689.00	23.66
$LC^{450}{}_{(1)}$	209.00	353.00	518.00	29.50
$LC^{450}{}_{(2)}$	219.00	370.00	511.00	34.90
$LC^{450}{}_{(3)}$	213.00	360.00	513.00	31.40
$LC^{450}{}_{(4)}$	225.00	428.00	539.00	32.10
$LC^{450}{}_{(Av)}$	216.50	377.75	520.25	31.98

Sample Id	Moduli of Elasticity, GPa	Yield Strength, MPa	UTS, MPa	% Enlonogation
$IC^{450}_{(1)}$	198.50	489.00	600.00	29.20
$IC^{450}_{(2)}$	219.00	490.00	608.00	27.70
$IC^{450}_{(3)}$	229.00	498.00	611.00	29.60
$IC^{450}_{(4)}$	208.00	479.00	505.00	21.30
$IC^{450}_{(Av)}$	213.63	489.00	581.00	26.95
$LC^{550}_{(1)}$	248.00	336.00	492.00	32.20
$LC^{550}_{(2)}$	188.5.00	359.00	509.00	29.70
$LC^{550}_{(3)}$	214.00	363.00	509.00	34.10
$LC^{550}_{(Av)}$	216.83	352.67	503.33	32.00
$IC^{550}_{(1)}$	230.00	474.00	562.00	30.40
$IC^{550}_{(2)}$	225.00	432.00	535.00	31.70
$IC^{550}_{(3)}$	235.00	479.00	573.00	31.00
$IC^{550}_{(Av)}$	230.00	461.67	556.67	31.03
$LC^{650}_{(1)}$	221.00	329.00	480.00	34.80
$LC^{650}_{(2)}$	246.00	352.00	478.00	38.70
$L\ C^{650}_{(3)}$	201.00	336.00	481.00	35.80
$L\ C^{650}_{(4)}$	211.00	336.00	480.00	31.30
$LC^{650}_{(Av)}$	219.75	338.25	479.75	35.15

Sample Id	Moduli of Elasticity, GPa	Yield Strength, MPa	UTS, MPa	% Enlonogation
$IC^{650}_{(1)}$	256.00	411.00	487.00	35.90
$IC^{650}_{(2)}$	209.00	428.00	503.00	36.50
$IC^{650}_{(3)}$	223.00	433.00	510.00	31.50
$IC^{650}_{(4)}$	230.00	406.00	489.00	36.50
$IC^{650}_{(Av)}$	229.50	419.50	497.25	35.10
$LW_{(1)}$	195.60	331.00	377.00	6.08
$LW_{(2)}$	201.00	315.00	386.00	4.88
$LW_{(3)}$	202.00	279.00	318.00	4.36
$LW_{(4)}$	198.00	324.00	377.00	6.08
$LW_{(Av)}$	199.15	312.25	364.50	5.35
$IW_{(1)}$	210.00	278.00	373.00	2.81
$IW_{(2)}$	210.00	248.00	284.00	2.17
$IW_{(3)}$	210.00	321.00	421.00	3.48
$IW_{(4)}$	206.00	236.00	272.00	2.13
$IW_{(Av)}$	209.00	270.75	337.50	2.65
$LW^{450}_{(1)}$	203.00	315.00	350.00	2.82
$LW^{450}_{(2)}$	214.00	314.00	359.00	2.97
$LW^{450}_{(3)}$	202.00	320.00	381.00	3.80
$LW^{450}_{(Av)}$	206.33	316.33	363.33	3.20

Sample Id	Moduli of Elasticity, GPa	Yield Strength, MPa	UTS, MPa	% Enlonogation
$IW^{450}_{(1)}$	210.00	234.00	290.00	3.88
$IW^{450}_{(2)}$	182.90	220.00	265.00	3.25
$IW^{450}_{(Av)}$	196.45	227.00	277.50	3.57
$LW^{550}_{(1)}$	207.00	220.00	270.00	1.83
$LW^{550}_{(2)}$	193.00	296.00	320.00	2.10
$LW^{550}_{(3)}$	197.30	229.00	295.00	1.73
$LW^{550}_{(Av)}$	199.10	248.33	295.00	1.89
$IW^{550}_{(1)}$	207.00	242.00	350.00	12.50
$IW^{550}_{(2)}$	229.00	238.00	330.00	6.58
$IW^{550}_{(3)}$	216.00	235.00	325.00	2.71
$IW^{550}_{(4)}$	216.00	230.00	280.00	1.90
$IW^{550}_{(Av)}$	217.00	236.25	321.25	5.92
$LW^{650}_{(1)}$	206.00	272.00	303.00	2.24
$LW^{650}_{(2)}$	217.00	283.00	374.00	6.29
$LW^{650}_{(3)}$	141.60	138.50	148.90	1.48
$LW^{650}_{(Av)}$	188.20	231.17	275.30	3.34

Sample Id	Moduli of Elasticity, GPa	Yield Strength, MPa	UTS, MPa	% Enlonogation
$IW^{650}_{(1)}$	147.70	191.80	224.00	4.23
$IW^{650}_{(2)}$	202.00	248.00	287.00	4.88
$IW^{650}_{(3)}$	251.00	235.00	281.00	2.59
$IW^{650}_{(Av)}$	200.23	224.93	264.00	3.90
$LW^{450*}_{(1)}$	174.10	319.00	396.00	3.51
$LW^{450*}_{(2)}$	211.00	337.00	373.00	2.55
$LW^{450*}_{(3)}$	202.00	267.00	292.00	2.42
$LW^{450*}_{(Av)}$	195.70	307.67	353.67	2.83
$IW^{450*}_{(1)}$	202.00	223.00	281.00	3.12
$IW^{450*}_{(2)}$	223.00	278.00	339.00	3.45
$IW^{450*}_{(3)}$	208.00	246.00	260.00	2.05
$IW^{450*}_{(Av)}$	211.00	249.00	293.33	2.87
$LW^{550*}_{(1)}$	234.00	271.00	293.00	1.34
$LW^{550*}_{(2)}$	133.00	262.00	323.00	3.26
$LW^{550*}_{(3)}$	195.30	299.00	322.00	3.33
$LW^{550*}_{(4)}$	207.00	240.00	273.00	3.63
$LW^{550*}_{(Av)}$	192.33	268.00	302.75	2.89

Sample Id	Moduli of Elasticity, GPa	Yield Strength, MPa	UTS, MPa	% Enlonogation
$IW^{550*}_{(1)}$	201.00	233.00	291.00	4.00
$IW^{550*}_{(2)}$	207.00	237.00	293.00	4.10
$IW^{550*}_{(3)}$	210.90	156.70	169.60	3.39
$IW^{550*}_{(4)}$	209.00	228.00	255.00	3.89
$IW^{550*}_{(Av)}$	206.98	213.68	252.15	3.85
$LW^{650*}_{(1)}$	147.40	272.00	324.00	2.80
$LW^{650*}_{(2)}$	187.40	238.00	239.00	4.33
$LW^{650*}_{(3)}$	209.00	221.00	243.00	3.66
$LW^{650*}_{(4)}$	151.00	239.00	258.00	2.13
$LW^{650*}_{(Av)}$	173.70	242.50	266.00	3.23
$IW^{650*}_{(1)}$	230.00	269.00	337.00	4.11
$IW^{650*}_{(2)}$	190.50	172.40	201.00	3.67
$IW^{650*}_{(Av)}$	210.25	220.70	269.00	3.89

Appendix B

Impact Test Results

Sample Id	Impact strength/J
$LC_{(1)}$	168.00
$LC_{(2)}$	171.00
$LC_{(3)}$	143.00
$LC_{(Av)}$	160.67
$IC_{(1)}$	213.00
$IC_{(2)}$	204.00
$IC_{(3)}$	208.00
$IC_{(4)}$	233.00
$IC_{(Av)}$	214.50
$LC^{450}{}_{(1)}$	204.00
$LC^{450}{}_{(2)}$	213.00
$LC^{450}{}_{(3)}$	231.00
$LC^{450}{}_{(Av)}$	216.00
$IC^{450}{}_{(1)}$	294.00
$IC^{450}{}_{(2)}$	285.00
$IC^{450}{}_{(3)}$	332.00

Sample Id	Impact Strength/J
$IC^{450}_{(4)}$	295.00
$IC^{450}_{(Av)}$	301.50
$LC^{550}_{(1)}$	193.00
$LC^{550}_{(2)}$	218.00
$LC^{550}_{(3)}$	243.00
$LC^{550}_{(Av)}$	218.00
$IC^{550}_{(1)}$	319.00
$IC^{550}_{(2)}$	330.00
$IC^{550}_{(3)}$	333.00
$IC^{550}_{(4)}$	327.00
$IC^{550}_{(Av)}$	327.25
$LC^{650}_{(1)}$	312.00
$LC^{650}_{(2)}$	285.00
$L\ C^{650}_{(3)}$	346.00
$LC^{650}_{(Av)}$	314.33
$IC^{650}_{(1)}$	384.00
$IC^{650}_{(2)}$	398.00

Sample Id	**Impact Strength/J**
$IC^{650}_{(3)}$	365.00
$IC^{650}_{(4)}$	342.00
$IC^{650}_{(Av)}$	372.25
LW_1	28.00
LW_2	30.00
LW_3	23.00
LW_{Av}	27.00
IW_1	37.00
IW_2	26.50
IW_3	55.00
IW_4	47.00
IW_{Av}	41.38
$LW^{450}_{(1)}$	25.00
$LW^{450}_{(2)}$	30.00
$LW^{450}_{(3)}$	32.00
$LW^{450}_{(Av)}$	29.00
$IW^{450}_{(1)}$	54.00
$IW^{450}_{(2)}$	32.00
$IW^{450}_{(3)}$	28.50

Sample Id	**Impact Strength/J**
$IW^{450}_{(4)}$	55.50
$IW^{450}_{(Av)}$	42.50
$LW^{550}_{(1)}$	27.50
$LW^{550}_{(2)}$	84.00
$LW^{550}_{(3)}$	16.50
$LW^{550}_{(4)}$	16.50
$LW^{550}_{(Av)}$	36.13
$IW^{550}_{(1)}$	72.00
$IW^{550}_{(2)}$	71.00
$IW^{550}_{(3)}$	88.00
$IW^{550}_{(4)}$	35.50
$IW^{550}_{(Av)}$	66.63
$LW^{650}_{(1)}$	18.00
$LW^{650}_{(2)}$	62.00
$LW^{650}_{(3)}$	104.50
$LW^{650}_{(4)}$	32.00
$LW^{650}_{(Av)}$	54.13
$IW^{650}_{(1)}$	108.50
$IW^{650}_{(2)}$	35.00

Sample Id	**Impact Strength/J**
$IW^{650}_{(3)}$	145.00
$IW^{650}_{(4)}$	84.00
$IW^{650}_{(Av)}$	91.13
$LW^{450*}_{(1)}$	36.50
$LW^{450*}_{(2)}$	34.00
$LW^{450*}_{(3)}$	31.00
$LW^{450*}_{(4)}$	33.00
$LW^{450*}_{(Av)}$	33.63
$IW^{450*}_{(1)}$	37.00
$IW^{450*}_{(2)}$	35.00
$IW^{450*}_{(3)}$	42.00
$IW^{450*}_{(4)}$	41.00
$IW^{450*}_{(Av)}$	38.75
$LW^{550*}_{(1)}$	33.00
$LW^{550*}_{(2)}$	39.00
$LW^{550*}_{(3)}$	30.50
$LW^{550*}_{(4)}$	37.00
$LW^{550*}_{(Av)}$	34.88

Sample Id	Impact Strength/J
$IW^{550*}_{(1)}$	44.50
$IW^{550*}_{(2)}$	38.50
$IW^{550*}_{(3)}$	35.50
$IW^{550*}_{(4)}$	39.00
$IW^{550*}_{(Av)}$	39.38
$LW^{650*}_{(1)}$	41.00
$LW^{650*}_{(2)}$	44.00
$LW^{650*}_{(3)}$	45.00
$LW^{650*}_{(4)}$	39.00
$LW^{650*}_{(Av)}$	42.25
$LW^{650*}_{(1)}$	45.00
$LW^{650*}_{(2)}$	47.50
$LW^{650*}_{(3)}$	41.50
$LW^{650*}_{(4)}$	42.00
$LW^{650*}_{(Av)}$	44.00

Appendix C

Error Calculations

The errors in the UTS, Yield strengths, Impact strengths, Moduli of elasticity and Percent elongations were calculated using an inbuilt formula in Microsoft Excel which first calculates the standard deviation of a data set followed by the standard error. The data for the error calculations were exported into excel. The inbuilt formula for the computation of the standard deviation σ, of a data set is

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2},$$

Where $x_1, \ldots, x_N$ are the N elements in the data set having a mean of $\overline{x}$.

The error, s, was computed from the formula

$$s = \sigma/\sqrt{N}$$

Computing the error in the UTS of local steel "as-received" (LC):

Arithmetic Mean ($\overline{x}$) = (237 + 231 + 251 + 242)/4 = 240.25

x	$(x_i - \overline{x})$	$(x_i - \overline{x})^2$
237	-3.25	10.5625
231	-9.25	85.5625
251	10.75	115.5625
242	1.75	3.0625
		$\Sigma(x_i - \overline{x})^2 = 214.75$

$$\sigma = \sqrt{(214.75/4)} = 7.33 \text{ to 3 s.f.}$$

Appendix D

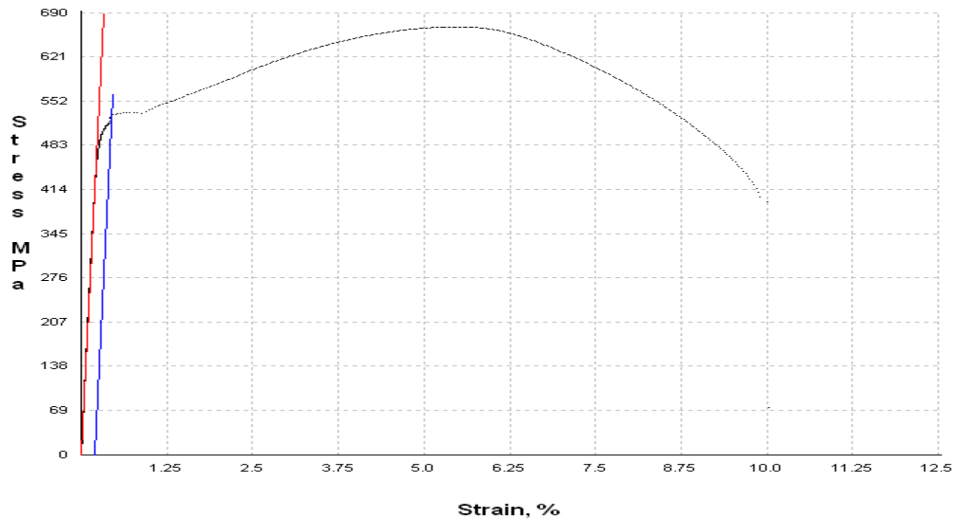

Fig 1 Stress-strain curve of as-received imported steel (0.19% C) sample, showing the stresses in the full range of the strain

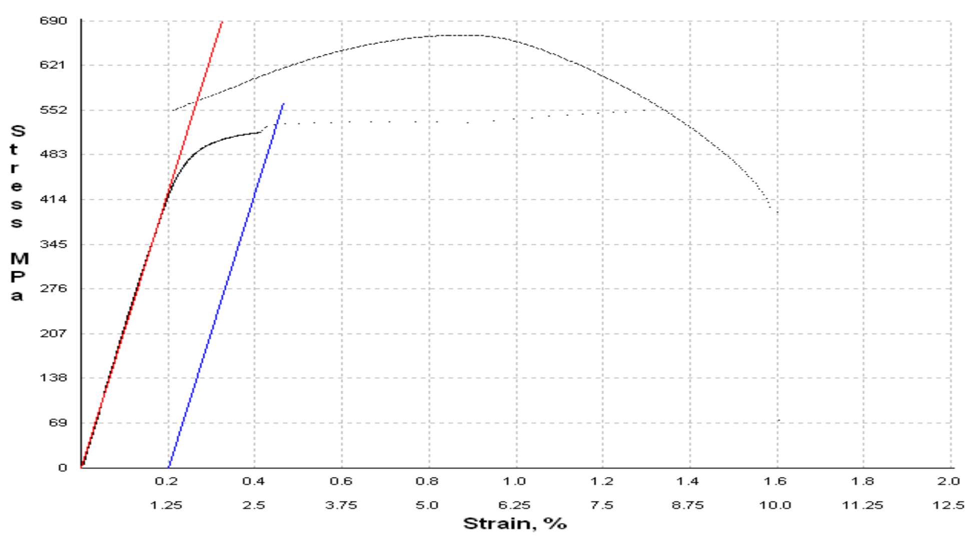

Fig 2 Stress-strain curve of as-received imported steel (0.19% C) sample, showing a magnified linear section (in red) and the 0.2% proof stress

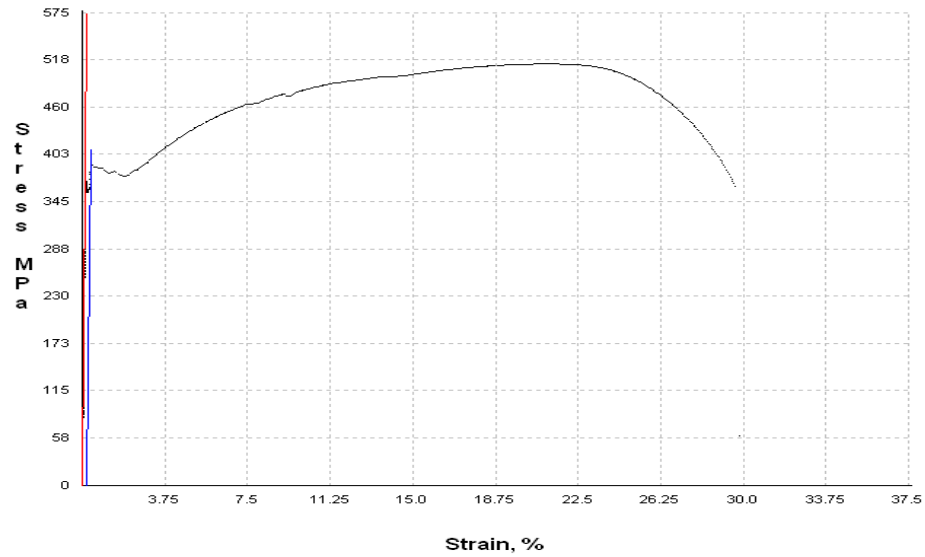

Fig 3 Stress-strain curve of as-received local steel (0.06% C) sample, showing the stresses in the full range of the strain

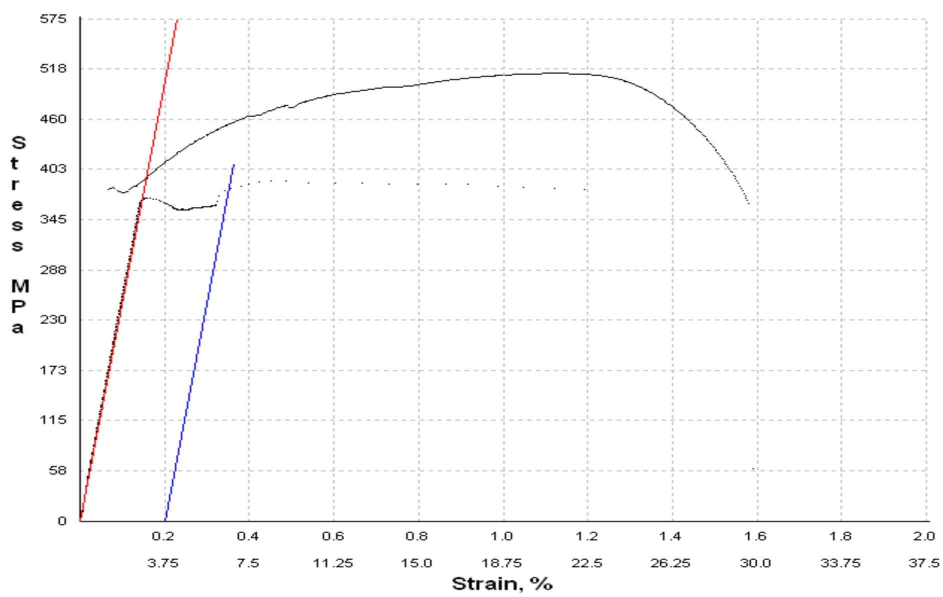

Fig 4 Stress-strain curve of as-received local steel (0.06% C) sample, showing a magnified linear section (in red) and the 0.2% proof stress

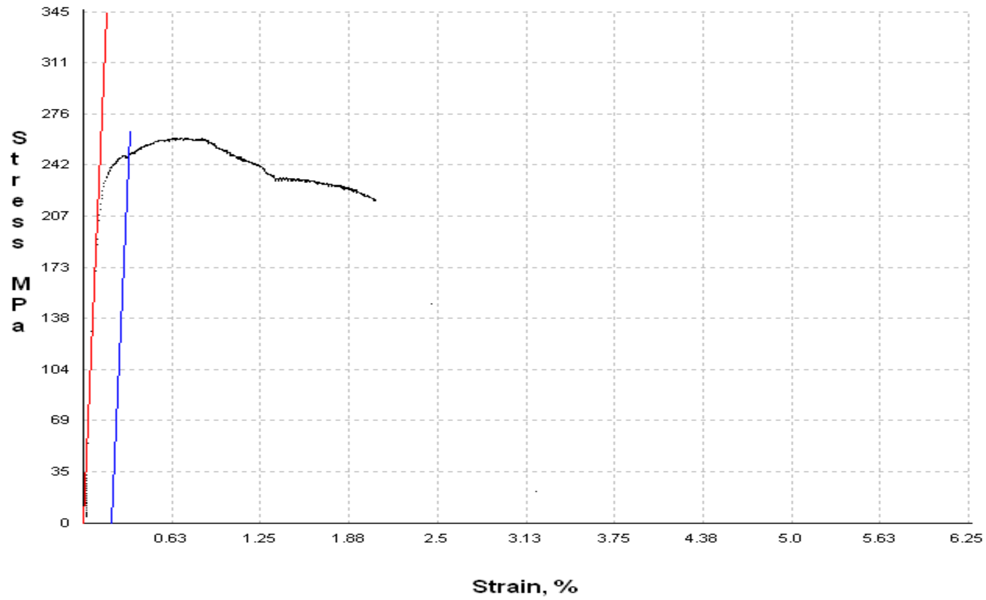

Fig 5 Stress-strain curve of welded imported steel sample (0.19% C), showing the stresses in the full range of the strain

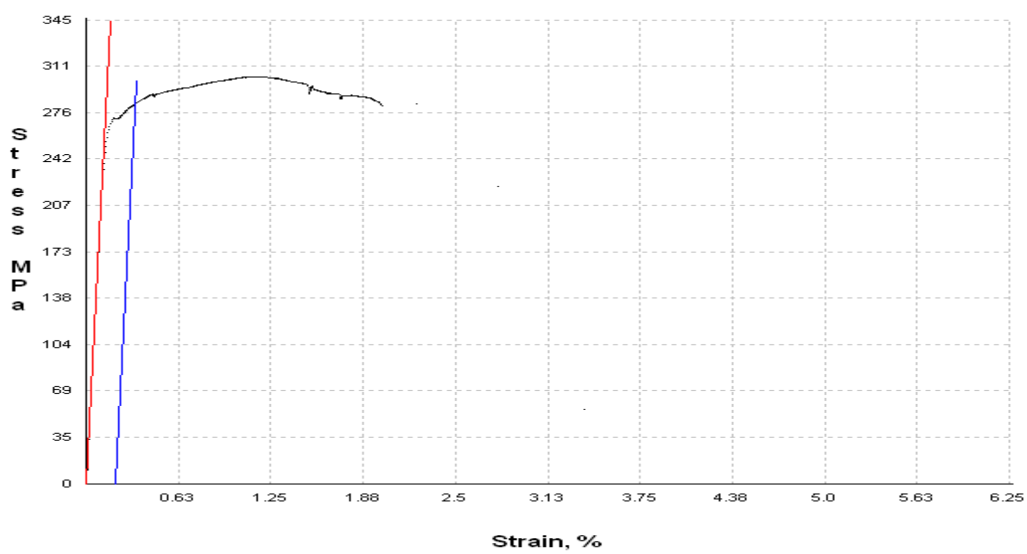

Fig 6 Stress-strain curve of welded local steel sample (0.06% C), showing the stresses in the full range of the strain

Appendix E

Pictures of fractured surfaces

(a)

(b)

Fig.1Pictures showing surfaces of (a) fractured un-welded and (b) fractured welded sample after the test