INVESTIGATION OF EFFECT OF HARDENING HEAT TREATMENT ON THE STRENGTH, WEAR AND CORROSION RESISTANCE OF 0.44% C STEEL FOR PRODUCING AGRICULTURAL IMPLEMENTS

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CERTIFICATION

This is to certify that the seminar titled **INVESTIGATION OF EFFECT OF HARDENING HEAT TREATMENT ON THE STRENGTH, WEAR AND CORROSION RESISTANCE OF 0.44% C STEEL FOR PRODUCING AGRICULTURAL IMPLEMENTS** was presented by **AKPOGUMA EJOVI FELIX** with Matriculation number **PG-ENG1715335**, Department of Mechanical Engineering (Industrial Metallurgy and Corrosion Management) Faculty Of Engineering, University Of Benin,

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ABSTRACT

The importance of steel cannot be over-emphasized, especially in the field of agricultural planting, harvesting and processing. Medium-carbon steel being more prevalent in use for tool steel and machine parts was adopted for this study. This research was aimed at investigating the mechanical properties (hardness and impact strength) as well as wear and corrosion resistance of medium carbon steel for producing agricultural farm implements, thus, microstructure analysis was also carried out for further investigation.

The medium carbon steel as received was prepared in line with every ASTM standard procedure through sizing, cutting and cleaning before heat treatment. During hardening, the prepared specimens were heated in an electric furnace for a soaking time of one hour, thirty minutes, and then quenched with water for approximately 30 minutes. Afterwards, samples were then used exclusively for the hardness, impact strength, wearing resistance and corrosion resistance in line with ASTM specification.

After conducting the hardness test, an approximate hardness for the treated material is 2092.4 N/mm^2 as compared to the "as-received" value that was 1307.6 N/mm^2; thereby indicating a significant increase in the hardness of the material. Impact test conducted gave an approximated result of 14.7 J; thereby depicting the energy absorption capability of this medium carbon steel alloy. Wear rate of approximately 25 % was reduced for the hardened medium carbon steel in comparison to the untreated steel.

After testing for corrosion resistance of the steel in a corrosive acidic chloride environment, results obtained showed that the heat treatment process enhanced corrosion resistance of the medium carbon steel samples in the medium. The micrographs obtained showed that the grain boundaries of this material were

greatly attacked by this environment. The corrosion product at these grain boundaries were suspected to be precipitates of metallic inclusion.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Agricultural mechanization today has been viewed in several regards; These versed views include production, distribution and utilization of a variety of tools, machinery and equipments for the development of agricultural land, planting, harvesting and primary processing (Haruna & Junior, 2013). Today, development of agricultural mechanization has immensely implied improvement of agricultural techniques to ensure sustainability of agricultural system and food security. Evidence suggests that mechanization has a major impact on demand and supply of farm labour, agricultural profitability, and a change in rural landscape as well as a nation's economic viability if agriculture is a great part of its common wealth; Agricultural mechanization thus, can be defined as an economic application of engineering technology to increase the labour efficiency and productivity of agricultural practice system. The importance of steel cannot be over-emphasized, considering the ever-vast applications of steel to our everyday lives. It is generally believed that if a product is not made of steel, the chances are that it will be made from a machine made of steel. In agriculture, from basic hoes, shovels and forks, to modern ploughs, irrigation systems and grain storage silos, steel is employed for almost every step of the way, making agriculture easier and more efficient; Agriculture without steel is definitely then unimaginable. From tilling the land and planting seeds to watering, harvesting, storing and transporting crops, steel is vital. Steel also facilitates the feeding, shelter and transportation of livestock. The machines and equipment that process what we eat and drink are majorly also made with steel (Uddeholm, 2021). Steels used for manufacturing of parts are commonly called “tool steels”. They differ from other steels by their special performance, which is achieved through applying specific alloy contents and microstructures. This gives them unique properties such as high hardness and resistance to heat, wear and corrosion (Uddeholm, 2021). Addition of alloys to the base steel is necessary in order to shape and form often millions of parts for the end products each with the same quality and tolerance. The contemporary farming condition or particular agricultural processing phase will depict the type of steel that would be employed based on inherent material properties; even though some basic properties must always be a prerequisite. These properties would include mechanical strength, wear resistance as well as corrosion resistance.

Steel, being an alloy of carbon and iron is generally classified based on some criteria such as its manufacturing process, carbon content, alloying content, method of forming or even its uses. The strength, durability of implements and machines depend upon material used in their fabrication. The strength of the material is thus measured by the amount of stress that it can bear when subjected to some working conditions (Shah, 2021). Even though measures of mechanical properties of materials would include the various types of strengths, brittleness, malleability, ductility, creep, impact, fatigue, toughness, hardness, elasticity, etc. (Saif, 2020), the most important to agricultural tools are the hardness and impact strength (Shah, 2021).

Medium-carbon steel has witnessed immense application in the agricultural sector has approximately 0.3–0.6% carbon content. These alloys may be heat-treated by austenitizing, quenching and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructures of tempered martensite (William & David, 2013). Medium-carbon steel generally balances ductility and strength and has good wear resistance. This grade of steel is mostly used in the production of machine components, shafts, axles, gears, crankshafts, coupling and forgings; it has also found ample applications in rails, railway wheels, several advanced machine parts and high-strength structural components; thereby displaying a combination of high strength, wear resistance as well as toughness (Ashby, Shercliff, &Cebon, 2007). The consideration for impact strength on agricultural steel is very critical; considering the exposure of these parts to a dynamic working condition of the soil while deployed to service. Impact strength, also called impact toughness is essentially seen as the amount of energy that a material can withstand when a load is suddenly applied on it. It may also be seen as the threshold of force per unit area before the material undergoes fracture. Some of the factors that affect impact strength include temperature and material thickness; meanwhile, other intrinsic factors that dictate a material's impact resistance include topology, in which impact resistance is inversely proportional to the material's crystallinity and the amount of voids, and molecular weight, where a higher molecular weight enhances the material's impact resistance. In this regard, the morphology of the medium carbon steel would be studied critically in this work.

Wear-resistant steel, also called abrasion-resistant or AR steels, are generally made from steel billets and come in many grades (SSAB, 2021). Alloys like carbon, manganese, nickel, chrome and boron are essentially added in different proportions to build this class of steel. The grades therefore have different mechanical and chemical properties that will produce different results in an end product. Carbon plays a key role in making the steel wear-resistant because it increases the steel's hardness and toughness. But too much carbon alloy will reduce the steel's tensile strength, making it brittle and susceptible to cracking (SSAB, 2021); as such the carbon is well optimized while producing the steel for some specific applications. On the other hand, corrosion may be broadly seen as the destruction or deterioration of metal by direct chemical and electrochemical reaction with its environment. Most simply stated, metallic corrosion is the reverse of electroplating (Uzorh, 2013); the metal being corroded forms the anode while the cathode is that being electroplated. Metallic corrosion occurs because in many agriculturalenvironments, most metals are not inherently stable and tend to revert to some more stable combination as the metallic ores found in nature.

In lieu of the statements above, this research sees to investigating the topology, mechanical properties as well as wear and corrosion resistance of medium carbon steel for agricultural machinery applications

1.2 Statements of the Problem

The performance characteristics of the agricultural equipment's metallic parts are sometimes, extremely different even, in some ways, conflicting with each other. The careful selection of special and high-strength steels allows to effectively reconcile the various needs for the particular agricultural application. In this regard, the demand for medium carbon low alloy steels is progressively increasing in automotive, aerospace, defense, and other industries; owing to their superior mechanical properties, excellent fracture toughness, and high fatigue resistance and wear resistance. Therefore, the steels used for agricultural machinery/implements, certainly cannot be of a common type, but rather should possess specific characteristics, which sometimes may seem in conflict with each other; (i.e. it becomes extremely difficult to bring together in a single material, outstanding quality of toughness, tenacity, wear and corrosion resistance, and at the same time elasticity, ductility, and ease of processing).

Sustainability of any economy around the globe has always been tied to level of production of that nation. Studies have clearly shown that major mechanized agricultural implements used in Nigeria are often imported and that has created a negative productivity growth in the agricultural sector that has a major stake in the Gross Domestic Product (GDP) of the country. Generally, the life cycle of agricultural implements completely depends on several factors like the strength, wear and corrosion resistance of the material used due to problems associated with surface-soil interaction. Basic requirements of finished agricultural implements for normal soil are generally high hardness and high abrasion resistance in addition to excellent corrosive resistance. In an attempt to domesticate production of these agricultural implements, there is then the need for local production of the steel to be used in producing these farm implements.

To this end, developing countries, on their path to achieving food security, need to design their own strategies for agricultural mechanization or other related agricultural issues because achieving food security in an environmentally sustainable way is one of the greatest challenges of developing nations.

1.3 Aim and Objectives

1.3.1 Aim

The aim of this research is to investigate effect of hardening heat treatment on strength, wear and corrosion resistance of medium carbon steel for producing agricultural implements.

1.3.2 Objectives

The specific objectives:

i. Determine the mechanical properties of the test samples.
ii. Evaluate the corrosion characteristics of the test samples.
iii. Examine the micro structural characteristics of the test samples,

1.4 Justification

Medium carbon steels are widely used for many industrial applications and manufacturing on account of their low cost and ease of fabrication. Hence considering the excessive availability of these steels around our contemporary environment, it then justifies its use. In lieu of our present economic situation in Nigeria, surely mechanized agriculture would assist immensely in GDP of the Nation. A better developed material tailored for some specific application would enhance the working performance of the farm implement while deployed to service.

1.5 Scope of the Study

The scope of this research covers and limited to using o.44 %C steel, samples are prepared by cutting into 40mm test piece. The test samples were heated in electric arc furnace to austenizing temperature (950^0 C) for 1 hour 30 minutes and quenched in a water bath for 30 minutes. Determination of mechanical properties (hardness, impact strength and wear resistance) respectively, Corrosion rate evaluation is carried out using the weight loss method in an acidic chloride environment for 100 days, then micro-structural characteristics of the corrosion test samples examined.

CHAPTER TWO

LITERATURE REVIEW

2.1 Steel Overview

Steel, being an alloy of majorly iron and carbon contains carbon content ranges up to approximately 2 percent; in most situations, the material is seen as cast iron and no more steel once the carbon content is superseding this percent (Nutting, 2021). Steel is by far the most widely used material for building the world's infrastructure and industries, it is used to fabricate everything from as small as sewing needles to as large as oil tankers. In addition, the tools required to build and manufacture such articles are also made of steel (Nutting, 2021). As an indication of the relative importance of steel, in 2013 the world's raw steel production was about 1.6 billion tons, while production of the next most important engineering metal, aluminum, was about 47 million tons. Steel became very popular and so relevant for critical reasons such as the relatively low cost of making, forming, and processing it, the abundance of its two raw materials (iron ore and scrap), and its unparalleled range of mechanical properties (Nutting, 2021). The major component of steel is iron. Omitting very extreme cases, iron in its solid state is, like all other metals, polycrystalline; hence consisting of many crystals that join one another on their boundaries. A crystal is simply regarded as a well-ordered arrangement of atoms that can best be pictured as spheres touching one another (Lower, 2021). They are ordered in planes, called lattices, which penetrate one another in specific ways. For iron, the lattice arrangement can best be visualized by a unit cube with eight iron atoms at its corners. Steel is such a powerful element, thereby existing in several distinct grades and holding unique chemical compositions. Generally, these steels differ in characteristics and application majorly because of the exclusive additions of carbon contents as well as other alloying elements such as manganese and phosphorus that are introduced during its formulation. In lieu of these, steels are generally categorized in four classes as discussed thus (Weerg, 2021).

2.1.1 Carbon Steel

Carbon steel looks dull, matte-like, and is known to be vulnerable to corrosion. Overall, there are three subtypes to this one: low, medium, and high carbon steel, with low containing about 0.3% of carbon, medium about 0.6%, and high about 1.5%. These steels contain a very small amount of other alloying elements; they are exceptionally strong, which is why they are often used to make things like knives, high-tension wires, automotive parts, and other similar items. Carbon steels have been recorded to make up about 90% of all steel production around the globe; figure 2.1 shows an industrial application of carbon steel.

Figure 2.1 Machine application of C45/AISI 1045 steel (a medium carbon steel); suitablefor part such as gears, bolts, general-purpose axles and shafts, keys and studs.(Source: Weerg, 2021).

2.1.2 Alloy Steel

Alloy steel is generally a mixture of several different metals, like nickel, copper, and aluminium. These tend to be more on the cheaper side, more resistant to corrosion and are favoured for some car parts, pipelines, ship hulls, and mechanical projects. For alloy steels, the strength dependson the concentration of the elements that it contains. Figure 2.2 shows an industrial application of alloy steel.

Figure 2.2 Machine application of AISI 4317/18NiCrMo5 alloy steel having high corestrength and toughness: used on heavy duty bearings, cam followers, clutch dogs, compressor colts, fan shafts, heavy duty gears, pump shafts

2.1.3 Tool Steel

Tool steel generally refers to a variety of carbon steel and alloy steel that are particularly well-suited to be made into tools. Their suitability comes from their distinctive hardness, resistance to abrasion and deformation, and their ability to hold a cutting edge at elevated temperatures. As a result, tool steels are suited for use in the shaping of other materials. With carbon content between 0.5% and 1.5%, tool steels are manufactured under carefully controlled conditions to produce the required quality. The presence of carbides in their matrix plays the dominant role in the qualities of tool steel. The four major alloying elements amongst others that form carbides in tool steel are: tungsten, chromium, vanadium and molybdenum. The rate of dissolution of the different carbides into the austenite form of the iron determines the high-temperature performance of steel (slower is better, making for a heat-resistant steel). Proper heat treatment of these steels is important for adequate performance (Verhoeven, 2007)

2.1.4 Stainless Steel

Stainless steels are probably the most well-known type on the market majorly because of food processing or aesthetic concerns. This type of steel is shiny and generally has around 10 to 20% chromium, which is their main alloying element. With this combination, it allows the steel to be resistant to corrosion and very easily moulded into varying shapes. Because of their easy manipulation, flexibility, and quality, stainless steel can be found in surgical equipment, home applications, silverware, and even implemented as exterior cladding for commercial/industrial buildings. Different types of stainless steel would include the elements carbon (from 0.03% to greater than 1.00%), nitrogen, aluminium, silicon, sulphur, titanium, nickel, copper, selenium, niobium, and molybdenum (International Stanless Steel Forum, 2016); hence there exist over 100 grades of stainless steel, making it an incredibly versatile, customizable material.

2.2 Overview of Carbon Steel

Carbon steel, or plain-carbon steel, is a metal alloy. It is a combination of two elements, iron and carbon. It is separated into three main subcategories; high carbon steel, medium carbon steel, and low carbon steel, even though ultra-low and extra-low have been also classified in recent studies (Masteel, 2018). Carbon steel thus unites the malleability of iron with the high strength of carbon. While it is brittle at first, carbon steel can be heat-treated into a formable state for the production of custom shapes and plates. It preserves its high toughness and tensile strength during the entire heat treatment processes, but its surface layer will afterwards be susceptible to corrosive elements, such as weathering and oxidization. Carbon steel can be produced from recycled steel, virgin steel or a combination of both. Virgin steel is made by combining iron ore, coke (produced by heating coal in the absence of air) and lime in a blastfurnace at around 1650 °C. The molten iron extracted from the iron ore is enriched with carbon from the burning coke. The remaining impurities combine with the lime to form slag, which floats on top of the molten metal where it can be extracted. The resulting molten steel contains roughly 4 wt.% carbon. This carbon content is then reduced to the desired amount in a process called decarburization. This is achieved by passing oxygen through the melt, which oxidizes the carbon in the steel, producing carbon monoxide and carbon dioxide (Matmatch, 2021).

2.2.1 Low Carbon Steel

Low-carbon steel is the most widely used form of carbon steel. These steels usually have a carbon content of less than 0.25 wt.%. They cannot be hardened by heat treatment (to form martensite) so this is usually achieved by cold work. Carbon steels are usually relatively soft and have low strength. They do, however, have high ductility, making them excellent for machining, welding and low cost. High-strength, low-alloy steels (HSLA) are also often classified as low-carbon steels, however, also contains other elements such as copper, nickel, vanadium and molybdenum. Combined, these comprise up to 10 wt. % of the steel content. High-strength, low-alloy steels, as the name suggests, have higher strengths, which is achieved by heat treatment. They also retain ductility, making them easily formable and machinable. HSLA are more resistant to corrosion than plain low-carbon steels. Low carbon steels are often used in automobile body components, structural shapes (I-beams, channel and angle iron), pipes, construction and bridge components, and food cans (Matmatch, Matmatch, 2021).

2.2.2 Medium Carbon Steel

Medium-carbon steel has a carbon content of 0.25 - 0.60 wt. % and a manganese content of 0.60 – 1.65 wt. %. The mechanical properties of this steel are improved via heat treatment involving austenitizing followed by quenching and tempering, thereby giving them a martensitic microstructure. Heat treatment can only be performed on very thin sections, however, additional alloying elements, such as chromium, molybdenum and nickel can be added to improve the steels ability to be heat treated and thus, hardened. Hardened medium carbon steels have greater strength than low-carbon steels; however, this comes at the expense of ductility and toughness. As a result of their high strength, resistance to wear and toughness, medium carbon steels are often used for railway tracks, train wheels, crankshafts, gears and machinery parts requiring this combination of properties (Matmatch, 2021).

2.2.3 High Carbon Steel

High-carbon steel has a carbon content of 0.60 - 1.25 wt. % and a manganese content of 0.30 – 0.90 wt. %. It has the highest hardness and toughness of the carbon steels and the lowest ductility. High-carbon steels are very wear-resistant as a result of the fact that they are almost always hardened and tempered. Tool steels and die steels are types of high-carbon steels, which contain additional alloying elements including chromium, vanadium, molybdenum and tungsten. The addition of these elements results in the very hard wear-resistant steel, which is a result of the formation of carbide compounds such as tungsten carbide. Due to their high wear-resistance and hardness, high-carbon steels are used in cutting tools, springs high strength wire and dies (Matmatch, 2021).

2.2.4 Medium Carbon Steel for Agricultural Application

The most popular materials for agricultural soil cutting tools are medium carbon steels with the addition of manganese and silicon, usually 18G2, 40GS and 38GSA. Although the alloyed steels with high abrasive and corrosion resistance are excellent alternatives, but are seldom applied due to high costs. The work conditions of agricultural tools are particularly difficult. The working elements for example of tools for the tillage of soil undergo wear mainly because of the abrasive influence on their surface of the hard-mineral particles. Hence, manufacturersgenerally deliver tools of a low hardness of 200–250 HV or a hardness of up to 400–550 HV. Heat treatments generally applied to this type of steels are usually full quenching and tempering or surface hardening. Most of the fast wearing components of agricultural machines like plough share, cultivator sweep, rotavator blade, weeder blade, thresher pegs are made up of various grades of medium carbon steel. High strength and abrasive wear resistance is primary requirement for these components to overcome abrasive wear, fatigue and chemical reaction during operation (Singh, Saha, &Mondal, 2014)

2.3 Mechanical properties of Metals

The mechanical properties of metals determine the range of usefulness of the metal and also establishes the service that can be expected when deployed to service; thus, it will include how they deform (twist, compress, elongate) or break as a function of applied temperature, time, load and other conditions. Mechanical properties are very important, considering that they are also used to help specify and identify the metals. Generally, mechanical properties are characterized by stress and strain (tension, compression, shear, torsion), elastic deformation and plastic deformation (yield strength, tensile strength, ductility, toughness, hardness). The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions. Although more than 30 mechanical properties of metals exist, only hardness and Impact Strength would be discussed herein considering the scope of this present research.

2.3.1 Hardness

Hardness is one very critical mechanical property for agricultural machinery steels. Hardness is generally a measure of the resistance to localized plastic deformation induced by either mechanical indentation or abrasion; this mechanical property is also dependent on other material properties such as ductility, elastic stiffness, plasticity, strain, strength, toughness, viscoelasticity, and viscosity. Generally, in measuring or evaluating hardness of materials, three main types of hardness measurements have been established: scratch, indentation, and rebound. Within each of these classes of measurement are individual measurement scales, hence for practical reasons, conversion tables are used to convert between one scale and another (Samuel, 2009). In line with engineering practice, the indentation had found more relevant applications compared to the other two types. Indentation hardness measures the resistance of a sample to material deformation due to a constant compression load from a sharp object; hence the test is based on measuring the critical dimensions of an indentation left by a specifically dimensioned and loaded indenter. Common indentation hardness scales are Rockwell, Vickers, Brinell amongst others (Samuel, 2009).

2.3.1.1 Rockwell Hardness Test

In this test, an indenter is forced into the surface of a test piece in two operations, measuring the permanent increase in depth of an indentation from the depth increased from the depth reached under a datum load due to an additional load. Measurement of indentation is made after removing the additional load. Indenter used is the cone having an angle of 120 degrees made of black diamond. The principle of Rockwell hardness test has to do with the application of a standard load (Based on the type of material) through a standard indenter (cone or ball indenter) for a standard duration of time. The hardness number is directly obtained in the experiment. The Rockwell hardness is then derived from the measurement of the depth of the impression as thus:

i. EP = Depth of penetration due to Minor load of 98.07 N
ii. Ea = Increase in depth of penetration due to Major load
iii. E = Permanent increase of depth of indentation under minor load at 98.07 N even after removal of Major load.

Essentially, Rockwell hardness test is a quick test mainly used for metallic materials and is generally used for larger sample geometries. It can also be used for advanced tests, such as the Jominy (end quench) test (HRC) (Obianyo, 2019). The machine used for this test is seen in figure 2.3.

Figure 2.3 Rockwell Hardness Testing Machine (Source: Obianyo, 2019)

2.3.1.2Brinell Hardness Test

The Brinell Hardness Test is used to determine the Hardness Number of hard, moderately hard, and soft material E.g.: Brass, Bronze, Aluminium, Gold, and Copper. Very hard material and Brittle material cannot be tested by Brinell hardness tester. Brinell hardness number (BHN) is obtained by the ratio of the calculated load and the spherical area of the Indentation or Impression made on the specimen by the corresponding Indenter Ball. In Brinell hardness test, a steel ball of diameter (D) is forced under a load (F) on to a surface of the test specimen. Mean diameter (d) of indentation is measured after the removal of the load (P). The Brinell Hardness Number (BHN) is obtained by dividing the applied force P, in kg-F; by the curved surface area of the indentation, which is actually a segment of a sphere (Obianyo, 2019).

2.3.1.3 Vickers Hardness Test

Very Hard materials like Mild steel, case hardened steel, amongst several others can also be tested by the Vickers method. This test is similar to the Brinell hardness test; although having similar relationship, tends to eliminates most of the errors of the Brinell test. The produced impression is projected onto a focusing screen and the diagonals of the impression are measured by means of the measuring equipment. Due to small impressions, it is very suitable for testing polished and hardened material surfaces. This test is rapid and accurate. The required load as calculated by P/D2 ratio is applied on the specimen for a standard time of 8-10 seconds and VHN is calculated by the ratio of load and the spherical area of indentation. The diameter of the indentation is measured on the focusing screen of the machine. Suitable Application of the Vickers hardness test is seen in it being very resourceful for testing of all solid materials, including metallic materials. It can also be used for a sub-group of hardness testing of welds. A recent Vickers Hardness testing machine is seen in figure 2.4

Figure 2.4 Vickers Hardness Testing machine

2.3.2 Impact Strength

Impact strength is essentially the amount of energy that a material can withstand when the said load is suddenly applied to it. It may also be defined as the threshold of force per unit area before the material undergoes fracture (Matmatch, 2021). In contrast to method of determining other mechanical strengths of materials such as tensile, yield, creep amongst others, impact strength involves the application of force upon the test material in mere milliseconds or less; hence the near-instantaneous implementation of load then causes the material to absorb the energy. When the amount of energy exceeds that which it can accommodate, the material will then experience fracture, tear, or damage. Thus, it will be said that the impact strength of the material has been surpassed. Although hardness and impact strength are very much closely related, it is a general misconception is that materials with high impact strength also have a high degree of hardness. Some of the factors that affect impact strength include:

i. temperature: impact strength increases with increasing temperature
ii. material thickness: increasing the thickness reduces impact strength
iii. notch radius: a smaller notch tip radius lowers the impact strength.

Meanwhile, other intrinsic factors that dictate a material's impact resistance include topology, in which impact resistance is inversely proportional to the material's crystallinity and the number of voids, and molecular weight, where a higher molecular weight enhances the material's impact resistance (Kutz, 2005). Hence an impact load exceeds the impact strength; the material may exhibit any of the following types of failures: brittle fracture, slight cracking, ductile fracture and possibly yielding also. A material's impact strength or toughness may be measured either by using Charpy Impact testing or the Izod Testing method.

2.3.2.1 Charpy impact test

The Charpy impact test makes use of a pendulum arm attached to a pre-calibrated energy gauge. Thus, the material specimen is customized to take the shape of a bar with a small V- or U-shaped notch in the middle. Figure 2.5 shows the device and method for conducting the Charpy impact test. In conducting this experiment, the pendulum arm is set at a particular position correspondent to an energy setting, the arm is then released and its hammer end is allowed to hit the centre of the specimen. The impact strength of the material is determined by the amount of energy needed to break or fracture the specimen.

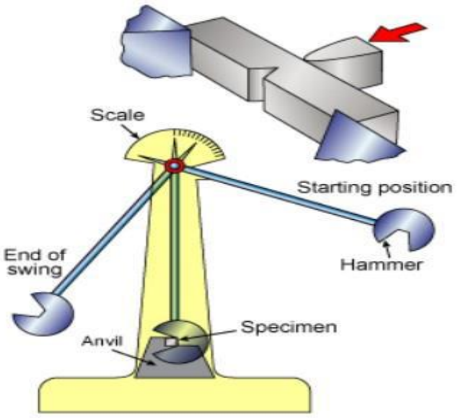

Figure 2.5 Schematic of a Charpy impact test machine also showing how the specimen is placed

2.3.2.2Izod test

This kind of impact test is similar to the Charpy test in the sense that it also uses a hammer attached to a pendulum arm to hit a custom-made specimen bar and measure the energy needed to fracture it. The main difference between the Izod test and the Charpy test is the orientation of the specimen in the measuring equipment. While the specimen is set horizontally in the Charpy impact test, the Izod test examines a vertically positioned sample with a V-Notch. Here, the pendulum hammer is made to strike the upper tip of the notched specimen. Figure 2.6 shows the device and method for conducting the Izod impact test.

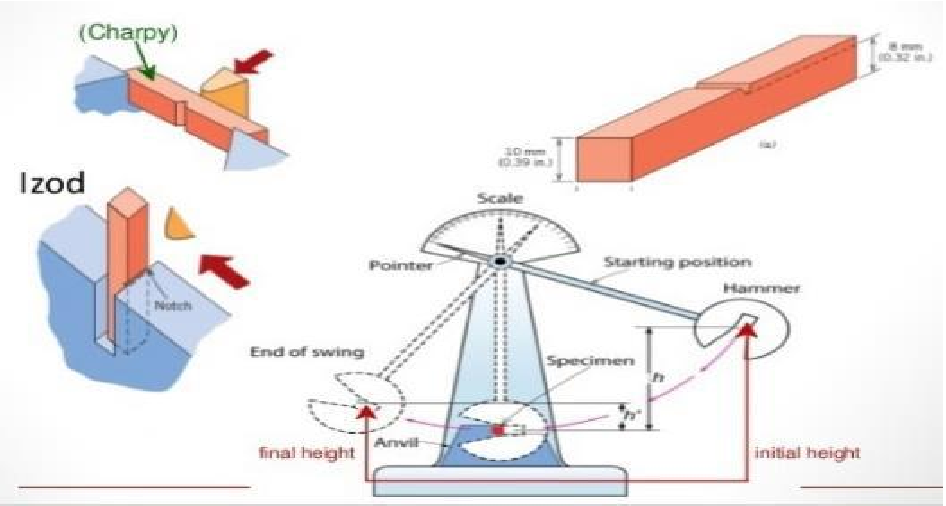

Figure 2.6 Schematic of an Izod impact test machine also showing how the specimen is placed

Other differences between the Charpy and the Izod impact tests could include the specimen size, notch face direction, type of hammer, and type of tested material. Essentially, the Charpy test examines metal specimens with the notch facing away from a striking ball peen hammer. The Izod test, on the other hand, is used to test relatively longer metal or plastic specimens with the notch facing towards a farming hammer (Matmatch, 2021).

2.4 Wear resistance in Metals

Wear is generally the displacement of material on a surface and/or removal of material from a surface and is often measured as volume or mass loss of material and can be majorly identified through microscopic studies of the surface. Essentially, there are two types of wear; adhesivewear and abrasive wear. These forms of wear would generally depend on some few factors such as impact angle of abrasives, presence of particles, ambient temperature, humidity, presence of fluids and probably even environmental pollution (Hosseini, 2011). Adhesion wear occurs when two solid surfaces are in sliding or in rolling contact with each other. At local spots, so-called asperities, atomic contact between the surfaces are then formed; because of sliding movements, shear deformation between the contact spots will appear forming a plastic zone on the surface. Continued sliding will cause shear failure. On the other hand, abrasive wear is when particles or sharp irregularities on the surface scratches a softer surface and makes a volume loss or plastic deformation of the specimen. Two-body and three-body abrasion wear are two different forms of sliding abrasion. In two-body abrasion no wear-debris is present and the mating surfaces wear by direct contact; while in three-body abrasion, wear-debris between the mating surfaces play an important role, forming a number of rolling contacts between the two mating surfaces. When developing new steel grades/heat-treatments for wear resistant steel grades, it is desired to have a proper method for evaluating wear properties. These test methods are discussed herein.

2.5 Corrosion resistance in Materials

Corrosion is a chemical reaction between a metal and the surrounding environment. All metals are susceptible to corrosion. The speed of which a metal corrodes depends on the alloy and environmental factors. The driving force for a metal to corrode is reaching the most stable phase. Corrosion can be simply described in a corrosion cell, where a metal and a hydrogen-based fluid interacts as seen in figure 2.7. The metal will react with the fluid and then emit electrons to the fluid, the hydrogen in the fluid will then bond with the electrons; this is called the cathode reaction. Hence the metal ion will then react with the oxygen and oxidized and new material is formed on the surface, having other mechanical properties than the original one.

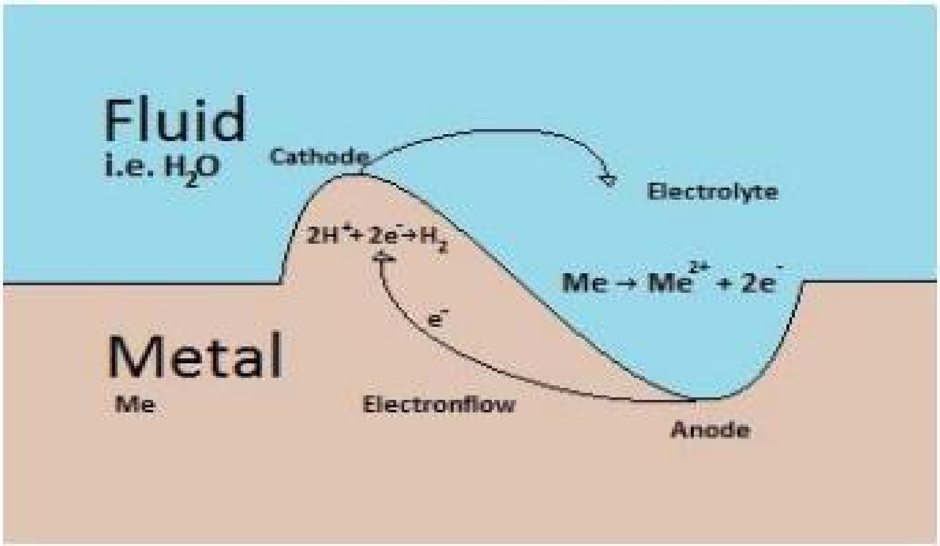

Figure 2.7 A simple corrosion cell between hydrogen-based fluid and metal

2.6 Review of Past Related Works

Ismail, et al., (2015) investigated the effect of heat treatment on the hardness and impact properties of medium carbon steel, treated at different heat treatment processes. Three types of heat treatment were performed in this project which are annealing, quenching and tempering. During annealing process, the specimens were heated at 900 degrees C and soaked for 1 hour in the furnace. The specimens were then quenched in a medium of water and open air, respectively. The treatment was followed by tempering processes which were done at 300 degrees C, 450 degrees C, and 600 degrees C with a soaking time of 2 hours for each temperature. After the heat treatment process completed, Rockwell hardness test and Charpy impact test were performed. The results collected from the Rockwell hardness test and Charpy impact test on the samples after quenching and tempering were compared and analysed. The fractured surfaces of the samples were also been examined by using Scanning

Electron Microscope. It was observed that different heat treatment processes gave different hardness value and impact property to the steel. The specimen with the highest hardness was found in samples quenched in water. In this study too, the microstructure obtained after tempering provided a good combination of mechanical properties due to the process reduce brittleness by increasing ductility and toughness.

Ahmed & Frhan, (2018) investigated the effect of quenching media (water, oil, Poly Vinyl Chloride PVC) on mechanical properties of 1030 steel used formachinery parts where strength and hardness were requisites. Within this study, the steel was heated to about 950 degrees celcius and soaked for 1hr in electrical furnace and then quenched in different quenching medium such as water, oil and poly vinyl chloride. After heat treatment by quenching, the specimens were tempered at 250 degrees for 1hr and then cooling in air. The mechanical properties of the specimens were then determined by using universal tensile testing machine for tensile test, Vickers hardness apparatus for hardness testing, measuring the grain size of the phases and examine the microstructure of the specimens before and after heat-treatment. The results of this work showed that improving the mechanical properties of medium carbon 1030 steel, by quenching with water gave the preferred results by leading to increase σy, σu.t.s, K and hardness;although with a consequential decrease in E and n. On another regard, the quenching by water, followed by tempering also led to improvement the microstructure and decreasing (refining) the grain size of ferrite and pearlite phases of the steel used in this work.

Singh, *et al.,* (2018) investigated the effect of heat treatment on wear rate of different agricultural grade steels and associated cost economics. In this study thus, three different types of agricultural grade steels (mild steel (MS), medium carbon steel (MCS) and medium carbon low alloy steel (MCLAS)) underwent heat-treatment processes. MS was carburized (950 °C for 720 min), MCS and MCLAS were austenised at 900 and 850 °C for 120 min. These steels were oil quenched and tempered at 200, 300 and 400 °C. The steel specimens were evaluated in laboratory condition using dry sand abrasion tester before and after heat-treatment. Effect of heat-treatments on abrasive wear, hardness and associated cost economics were studied. The results exhibit that under heat untreated conditions, wear rate of MCS and MCLAS were 13.10% and 32.33% less than that of MS. Whereas, under heat treated specimens wear rate reduced by 18.83%, 36.94% and 48.13% in MS, MCS and MCLAS, respectively. The hardness of all steels after heat treatment was found to increase more than two folds. Enhancement in the life of the selected steels were found to be 64.83% higher in case of MCLAS followed by 45.15% in case of MCS over MS.

Abumandil & Ahmed, (2019) investigated the effect of some heat treatment processes on the mechanical properties of medium carbon steel. In this study, heat treatment applications, like full annealing, normalizing, and hardening were carried out on medium carbon steel alloy, AISI 1040. The change in mechanical properties were checked via hardness and impact tests. Micro-structure photos of steel samples were taken out to obtain the change in grain structures after the heat treatment. All results were then checked and modeled by SPSS statistical software version 24. Thus, the throng correlation factors between the heat treatment levels in one hand, and samples surface hardness, impact energy, in another hand were obtained. Conclusively, the best internal grain structure were gotten in normalizing heat treatment on the samples.

Guma, *et al*., (2019) studied the effects of some heat treatments on corrosion of low and medium carbon steel in acidic chloride medium. Thus, the study systematically investigated the effects of normalizing, annealing and water-quenching heat treatments on corrosion of samples of the steel types in 0.5M

H_2SO_4 containing 3.5%-Wt sodium chloride at ambient temperature. Non-heat-treated (control) and heat-treated samples of low and medium carbon steel with respective carbon contents of 0.207% C and 0.46% C were produced, cleaned, weighed and immersed in pairs in the chloride medium for various durations of 72, 96 and 168 hours. Thereupon, the samples were removed, re-cleaned, dried, and re-weighed. The respective average pair weight losses were evaluated and used to determine the corrosion penetration rates of the samples in the medium. Analysis of the entire obtained rates data showed that corrosion of the samples tends to increase passivity with the exposure time in all cases. The low carbon steel samples generally showed much less resistance to corrosion in the medium, compared to the medium carbon steel. The study hence demonstrated that the control, annealed, normalized, and quenched low carbon steel samples comparably resisted corrosion in the medium. Furthermore, the quenched medium carbon steel samples exhibited much better corrosion resistance than their annealed and the annealed better than their normalized.

Hafeez, *et al.*, (2020) investigated the mechanical and corrosion properties of medium carbon low alloy steel after cyclic quenching and tempering heat–treatments. In this study, Cyclic single quenching and tempering (SQT), double quenching and tempering (DQT), and triple quenching and tempering (TQT) heat–treatment processeswere carried out on the medium carbon low alloy steel. X–ray diffraction analysis validated the formation of fine ε–carbide ($Fe_{2.4}C$) after intermediate low–temperature tempering in DQT andTQTheat–treatments. These fine carbides provided preferential nucleation sites for the formation of new austenitic grain, resulting in a refinedmicrostructure composed of supersaturated (carbon) lath martensite (α’) and retained austenite (γ). The DQT and TQT heat–treatments improved 19%tensile strength, 100%elongation, and 95%impact absorption energy in comparison to SQT heat–treatment.DQTand

TQT heat–treatments also transformed the brittle behavior ofSQT steel into a ductile behavior. It was also revealed by the small number and size of dimples alongwith a large number of short tear ridges in fractographs.Morphology of corrosion products of heat–treated experimental steel was also studied in a 5%NaCl solution. The SQT heat–treated sampleshowed porous morphology of corrosion products, while the TQT sample showedmorphologywith less porosity on the surface. TheDQTsample showed solid corrosionmorphologywith littleporosity. In addendum, as the grain size went on decreasing in the cyclic heat–treatments, the corrosion rate was also dropped.

Nwigwe, *et al.*, (2021) investigated the effects of different holding time and quenchants on the hardness and corrosion rate of medium carbon steel, after austenising at a temperature of 750 degrees C and soaking for a varied time of 1hr and 3hrs, the samples were quenched using three quenching media water, brine and condemned engine oil, and after which a hardness and corrosion test were conducted. The corrosion test was then done in a 25%wt NaCl solution using Potentiodynamic method. The experimental result obtained revealed a hardness value of 43.7, 37.4, 36.1 and 26.9 HRC for condemned engine oil, water, brine and As-received respectively for 1hr holding time; and those of 3hrs holding time had hardness value of 40.1, 33.3, and 31.7 HRC respectively. It was therefore observed that the corrosion rate for the sample quenched in water after 1hr soaking time had the highest value with 1.523e002 mil/yr and a lowest value in the sample quenched in water after 3 hours with a value of 1.941e-003 mil/yr. The corrosion rate of the As-received sample had the highest value with 4.331e+002 mil/yr and a smallest value in water quenched sample at 1.213e+001 mil/yr.

CHAPTER THREE

METHODOLOGY

3.1 Materials and Preparation

In this work the material used is medium carbon steel obtained from delta steel company owian aladja delta state; (considering it being generically used for most industrial applications, such as machinery parts with high strength and hardness). The chemical composition of the material as supplied are given in Table 3.1

Table 3.1 Chemical Composition of the Steel Specimen in (wt%)

	Weight composition (Wt%)
C	0.44
Si	0.23
Mn	0.5
P	0.32
Cr	0.17
S	0.06

The medium carbon steel rods were appropriately marked into lengths of 40 mm and mechanically cut into equal-sized samples for the heat treatment process. A smooth file was then used to scrip out machining burrs and smoothen the cut ends of the samples. Rust and other visible contaminants on the samples were also brushed off with bristle brush to expose their surfaces for more uniform heat input during heating.

Figure 3.1 Cross-section of samples during preparation

3.2 Heat Treatment Procedure

The process of heat treatment involves heating of solid metals to specified temperatures, holding them at that temperature, and then cooling them at suitable rates in order to enable the metals to acquire desired properties to the required extents. Considering the application of the material for this study, a hardening heat treatment process was adopted herein. Thus the heat treatment was done by heating the specimens of medium carbon steel in an electric furnace at austenizing temperature (950^0C) for 1hour 30 minutes and quenched in water.The heat treatments were conducted in accordance with the ASM international standards for conducting heat treatments. The quenching of the heat treated samples in the water bath at ambient room temperature was carried out for 30 minutes. This heat treatment is done for all the specimens which have been prepared for different tests.

3.3 Measurement of Corrosion Characteristics

The test acidic chloride medium was prepared in the laboratory by admixtures of 96.5%-Wt of 0.5 M H_2SO_4 and 3.5%-Wt NaCl. The 0.5M H_2SO_4 acid was prepared using the procured anal grade H_2SO_4 and distilled water by slowly adding 30 ml of the anal grade acid with stirring to 1000 ml of distilled water and allowing to cool to room temperature. All samples, were each weighed to the nearest 0.1mg using an accurate functional analytical balance.

The control and water-quenched coupons of the medium carbon steel were then separately immerse-placed in the medium in the jars for various earmarked durations of 20, 40, 60, 80 and 100 days respectively. Identification labels were inscribed on the acidic jars to show the sample types exposed therein. The jars were left in the laboratory at ambient temperature, and undisturbed throughout the test.

The sample pairs were then removed from each jar immediately after the 20, 40, 60, 80 and 100 days of exposure therein, rinsed to remove residual test solution and loose corrosion products and re-cleaned according to the ASTM G-1 standard practice, dried in air for one hour and re-weighed. The sample weight losses were determined as the differences between their respective weights before and after the immersion exposure in the test acidic chloride medium. Obtained weight losses were then used to determine the respective corrosion penetration rate (CPR) of each sample for its exposure duration according to the folowing equation

$$CPR = \frac{87.6\,W}{\rho A t} \tag{3.2}$$

where,

W was weight loss (mm)

ρ was mass density of the material (approximately 7.75 g/cm^3)

A was the total exposed surface area of the coupon (cm^2)

t was the exposure time the coupon (hours)

The corrosion rates were then reported as the respective average pair values of the as-exposed samples in the test medium. The average pair values were used to calculate the percentage level of corrosion inhibition efficiency (IE) of the medium carbon steel by the heat treatment processes for the exposure durations according to the equation

$$IE = \frac{CRO - CPR}{CRO} \tag{3.3}$$

where,

CRO was corrosion rates in the test medium with heat treatment

CPR was corrosion rates in the test medium without heat treatment.

3.4 Determination of Mechanical Properties

Before the hardening process, the specimens have been prepared for tensile test and hardness test by manufacturing them according to standard of ASTM E384 for hardness test, and ASTM A370 (i.e. 10 mm × 10 mm × 55 mm) for impact test. Hence, all of the specimens were properly grinded and polished mechanically. The polishing was made by emery paper (320, 500, 1000 µm) in size.Thereupon, the samples were cleaned with acetone, rinsed in distilled water, dried in air, stored in moisture-free desiccators according to ASTM G-1 standard practice for preparing, cleaning, and evaluating corrosion test specimens.

Figure 3.2 Hardened Specimen before polishing and after polishing

To assess the performance of the medium carbon steel alloy, mechanical properties were ascertained in addendum to the wear resistance and corrosion resistance. A microstructural assessment was also made on the material to probe more into its possible characteristics. For the mechanical strength, two main tests (i.e. impact and hardness) were carried out for the test samples.

3.4.1 Vicker’s Hardness Test

The hardness testing was done using a Vickers Hardness Testing machine. Thus, macrohardness was carried out for each specimen before and after hardening process.The applied load for the test was 10 kgf, applied for 15 second. Three readings were taken for each specimen, and the average of these readings was taken finally. Vickers’s hardness number was then calculated according to the following formula

$$V.H.N = 1.8544 \times {}^{F}\!/_{{d_{av}}^{2}} \tag{3.1}$$

The result obtained is presented in table 4.1

3.4.2 Charpy Impact Test

The Charpy V-notch test, is a standardized high strain-rate test that was used to determine the amount of energy absorbed by a medium carbon steel during fracture. This absorbed energy was a measure of the alloy's notch toughness. The charpy impact testing machine was employed herein for this test. The Charpy Impact Test entails striking the notched impact specimen of the medium carbon steel with a swinging weight or a "tup" attached to a swinging pendulum. The specimen (as seen in figure 3.2) breaks at its notched cross-section upon impact, and the upward swing of the pendulum was used to determine the amount of energy absorbed (notch toughness) in the process.

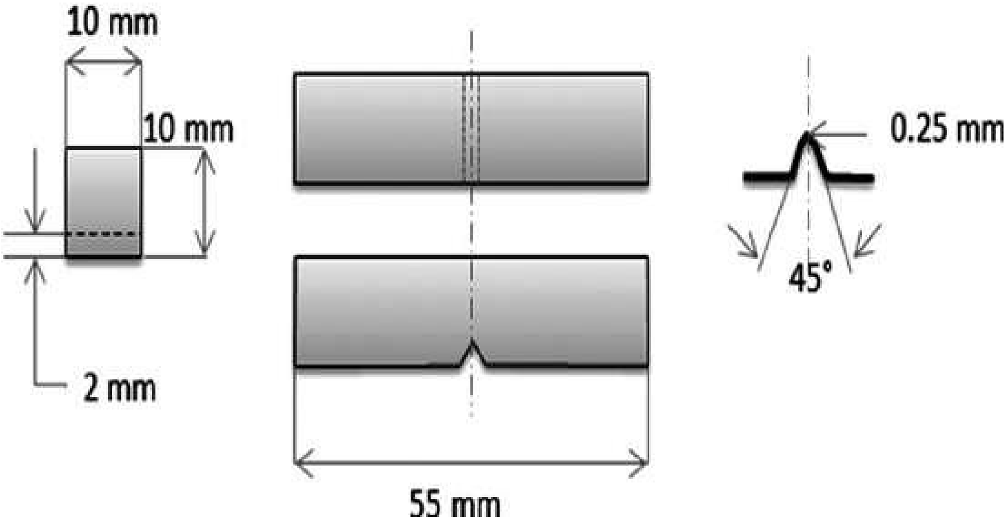

Figure 3.3 ASTM A370 (i.e. 10 mm × 10 mm × 55 mm) for impact test

Herein thus, Energy absorption was directly related to the brittleness of the material. The charpy test was performed at room temperature.

The results obtained are presented in table 4.2

3.4.3 Wear Test

Abrasive wear tests were undertaken herein using a rubber wheel dry sand abrasion test machine as per ASTM G-65. In this test, a rubber wheel of approximately 180 mm diameter and 12 mm width is rotated in a specified speed against the stationary flat specimen of size 76.2 mm × 25.4 mm × 6 mm and held firmly over the wheel surface. Crushed silica sand was used as the abrasive medium during evaluation. Translationally, the wheel is rotated at a fixed speed of 1.86 m/s and moved up to a distance of 2.6 km. All the tests in the study were conducted at 75 N load. After the completion of each of the test, the specimens were weighed. Wear rate WR of the specimen was measured from the weight loss measurement at a regular interval of 144 m of sliding distance by using formula

$$W_r = \frac{W_i - W_f}{S} \tag{3.2}$$

where,

Wi was Initial weight of specimen before the test, (g)

Wf was Final weight of specimen after the wear test (g)

S was Sliding distance (m)

Wr was Wear rate, (g/m)

The result obtained are presented in Table 4.3

3.5 Microstructural Examination

The chemical analysis of the medium carbon steel used was carried out in Dana steel limited, Katsina, by using Mass spectrographic Analyzer (computerized type). All the specimens (both As-received, heat-treated and corroded) were prepared for optical microscopic examination. The specimens were ground on a water lubricated silicon carbide abrasive papers of 180, 240, 320, 400 and 600 grit sizes. Polishing was carried out on 15cm rotating discs of a METASERV universal polishing machine with synthetic velvet polishing clothes impregnated with 1 μm Alumina paste. The specimens were then etched with 2% Nital solution using the swabbing method with cotton wool soaked in the etchant. The microscopic examinations were then finally carried out on M100 optical metallurgical microscope and the microstructures obtained were captured with the aid of in-built camera.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

Upon completion of every necessary scientific method for the material testing, the results for the various evaluations (i.e. the mechanical property, wear and corrosion resistance) of the medium carbon steel are reported herein thus.

4.1.1 Hardness of the Medium Carbon Steel

The result for the hardness of the material is tabulated below

Table 4.1 Hardness of the As-received and hardened medium carbon steel

Experiment No.	**Control MCS (HV-N/mm^2)**	**Hardened MCS (HV-N/mm^2)**
Specimen 1	1314.1	2024.1
Specimen 2	1284.7	2140.8
Specimen 3	1323.9	2112.4
Mean	**1307.6**	**2092.4**

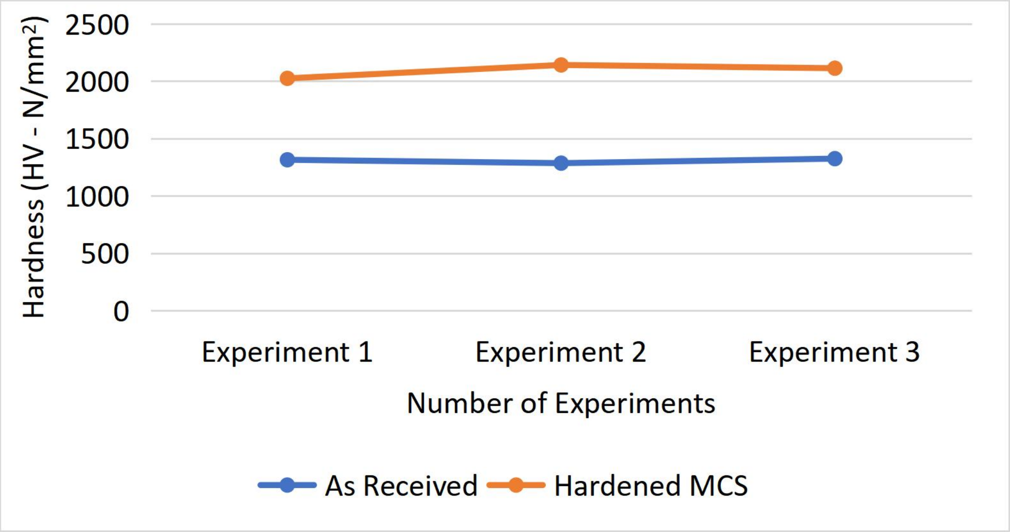

Figure 4.1 Graph showing the hardness for the untreated MCS and the hardened MCS

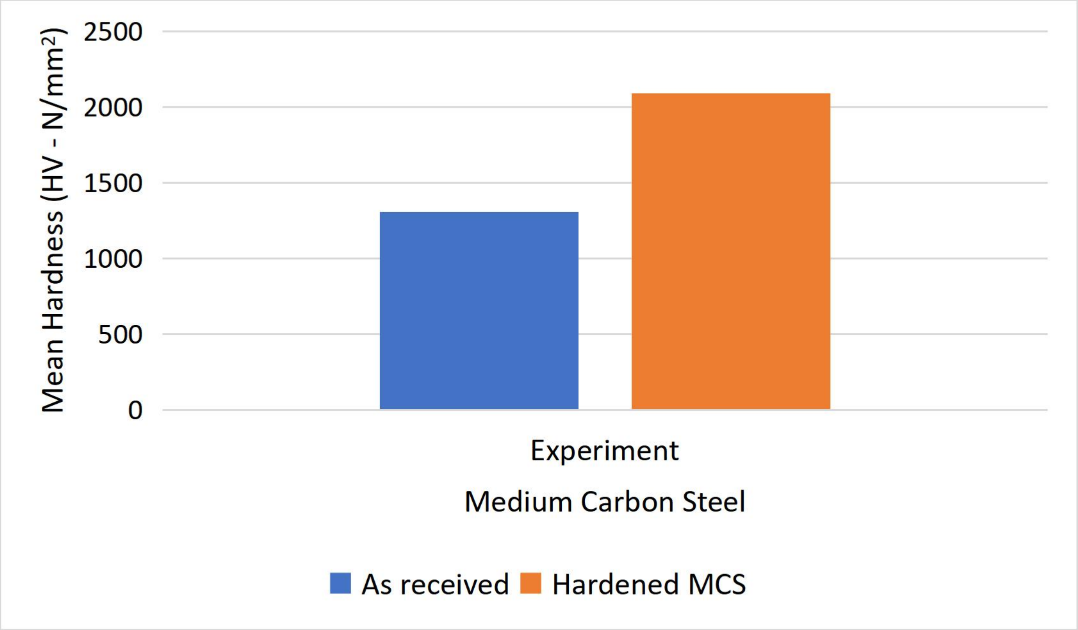

Figure 4.2 Graph showing the Mean hardness for the as-received MCS and the hardened MCS

4.1.2 Impact Strength of the Medium Carbon Steel

After heat treatment and subjection of some specimens (i.e. both the unheated and the heat treated specimens) to charpy impact test, the results obtained for three consecutive experiments are documented thus,

Table 4.2 Impact Strength of the unheated and hardened medium carbon steel

Experiment No.	**Control MCS (Impact Strength - J)**	**Hardened MCS (Impact Strength-J)**
Specimen 1	8.5	15.1
Specimen 2	8.2	14.3
Specimen 3	8.6	14.8
Mean	**8.4**	**14.7**

4.1.3 Wear Resistance of the Medium Carbon Steel

It is evident from figure 4.3 that abrasive wear significantly gets affected by the composition or heat treatment of the medium carbon steel. The wear rate of the steel is seen herein by varying the sliding distance at a selected speed of 0.93 m/s.

Table 4.3 Effect of Wear rate based on the sliding distance

Sliding discance (m)	**Control MCS Wear rate (g/m) x 10^{-5}**	**Hardened MCS Wear rate (g/m) x 10^{-5}**
50	12	8
150	11.7	7.3
400	11.5	7.5
500	10.8	6.9
750	10.3	6.8
1000	10.2	6.8
1200	9.8	6.7
1350	9.5	6.6
1500	9.5	6.5
1630	9.1	6.5
1750	9	6.4
1870	8.9	6.4
2000	8.9	6.3
2200	8.8	6.3
2350	8.8	6.2
2500	8.7	6.2
2600	8.7	6.1
2700	8.5	6

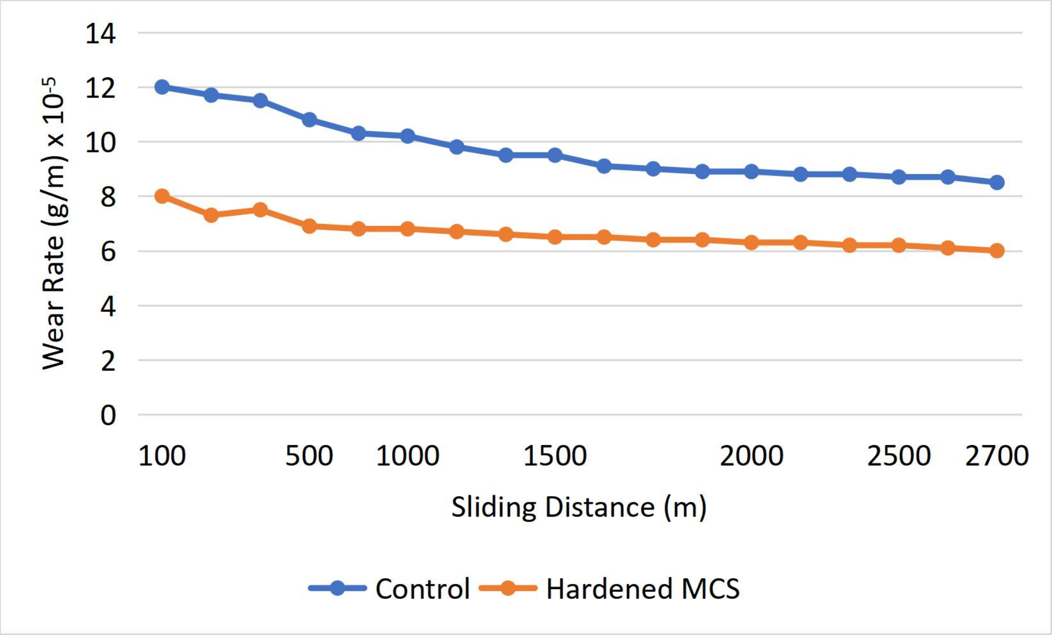

Figure 4.3 Effect of sliding distance on wear rate at 0.93 m/s

4.1.4 Corrosion Resistance of the Medium Carbon Steel

Results obtained for the corrosion tests of the heat treated samples of the medium carbon steels are presented herein

Table 4.4 Corrosion Results for the Untreated and Hardened MCS

Time (Days)	Weight of specimen before exposure (mg)	Weight of specimen after exposure (mg)	Weight loss (mg)	CPR of specimens (mm/yr)
20 days				
Control	154059	154029	30	0.112
Treated MCS	150031	150010	24	0.0751
40 days				

Control	154059	154027	32	0.135
Treated MCS	150031	150009	22	0.0698
60 days				
Control	154059	150032	27	0.0912
Treated MCS	150031	150012	19	0.0598
80 days				
Control	154059	154033	26	0.0768
Treated MCS	150031	150015	16	0.0556
100 days				
Control	154059	154034	25	0.0777
Treated MCS	150031	150017	15	0.0542

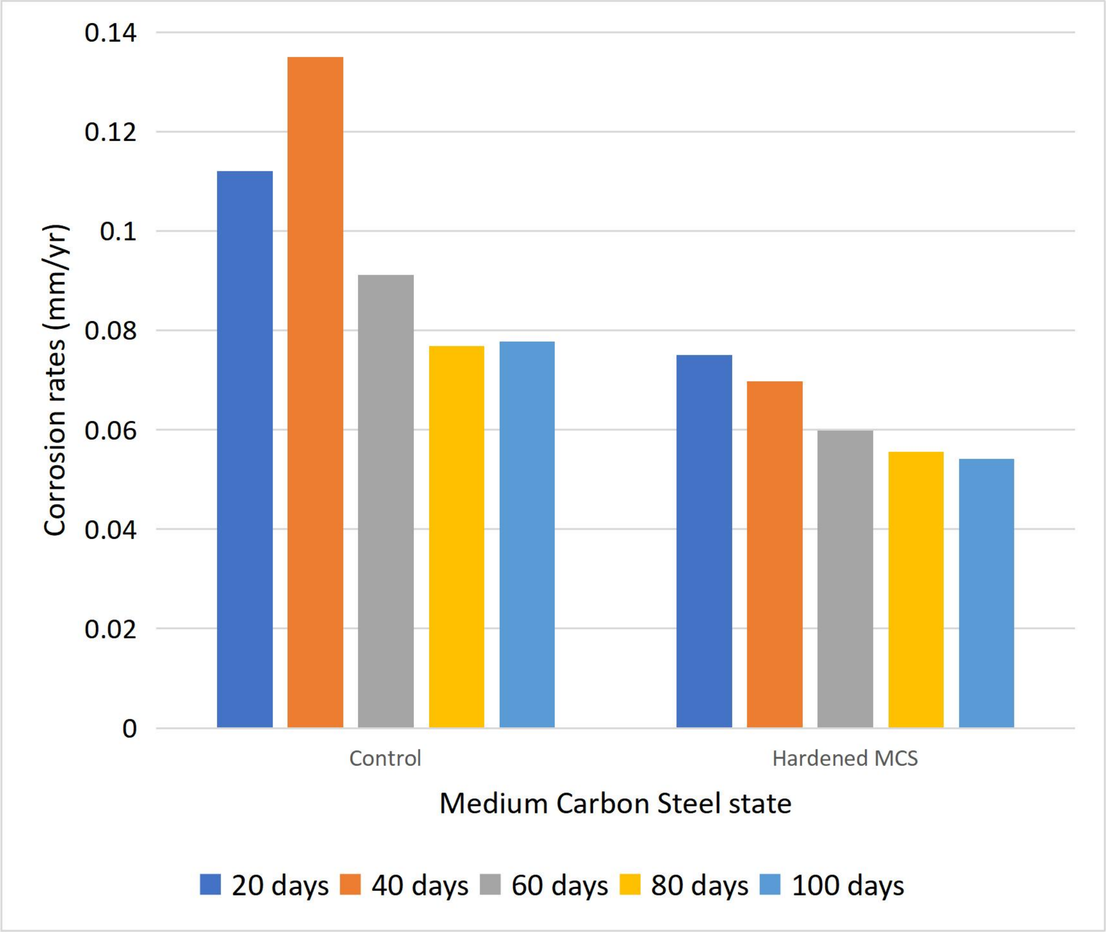

Figure 4.4 Corrosion rate for the control and hardened Medium Carbon Steel

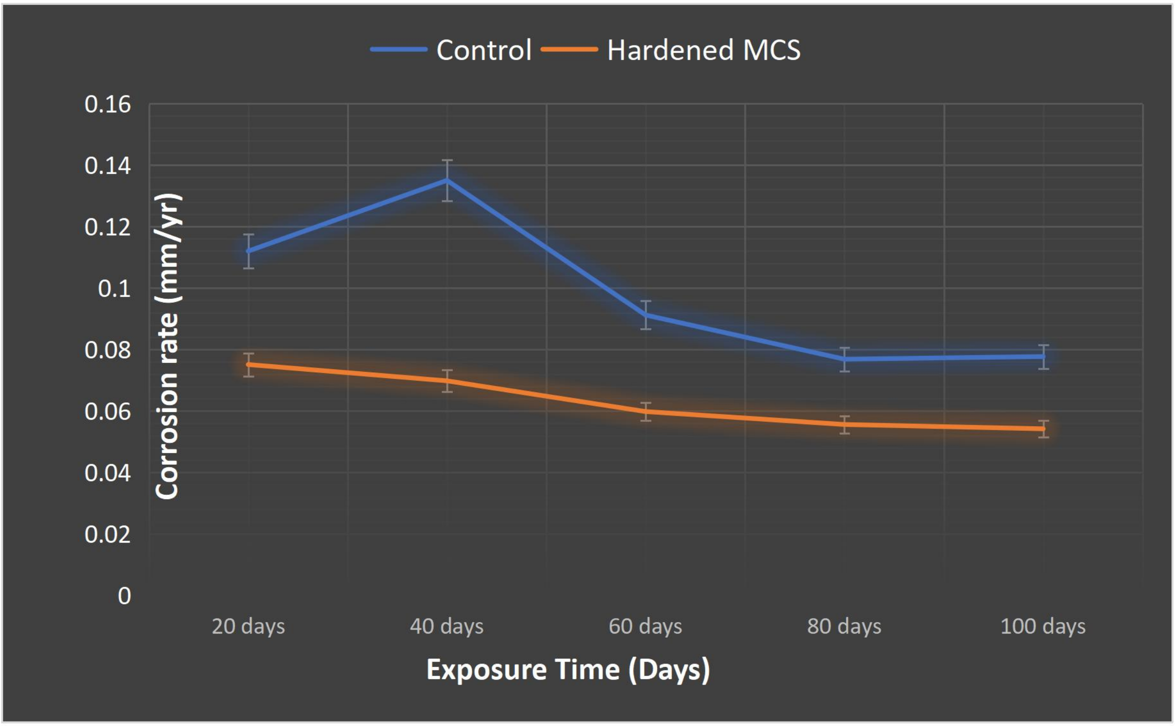

Figure 4.5 Line graph showing Corrosion rate for the control and hardened Medium carbon Steel

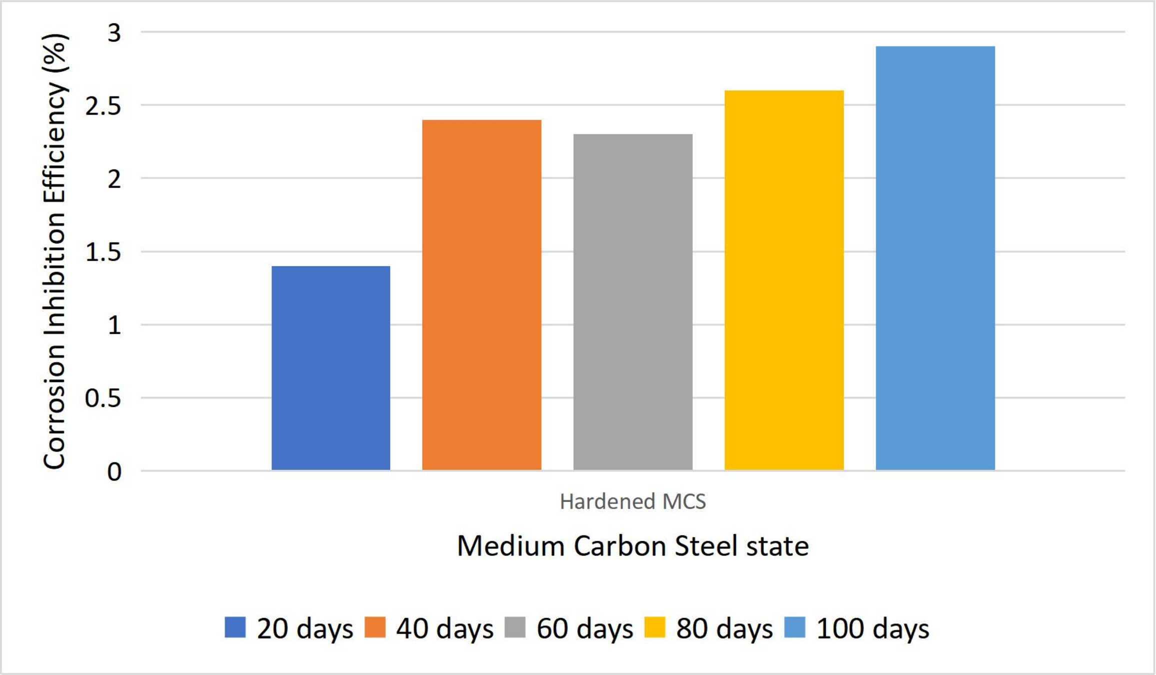

Figure 4.6 Bar chart showing Corrosion Inhibition Efficiency for the hardened Medium Carbon Steel

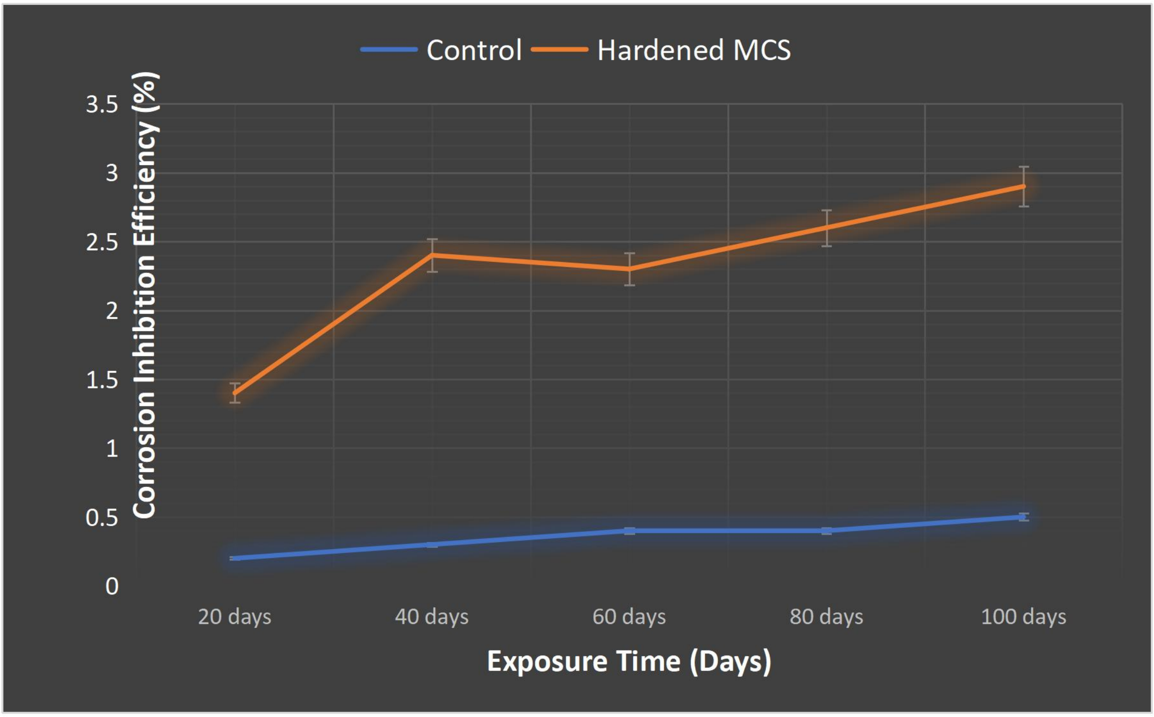

Figure 4.7 Line Graph showing Corrosion Inhibition Efficiency for the control and hardened Medium Carbon Steel

4.1.5 Microstructure of Samples

Microstructural examination performed using optical microscopy was to magnify microstructural features of the medium carbon steel alloy samples under analysis. Thus, the sizes as well as possible feature characteristics were observed, so to substantiate that the material had received the proper processing heat treatments or undergone the reaction processes, as in this research. Hence, the microstructure developed in the specimens before and after heat treatment (quench-hardening), then during corrosion tests are described below through plates 4.1 to 4.7.

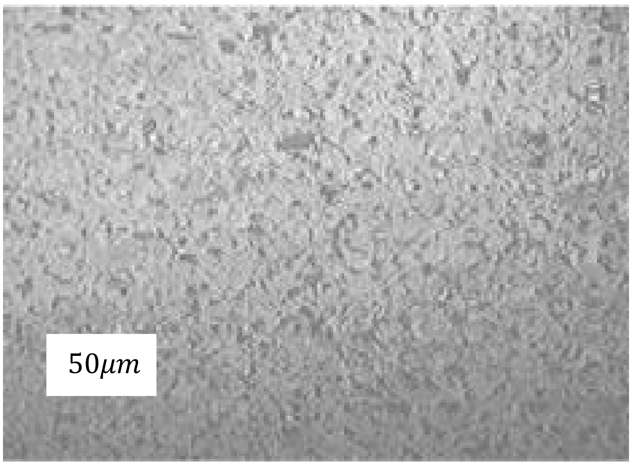

Plate 4.1 Optical Micrograph of the medium carbon steel as-received before hardening

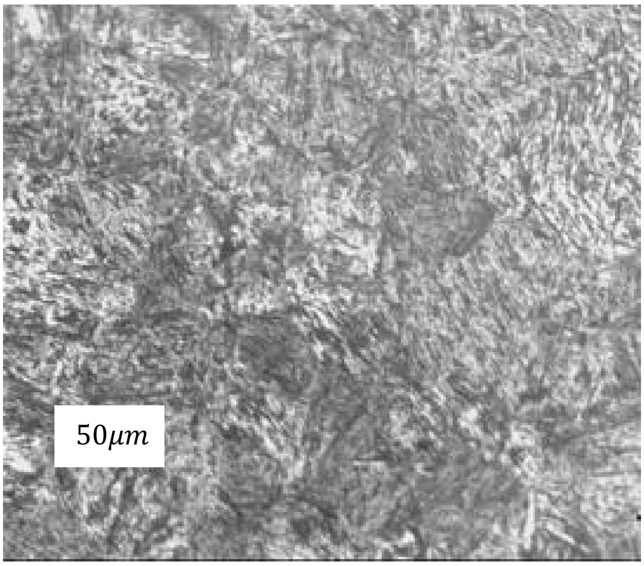

Plate 4.2 Optical Micrograph of the medium carbon steel after heat-treatment (quench-hardening)

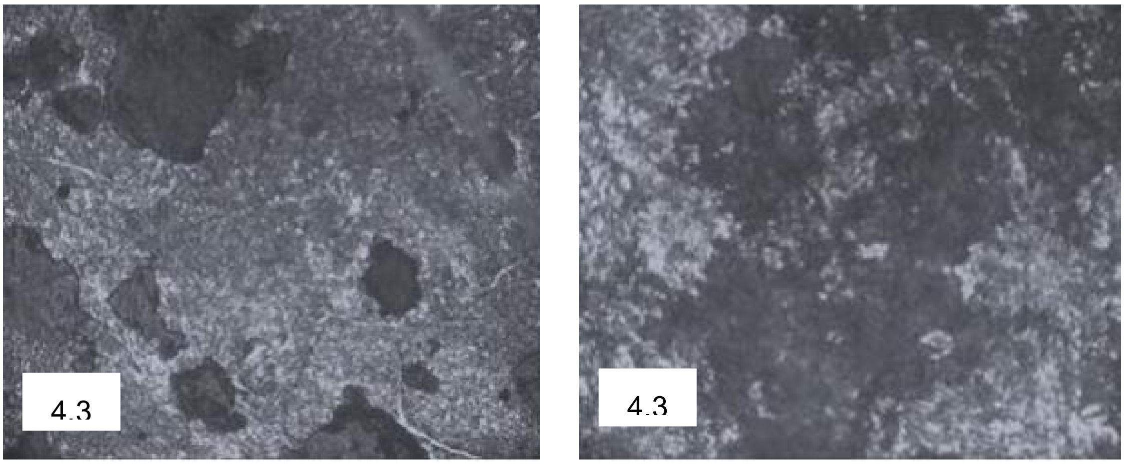

Plate 4.3 Microstructure of the untreated (a) and heat-treated sample (b) of the medium carbon steel after immersed in corrosive media for 20 days (x200)

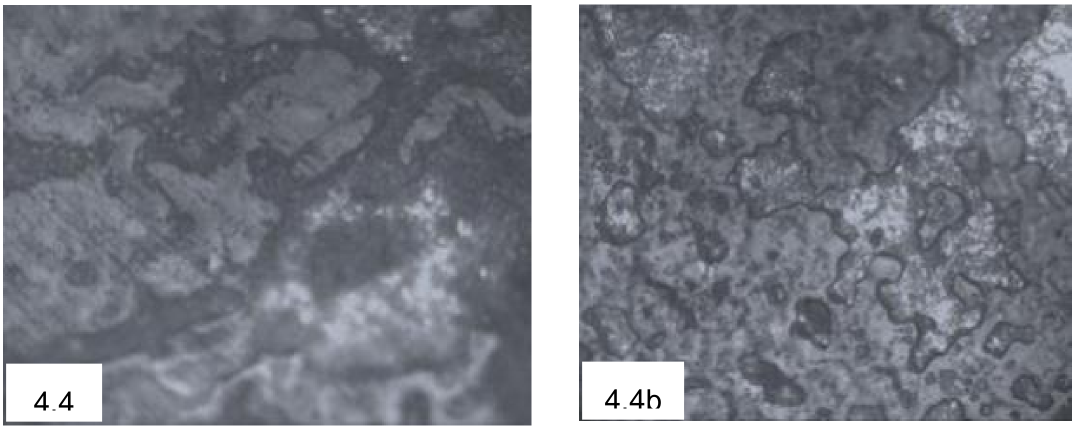

Plate 4.4 Microstructure of the untreated (a) and heat-treated sample (b) of the medium carbon steel after immersed in corrosive media for 40 days (x200)

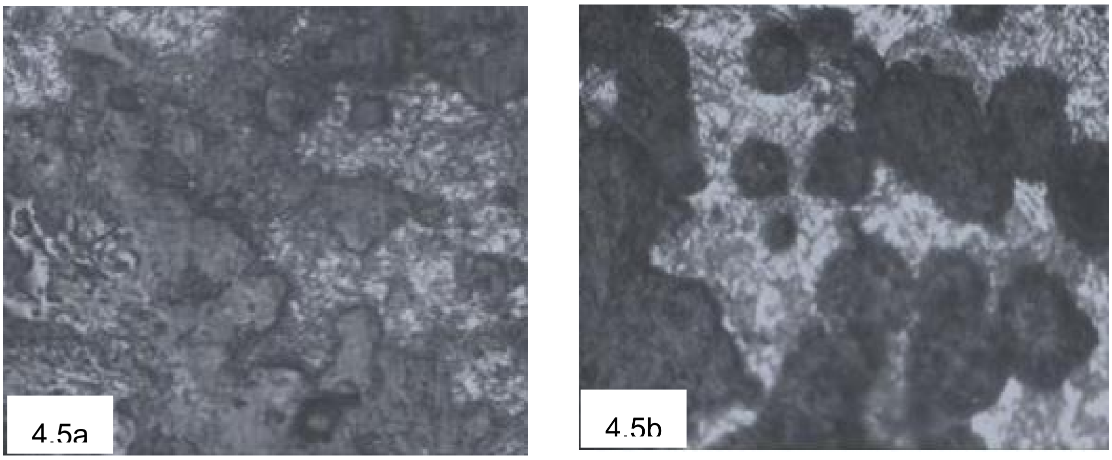

Plate 4.5 Microstructure of the untreated (a) and heat-treated sample (b) of the medium carbon steel after immersed in corrosive media for 60 days (x200)

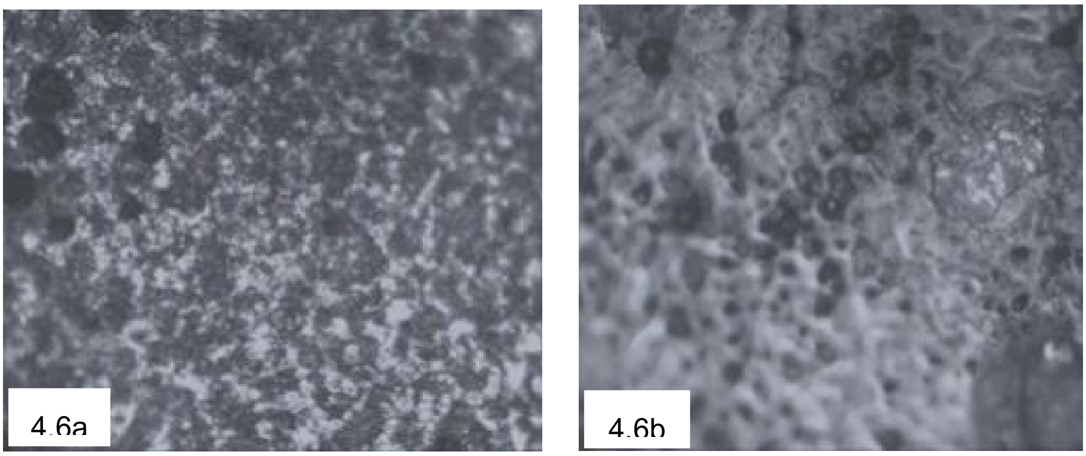

Plate 4.6 Microstructure of the untreated (a) and heat-treated sample (b) of the medium carbon steel after immersed in corrosive media for 80 days (x200)

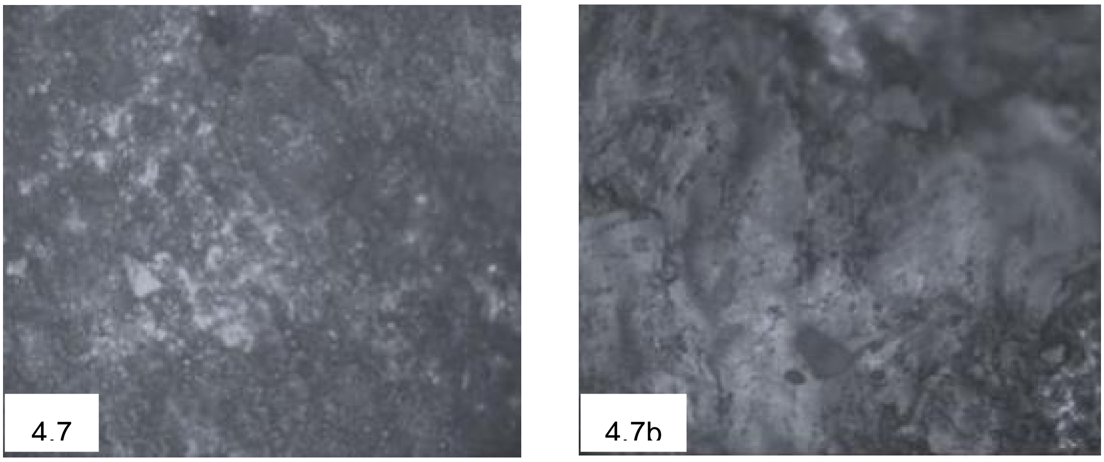

Plate 4.7 Microstructure of the untreated (a) and heat-treated sample (b) of the medium carbon steel after immersed in corrosive media for 100 days (at x200)

4.2 Discussion

4.2.1 Effect of Hardening on the Strengthof the Medium Carbon Steel

The graph in Figure 4.2 plotted the hardness (HV) against heat treatment process. This bar graph shows the result from Table 4.1. As can be seen from the graph, the hardness of medium carbon steel after quenching is much higher than the control specimen. This happened because quench hardening is a mechanical process in which steel are strengthened and hardened. Water has also been confirmed by the results obtained to be an efficient quenching media where maximum hardness is acquired,as observed by Guma,et al. (2019) However, there is a small chance that it may cause distortion and tiny cracking. Hence, quenching is a viable process to improving the hardness of medium carbon steel. Martensite phase developed leads to detrimental effects on toughness, which is generally produced during quenching in water. The increase obtained in hardness for the water quenched hardened specimen is attributed to the hardness which increases with the increase in percentage of carbon which dissolved in austenite before quenching.According to the work carried out by (Pashechko, Dziedzic, & Jozwik, 2020) ,wear-resistant coatings were obtained by means of boron thermal diffusion into the steel C45 substrate surface in order to make it suitable for the conventional plough steel material; in that study the hardness obtained was 1323.9 N/mm^2. This study have shown that the hardness value increased from 1307.6 N/mm^{2}of the as-received sample to 2092.4 N/mm^{2}of the heat treated sample, which is even more than that of the bononied C45 steel used for plough production.

4.2.2 Effect of Hardening on the Wear Resistance of the Medium Carbon Steel

It is apparent from figure 4.3 that the wear rate decreases with sliding distance and reaches to the stable steady state value. Thus initially, the wear rate was higher due to poor surface properties of the steel specimen. During heat treatment process or any other treatment when components surface temperature is high, the carbon available at surface burns with atmospheric oxygen and forms carbon dioxide. This gives poor surface properties. Again, lowering of the wear rate with sliding distance is due to subsurface work-hardening because of the subsurface plastic deformation during abrasive wear (Hosseini, 2011). The wear rate was reduced significantly through hardening heat treatment by the generation of lath martensitic structures that exhibit excellent combination of mechanical properties like strength and toughness to control the abrasive action by the sand particles.Comparing the average wear rate of 12g/m (x10^{-5}) obtained in this work and of 16g/m (x10^{-5}) obtained in the work of (Matrins & Verdins, 2017), it is seen that the wear rate obtained in this study was close to what was obtained for a conventional boronated steel used inplough production.

4.2.3 Effect of Hardening on the Corrosion Resistance of the Medium Carbon Steel in an Acidic Chloride Environment

From Figures 4.4 and 4.6, it is observable that the heat-treated and non-heat-treated (control) samples had different corrosion rates for various exposure durations in the acidic chloride medium. It can be observed from Fig 4.4, that the rates for the heat treated and control medium carbon steel samples ranged from 0.021 to 0.098mm/yr and 0.187 to 0.293mm/yr for the same time range respectively. Result herein also reflects this fact by the differences in the corrosion rates between the un-heat-treated, and hardened samples of the medium carbon steel; thereby depicting that within the sample exposure durations to the test acidic chloride medium, corrosion rates decrease with the exposure durations for all cases of the un-heat-treated and heat treated samples. From the results obtained, there was a clear indication that carbon content was a more critical variable in water-quench-hardenability and corrosion resistance of the steel samples, as observed in related works of Guma, et, al. (2019) ,The decrease in corrosion rates of the heat-treated steel samples with the exposure durations can be attributed to natural corrosion passivation ability of carbon steel which tends to decrease its environmental corrosion rate to more or less constant value within some exposure time being in line with the observations of Nwigwe, et, al. (2021) in a related work.

4.2.4 Microstructural Examination of the Effect of Hardening on the Medium Carbon Steel

The as-received microstructure of the sample as observed in plate 4.1, consists of bands of pearlite in the ferrite matrix.

The corrosion of the medium carbon steel alloys starts with the oxidation of the ferrite phase, the ferrite phase acts as anode, while the cementite as cathode which will further enhance corrosion of the medium carbon steel alloy. The martensite phase of the MCS alloy thus behaves as noble and acts as the cathodic phase while the Widmanstatten ferrite at the grain boundaries acts as an anode. The ball shape morphology of corrosion products was observed on the surfaces of the quenched samples of the medium carbon steel alloy after corrosion testing (as seen in plates 4.3 to 4.7) which might be lepidocrocite and goethite, as reported by (Kang, et al., 2014).

The microstructure developed in the specimens after heat treatment shown in plate 4.2 showed packets and blocks of lath martensite in the medium carbon steel alloy as observed in a related work by Abumandil & Ahmed (2019). It is observed also that the martensite laths also looked a bit finer. In the quench-hardened microstructure, carbon is entrapped in a BCT crystal structure, resulting in the uniform distribution of carbon in the matrix as observed by Ismail et,al. (2015)

The results presented in plates 4.3 to plates 4.7 following the corrosion rate its observed that in all the corrosiontest samples the corrosion rate increased, then started to decrease gradually with exposure time, with the hardened samples showing similar corrosion behaviour in this medium at the early stage, while the untreated samples however, showed increased corrosion rate at the early stage followed by gradual decrease in the corrosion rate. The corrosion attack was found to be more severe from 20 - 60 days of immersion for both the untreated and heat treated test samples within the corrosive media. However, the corrosion rate decreased gradually after 60 days. This indicates that even if the steel might have been treated for better strength quality and an improved corrosion resistance obtained, exposure time as observed in this investigation has a significant influence on the corrosion behavior of the medium carbon steel alloy. Thus, the levels of the carbide phase affecting the corrosion of the medium carbon steel alloy depends on both heat treatment as well as the matrix structures developed being in line with the findings of Hafeez, et, al. (2020)

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From the resuts obtained, the following conclusions are observed thus,

Hardness test shows that hardness for the hardened material was approximated at 2092.4 N/mm^2 which is greather compared to the "as-received" value given as 1307.6 N/mm^2. Hence indicating a significant increase in the hardness of the material that would make it suitable for Agricultural applications.

The impact test conducted gave an approximated result of 14.7 J compared to 8.4 J of the control sample; thereby depicting the energy absorption capability of this medium carbon steel alloy developed.Thus, the objective to investigate the impact toughness of medium carbon steel was also achieved.

The study revealed thatwear rate of approximately 25 % was reduced for the hardened medium carbon steel in comparison to the untreated steel; having associated maximum values of about 8g/m (x10^{-5}) for the hardend steel and 12g/m (x10^{-5}) for the control respectively.

The extents to which quench hardening heat treatments can enhance corrosion resistance of medium carbon steel in 0.5M H_2SO_4 containing 3.5% Wt sodium chloride has been procedurally investigated herein. Quench hardening the medium carbon steel resulted in better corrosion resistance,with the hardened steel sample having corrossion rate between 0.0751 mm/yr to 0.0542 mm/yr compared to the control sample with corrossion rate between0.112 mm/yr to 0.0777mm/yr.

5.2 Recommendations

Having studied the effect of hardening heat treatment on the strength, wear and corrossion resistance of 0.44 %C steel in acidic chloride environment,the following recommendations should be considered,

Eventhough water has been used as the quenching media, other quenching mediums could be explored.

Based on research reviews, an optimal soaking time of 1 hour 30 minutes was adopted for this research, thus other soaking times could be explored for the research so to gain more insight.

Based on research reviews, an optimal quenching time of 30 minutes was adopted for this research, thus other quenching times could be explored for the research so to gain more insight.

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