HARDENING CHARACTERISTICS OF LOW CARBON STEEL QUENCHED IN WATER, BRINE AND ENGINE OIL

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CERTIFICATION

This certificate acknowledges that this project presented to the Department of Materials and Metallurgical Engineering was conducted by OFOMALA FESTUS ESEOGHENE, ODEYEMI TIMILEHIN SAMUEL, OCHUBA CHIGOZIE DOMINIC,NWOKO ONYEKA GEORGE , NWAIKU ONYEBUCHI ALLWELL and all affiliated with the Department of Materials and Metallurgical Engineering, University of Benin, Benin City, Edo State, Nigeria under the guidance and Supervision of Engr. Wilfred Irogue

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DEDICATION

We dedicate this project to the Almighty God who saw us through the course of our study, and also to our families for their support and words of encouragement which have been a guiding light throughout this journey. This endeavor is dedicated to you, as a token of our appreciation for all that you do.

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ABSTRACT

This study delves into the intricate relationship between quenching mediums—brine, engine oil, and water—and the hardening characteristics of low carbon steel. Through a systematic investigation, we aimed to determine the optimal quenching medium that enhances the hardness of low carbon steel, thereby contributing to improved wear resistance and durability. Our research encompassed a comprehensive examination of the microstructure of quenched steel samples, enabling us to identify and understand the phases and structures formed during the hardening process with each quenching medium. Further, we assessed and compared the mechanical properties, including tensile strength, impact toughness, and yield strength, to ascertain their influence on material performance.

By establishing correlations between the cooling rates associated with brine, engine oil, and water quenching and the resulting microstructures and hardness of low carbon steel, we provided valuable insights into the relationship between cooling dynamics and material properties.

Our findings not only contribute to a deeper understanding of the quenching process but also offer practical guidelines and recommendations for industries seeking to implement effective and sustainable quenching processes for low carbon steel. These guidelines aim to optimize heat treatment processes, thereby enhancing the mechanical properties of low carbon steel and facilitating its utilization across various industrial applications.

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CHAPTER 1

1.1 BACKGROUND OF STUDY

The hardening of low carbon steel through heat treatment has a rich historical context and is an essential aspect of metallurgy that has been practiced for centuries. The process of hardening steel involves heating it to a specific temperature, known as the critical temperature, and then rapidly cooling it, often through quenching in water, oil, or other mediums. This process alters the internal structure of the steel, enhancing its hardness and strength. Traditional quenching mediums include water, but the growing interest in exploring alternative options like vegetable-based oils (engine oil) and brine solution due to environment and sustainability consideration.

The mechanical characteristics of steel are closely tied to the microstructure developed through heat treatments, which are typically conducted to attain desirable hardness and/or tensile strength while maintaining ample ductility (Mebarki et al., 2004). Presently, there's significant attention on how the cooling rate influences both the mechanical attributes and microstructure of industrially processed steels. In considering the microstructure, the influence of cooling on the microstructure of vanadium bearing steels has been investigated by transmission electron microscopy (Bangaru and Sachdev, 1982). It has been shown that oil quenching produce an essentially ferrite-martensite dual phase structure with about 4 volume pct of fine particle and thin film retained ausenite. In contrast, the slower air cooling results in a larger amount (about 10 volume pct) of retained ausenite in addition to the ferrite and martensite phases. On the other hand, with the applied cooling rate increasing, the transformed structure evolves from granular bainite, lower bainite, self-tempered martensite, to finally martensite without self tempering (Qiao et al., 2009). Among them, self-tempered martensite, obtained in the transformed specimens cooled with rates of 25 – 80°C/min, exhibits the highest hardness values due to the precipitation of fine carbides.

The cooling rate during the heat treatment of low carbon steel is a critical factor that significantly influences the resulting microstructure and mechanical properties of the steel. The importance of the cooling rate lies in its direct impact on the transformation phases within the steel, particularly the formation of martensite, which plays a key role in achieving desired hardness and strength. While low carbon steel is a widely used material in various industries due to its cost-effectiveness and versatility, the selection of an appropriate quenching medium is crucial to achieve desired hardness and strength. Brine, engine oil, and water are chosen as quenching agents due to their distinct thermal properties and cooling rates, which can impart unique characteristics to the steel.

One of the primary challenges addressed in this study is understanding how the choice of quenching medium affects the microstructure, hardness, and mechanical properties of the low carbon steel. This investigation seeks to identify the optimal quenching medium that balances the desired hardness with minimal distortion and cracking.

1.2 STATEMENT OF PROBLEM

The inquiry aims to explore the impact of various quenching agents on the hardness and microstructure of low carbon steel, as well as to determine the most effective quenching parameters for attaining specific mechanical properties. Through this exploration, the study endeavors to advance comprehension of the quenching process and its potential to improve the mechanical functionality of low carbon steel in industrial settings.

1.3 AIM AND OBJECTIVES

The aim of this project is to address the intricate relationship between quenching mediums (brine, engine oil, and water) and the hardening characteristics of low carbon steel. By thoroughly investigating the microstructural changes, hardness variations with each quenching medium, the findings will provide valuable guidelines for industries aiming to enhance the mechanical properties of low carbon steel through optimized heat treatment processes.

Aligned with the research problem, this study's objective encompasses the following

1. :Investigating and determining the quenching medium (brine, engine oil, or water) that optimally enhances the hardness of low carbon steel, contributing to improved wear resistance and durability.
2. Conduct a comprehensive examination of the microstructure of the quenched steel samples to identify and understand the phases and structures formed during the hardening process with each quenching medium.
3. Assess and compare the mechanical properties, such as tensile strength, impact toughness, and y\\\\\\ield strength, of the low carbon steel subjected \to quenching in different mediums to ascertain their influence on material performance.
4. Establish correlations between the cooling rates associated with brine, engine oil, and water quenching and the resulting microstructures and hardness of the low carbon steel, providing insights into the relationship between cooling dynamics and material properties..

5. Formulate practical guidelines and recommendations for industries seeking to implement effective and sustainable quenching processes for low carbon steel.

1.4 SCOPE OF THE STUDY

The scope of this project focuses on systematic investigation and comparing the effects of different quenching mediums on low carbon steel, with the aim of providing practical insights for both industrial and contributions.

1.5 METHODOLOGY

1. Obtain and ascertain the carbon equivalent of sample mild steel using spark test after machining
2. Carry out heat treatment, the furnace is to be pre heated to a temperature of 650 degree Celsius before the already machined low carbon steel is charged into the furnace
3. Conduct a series of quenching experiments with the varying concentrations of brine, engine oil and water to identify the optimum quenching medium for achieving maximum hardness in low carbon steel.

   Perform hardness testing using standardized methods (e.g., Rockwell or Vickers hardness tests) to quantify and compare the hardness values obtained from each quenching medium.
4. Utilize metallography techniques, such as optical and electron microscopy, to examine the microstructure of the quenched steel samples and identify the phases and structures formed during the hardening process. Correlate the observed microstructural changes with the specific

quenching medium to establish a clear understanding of the microstructural evolution.

5. Conduct tensile tests, impact tests, compressive test and fatigue test on the quenched steel samples to assess and compare their mechanical properties. Analyze the mechanical property data to identify trends and variations associated with different quenching mediums. Provide recommendations for sustainable quenching practices based on the environmental impact assessment..
6. Compile the research findings into a comprehensive guide for industries, including practical recommendations and best practices for implementing effective and sustainable quenching processes for low carbon steel.

1.6 SIGNIFICANCE OF THE STUDY

To understand the critical need for optimizing heat treatment processes, specifically quenching, which is a fundamental step in enhancing the hardness of low carbon steel used in various industrial applications. Analyzing the hardening characteristics which different quenching mediums contributes to improving the mechanical properties of low carbon steel, enhancing its overall performance, durability, and reliability in real-world applications. The research provides valuable insights into tailoring the material properties of low carbon steel by selecting an appropriate quenching medium, enabling industries to meet specific requirements for hardness, toughness, and wear resistance. Also to determine the optimal quenching conditions for efficient utilization of low carbon steel, minimizing waste and reducing the need for costly alloying elements to achieve desired material properties.

CHAPTER TWO (LITERATURE REVIEW)

2.0 LITERATURE REVIEW

The hardening characteristics of low carbon steel quenched in different media such as engine oil, water, and brine have been a subject of interest in materials science and metallurgy. Studies have examined how different quenching media affect the hardness, microstructure, and mechanical properties of low carbon steel. Research often compares the quenching rates, cooling curves, and resultant material properties when various quenching media and also microstructural changes in the steel after quenching in various media. This includes examining the formation of different phases (martensite, pearlite, etc.) and the distribution of these phases within the material, influencing its mechanical properties. Researchers typically evaluate the hardness, tensile strength, toughness, and other mechanical properties of low carbon steel after quenching in different media and comparative analyses are often conducted to understand the effects of each quenching medium on the final material characteristics.

Studies also delve into the cooling rates provided by each quenching medium and how they affect the transformation kinetics of the steel. The severity of quenching and its impact on phase transformations, residual stresses, and distortion in the material and also the corrosion resistance of the quenched steel when exposed to different environments after treatment in various media, this includes assessing the susceptibility to corrosion based on the quenching process. Certain studies aim to optimize the quenching process by selecting the most suitable medium for enhancing specific mechanical properties or achieving desired material characteristics. Practical implications for industrial applications could also be discussed.

The hardening of low carbon steel through the quenching process is a crucial aspect of metallurgical engineering, playing a pivotal role in tailoring the mechanical properties of the material to meet specific application requirements. The quenching process involves rapid cooling of heated steel to achieve desirable hardness, strength, and other mechanical characteristics. This controlled cooling alters the microstructure of the steel, influencing its final properties. The quenching process is a versatile and indispensable technique in the realm of metallurgy, providing a means to control the mechanical properties of low carbon steel. Understanding the nuances of quenching and its effects on the microstructure empowers engineers to design materials with tailored characteristics, meeting the demands of diverse industries, from manufacturing to automotive and beyond. As we delve into the existing literature, it becomes apparent that the choice of quenching medium, cooling rates, and other parameters significantly influences the final properties of low carbon steel, making it a rich area of research and exploration.

The main goal during the heating phase is to ensure uniform temperatures. If heating occurs unevenly, it can lead to distortion or cracking as one part of a component expands faster than another. Achieving uniform temperatures involves a slow heating process. The heating rate depends on various factors, including the metal's heat conductivity. Metals with higher heat conductivity heat up faster than those with lower conductivity. Additionally, the condition of the metal affects its heating rate; hardened tools and parts require a slower heating rate compared to untreated metals. Moreover, the size and cross-sectional area of the part influence the heating rate. Larger cross sections necessitate slower heating to maintain uniform temperature distribution, preventing warping or cracking. Although parts with uneven cross sections may experience irregular heating, they are less likely to crack or warp excessively when heated slowly.

Once the metal reaches the desired temperature, it is held at that temperature until the necessary internal structural changes occur. This process, known as soaking, involves maintaining the metal at the proper temperature for a specific duration, referred to as the soaking period. The choice of quenching medium depends on the metal's chemical composition and part mass. Carbon steels are typically water-hardened, while alloy steels are oil-hardened. During soaking, the metal's temperature gradually approaches the final temperature required for the desired structural changes. Quenching, the rapid cooling of metal in oil, water, brine, or another medium, is commonly associated with hardening processes. However, quenching doesn't always result in increased hardness; for instance, copper is usually annealed by quenching it in water. The choice of quenching medium depends on the metal's propensity to crack or warp during cooling. Brine or water is suitable for metals requiring rapid cooling, while oil mixtures are preferable for slower cooling rates.

2.1 Early Civilizations and Traditional Techniques

The practice of quenching metals dates back to ancient civilizations, such as the Egyptians, Greeks, and Romans. These cultures utilized basic water quenching techniques to harden bronze and iron tools and weapons. Water was the primary quenching medium during early civilizations. Its availability and simplicity made it a natural choice for cooling hot metals. However, the rapid cooling rate of water could lead to uneven hardening and cracking, limiting its effectiveness for certain applications. As metallurgical knowledge advanced during the Middle Ages, oil emerged as an alternative quenching medium. Unlike water, oil offered a slower cooling rate, reducing the risk of cracking. This method gained popularity for hardening steel, especially in the production of weapons and armor.

During the Renaissance, blacksmiths and metallurgists relied on empirical knowledge, honed through trial and error. They developed specific quenching practices for different types of steel, often keeping their methods closely guarded secrets. With the advent of the Industrial Revolution, the demand for consistent and controlled metal properties increased. Water and oil quenching continued to be widely used, but there was a growing awareness of the need for precision and repeatability in the quenching process. Innovations in the design of quenching tanks, such as the introduction of agitated and circulated quenching baths, helped improve the uniformity of cooling. This innovation aimed to address challenges associated with uneven quenching, reducing the likelihood of distortion and cracking in the hardened material.

In the 20th century, brine (saltwater) emerged as a quenching medium, offering faster cooling rates than water. This was particularly useful for certain alloy steels. Additionally, polymer quenching solutions gained popularity for their ability to provide precise control over cooling rates. Advances in metallurgical science led to the development of controlled atmosphere quenching. This involved quenching in controlled gas environments to further tailor the cooling process, minimizing oxidation and reducing the risk of distortion.

Today, the quenching process has evolved with advancements in fluid technology. Water, oil, and polymer solutions are still widely used, but modern formulations and additives are employed to enhance their performance and meet specific requirements. The advent of computer-aided simulation has revolutionized quenching practices.

Simulation software allows engineers to model and predict the effects of different quenching parameters, optimizing the process for desired material properties.

The historical development of quenching methods reflects a gradual refinement of techniques driven by empirical knowledge, technological innovations, and a deepening understanding of metallurgical principles. The evolution from traditional water quenching to the diverse range of quenching media and sophisticated methods used today underscores the ongoing quest for precision and control in tailoring the mechanical properties of metals

2.2 Martensite Formation

Martensite is a hard and brittle microstructure that forms in steel when it undergoes rapid cooling from a high temperature. During the quenching process, the steel is heated to a critical temperature (A3), where it transforms from austenite to a face-centered cubic (FCC) crystal structure. Upon rapid cooling, the transformation is not completed, and the steel bypasses the normal phase transformations. Martensite is characterized by a needle-like or lath structure. It is extremely hard due to its supersaturation of carbon and is often associated with high hardness and brittleness.

2.2.1 Key Factors

- **Critical Cooling Rate:** Martensite formation requires a critical cooling rate, typically achieved through quenching in water, oil, or other quenching media.
- **Temperature Control:** The cooling rate must be fast enough to avoid the diffusion of carbon atoms and allow the formation of a supersaturated solid solution of carbon in the iron matrix

2.2.2 Formation of Martensite: During quenching, the steel is heated to a temperature where it transforms from its initial phase (usually austenite) to martensite. The transformation involves a rapid cooling of the steel, typically by immersion in a quenching medium like water, oil, or air.

2.2.3 Microstructural Changes

- **Supersaturation of Carbon:** The fast cooling rate prevents the carbon atoms from diffusing to their equilibrium positions, resulting in a supersaturated solid solution of carbon in the iron matrix.
- **Formation of Needle-Like Structure:** Martensite has a characteristic needle-like or lath structure. The rapid cooling prevents the atoms from arranging themselves into a more equilibrium structure, leading to the unique morphology.

2.2.4 Properties

- **Hardness:** Martensite is extremely hard due to the supersaturation of carbon, making it one of the hardest microstructures in steel.
- **Brittleness:** Martensite is also brittle, which can lead to issues such as cracking in certain applications.

2.3 Pearlite Formation

Pearlite is a lamellar structure consisting of alternating layers of ferrite and cementite,the formation of pearlite occurs during the slow cooling of austenite. It involves the eutectoid reaction, where austenite transforms into a mixture of ferrite and cementite. Pearlite consists of layers of ferrite (alpha iron) and cementite (Fe_3C).

The alternating layers provide a balance between strength and ductility, making pearlite a relatively softer and more ductile microstructure compared to martensite.

2.3.1 Key Factors

- **Cooling Rate:** Slow cooling is essential for the diffusion of carbon atoms and the development of the lamellar structure.
- **Temperature Range:** The eutectoid reaction occurs at a specific temperature, known as the eutectoid temperature (727°C for low carbon steel).

2.3.2 Formation of Pearlite: Pearlite forms during slow cooling of austenite. The transformation involves the eutectoid reaction where austenite transforms into alternating layers of ferrite and cementite.

2.3.3Microstructural Changes

- **Lamellar Structure:** Pearlite consists of layers of ferrite (alpha iron) and cementite (Fe_3C). The slow cooling allows for the diffusion of carbon atoms, leading to the formation of this lamellar structure.

2.3.4 Properties

- **Ductility:** Pearlite is relatively softer and more ductile compared to martensite. It provides a good balance between strength and ductility.

The microstructural changes during quenching involve the rapid cooling of austenite, leading to the formation of martensite with its characteristic needle-like structure. Depending on the cooling rate and other factors, bainite or pearlite may also form, each with its unique microstructure and associated mechanical properties.

2.4 Bainite Formation

Bainite is a microstructure that forms during the transformation of austenite at intermediate cooling rates between those required for martensite and pearlite. Bainite forms through a displacive transformation mechanism, where the transformation is diffusion-controlled but occurs more rapidly than pearlite formation. Bainite consists of fine, acicular (needle-like) ferrite and can also contain retained austenite. The fine structure gives bainite a good combination of strength and toughness. Bainite forms at intermediate cooling rates between those required for martensite and pearlite. The transformation is diffusion-controlled but occurs more rapidly than pearlite formation.

2.4.1 Key Factors

- **Cooling Rate:** Intermediate cooling rates between those for martensite and pearlite are required.
- **Temperature Range:** The formation of bainite is favored at temperatures below the pearlite nose on the Time-Temperature-Transformation (TTT) diagram.

The formation of martensite, pearlite, and bainite in low carbon steel is influenced by factors such as cooling rate, temperature, and the specific transformation mechanisms involved. Understanding these processes is crucial for tailoring the mechanical properties of steel for different applications through heat treatment techniques The microstructural changes that occur during the hardening process, such as quenching, involve the transformation of austenite, the high-temperature phase, into different microstructures based on the cooling rate. Let's explore the key microstructural changes associated with quenching:

2.4.2 Microstructural Changes

- **Acicular Ferrite:** Bainite consists of fine, needle-like ferrite structures. The diffusion of carbon and other alloying elements is sufficient to form ferrite, but it occurs at a faster rate than in pearlite.

2.4.3 Properties

- **Strength and Toughness:** Bainite provides a good combination of strength and toughness, making it desirable for certain applications where a balance between these properties is crucial.

Some other important heat treatment processes for low carbon steel—annealing, normalizing, and tempering—and how each influences the hardening of the material. Additionally, we'll outline the advantages quenching has over these methods.

2.5 Annealing

Annealing is a heat treatment process that involves heating steel to a specific temperature and holding it there for a prolonged period, followed by slow cooling. It allows for the recrystallization and grain growth of the steel, resulting in a coarse pearlitic or ferritic structure. Annealing reduces hardness and brittleness, improving machinability and facilitating further processing.

2.5.1 Advantages

- **Softening:** Annealing softens the steel, making it more workable and less brittle.

- **Stress Relief:** It relieves internal stresses, minimizing the risk of distortion or cracking.

2.6 Normalizing

Normalizing is a heat treatment process similar to annealing but involves air cooling in ambient conditions. It results in a fine-grained ferritic-pearlitic microstructure. Normalizing refines the grain structure and enhances both strength and ductility.

2.6.1 Advantages

- **Uniform Structure:** Normalizing produces a more uniform and fine-grained structure, improving the overall mechanical properties.
- **Reduced Machining Costs:** The refined microstructure reduces machining costs and improves machinability.

2.7 Tempering: Tempering is performed after quenching and involves reheating the hardened steel to a temperature below the critical point, followed by controlled cooling. It results in the transformation of martensite into a mixture of ferrite and cementite. Tempering reduces the hardness and brittleness associated with fully hardened martensite, while improving toughness and ductility.

2.7.1 Advantages

- **Improved Toughness:** Tempering imparts toughness and ductility to the steel, making it suitable for applications requiring a balance of strength and toughness.
- **Stress Relaxation:** It helps relieve internal stresses induced during quenching.

2.8 Advantages of Quenching over Other Methods

1. Rapid Hardening:

- **Quenching Advantage:** Quenching provides rapid cooling rates, allowing for the formation of hard and brittle martensite, which may not be achieved with slower cooling methods like annealing and normalizing.

2. Enhanced Hardness

- **Quenching Advantage:** The rapid cooling in quenching results in a higher hardness compared to annealing and normalizing, making it suitable for applications where high hardness is required.

3. Fine Microstructure:

- **Quenching Advantage:** Quenching can produce a fine and uniform microstructure, especially when alloying elements are present, leading to improved mechanical properties.

4. Controlled Properties:

- **Quenching Advantage:** Quenching allows for precise control over the mechanical properties of steel by adjusting factors such as quenching medium, temperature, and time.

5. Application Flexibility:

- **Quenching Advantage:** Quenching is widely used in applications where high hardness and wear resistance are critical, such as in the production of cutting tools, gears, and various machine components.

While annealing, normalizing, and tempering contribute to the overall heat treatment of low carbon steel, quenching offers advantages in terms of rapid hardening, enhanced hardness, and the ability to achieve a fine microstructure. The choice of heat treatment method depends on the desired mechanical properties and the specific requirements of the intended application.

2.9 SIGNIFICANCE OF QUENCHING

1. **Enhancement of Hardness:** Quenching transforms the microstructure of low carbon steel by rapidly cooling it from a high-temperature austenitic phase to a hardened martensitic phase. This transformation leads to an increase in hardness, a key mechanical property that determines the material's resistance to deformation and wear.
2. **Improvement in Strength:** The quenching process not only enhances hardness but also contributes to the overall strength of the steel. The formation of a martensitic structure results in a material with improved tensile strength, making it suitable for applications where high strength is essential.
3. **Tailoring Mechanical Properties:** Different applications demand specific mechanical properties. The ability to control the quenching process allows metallurgists and engineers to tailor the material properties of low carbon steel to meet the requirements of diverse industries. For example, components

requiring high hardness and wear resistance may undergo more aggressive quenching, while those needing a balance of strength and ductility may undergo a milder treatment.

2.9.1 IMPACT ON MICROSTRUCTURE

1. **Phase Transformation:** During quenching, the austenitic phase of the steel undergoes a phase transformation to martensite. This change in crystal structure is critical for achieving the desired mechanical properties.
2. **Grain Size and Homogeneity:** The cooling rate during quenching also influences the grain size and homogeneity of the microstructure. Fine-grained structures often result in improved mechanical properties, such as increased toughness and fatigue resistance.

2.10 PURPOSE OF QUENCHING

The primary purpose of quenching is to alter the microstructure of the metal, particularly steel, in order to enhance its mechanical properties. By controlling the cooling rate during quenching, it's possible to achieve specific structures within the material, which, in turn, determine its hardness, strength, and other key characteristics.

2.10.1 MECHANISMS INVOLVED

1. **Phase Transformation:** Quenching involves a phase transformation in steel. When steel is heated to a high temperature, it undergoes a phase change from a crystalline structure called austenite to a harder phase known as martensite during rapid cooling. Martensite is characterized by a highly stressed and distorted lattice structure, contributing to the hardness of the material.

2. **Formation of Other Phases:** Depending on the alloy composition of the steel, quenching may also result in the formation of other phases, such as bainite or pearlite, each with its own set of mechanical properties. However, martensite is often the desired phase for achieving maximum hardness.

2.11 FACTORS INFLUENCING HARDENING CHARACTERISTICS

1. **Initial Microstructure:** The initial microstructure of the steel, particularly its composition and the presence of impurities, influences how it responds to quenching. Different alloys and initial structures will result in varying hardening characteristics.
2. **Quenching Medium:** The choice of quenching medium plays a critical role. Common quenching media include water, oil, and brine. Water provides rapid cooling but can lead to high stresses and the risk of cracking. Oil has a slower cooling rate, reducing the risk of cracking, but it may not provide as much hardness as water. Brine, being a saltwater solution, offers an intermediate cooling rate.
3. **Temperature Considerations:** The temperature at which quenching occurs is crucial. The steel is heated to the austenitic phase, where the crystalline structure is less ordered and more malleable. The specific austenitizing temperature varies depending on the steel composition. Quenching is typically performed rapidly from this high-temperature phase.
4. **Cooling Rates:** The cooling rate during quenching is a key factor in determining the final microstructure. Faster cooling rates generally result in a higher hardness. However, excessively rapid cooling can lead to distortion, cracking, or even incomplete transformation.

5. **Agitation and Circulation:** The agitation or circulation of the quenching medium around the metal being quenched helps ensure uniform cooling. Uneven cooling can result in non-uniform hardness and increased risk of distortion or cracking.
6. **Quenching Fixtures:** The design of fixtures used during quenching can also influence the cooling rate and, consequently, the hardening characteristics. Properly designed fixtures can help control distortion and improve uniformity.

2.12 QUENCHING PROCESS STEPS

The steel is heated to its austenitic phase, a temperature specific to the steel composition, the heated steel is rapidly immersed in the chosen quenching medium to induce rapid cooling. After quenching, some steels undergo a tempering process. Tempering involves reheating the steel to a lower temperature to relieve stresses and modify the hardness and toughness of the material.

The quenching process is a carefully controlled heat treatment step that transforms the microstructure of steel to achieve desired mechanical properties. The choice of quenching medium, temperature considerations, and cooling rates are critical factors that metallurgists carefully manipulate to tailor the hardness and strength of the final product.

2.13 PROPERTIES OF LOW CARBON STEEL

1. **Hardness:**
   - **Before Quenching:**
     - In its initial state, low carbon steel is relatively soft and ductile.
   - **After Quenching:**

        - The quenching process is primarily aimed at increasing the hardness of low carbon steel. Rapid cooling during quenching transforms the microstructure, favoring the formation of martensite, a hard and brittle phase. This leads to a significant increase in hardness.

2. **Tensile Strength:**
    - **Before Quenching:**
        - low carbon steel in its annealed or normalized state exhibits moderate tensile strength.
    - **After Quenching:**
        - Quenching is aimed at contributing a substantial increase in tensile strength. The formation of martensite, known for its high strength, is a key factor. However, the increase in tensile strength leads to increased brittleness.
3. **Impact Resistance**
    - **Before Quenching:**
        - In its initial state, low carbon steel tends to have better impact resistance, thanks to a more ductile microstructure.
    - **After Quenching:**
        - The rapid cooling of quenching aims to increase hardness but often at the expense of impact resistance. Martensite is a brittle phase, and as a result, the material becomes more susceptible to fracture upon impact.

2.14 INFLUENCE OF QUENCHING ON MECHANICAL PROPERTIES

1. **Hardness:**
    - **Higher Hardness:**
        - Quenching significantly increases the hardness of low carbon steel due to the formation of martensite. The rapid cooling prevents the transformation of austenite into softer phases, resulting in a harder material.
2. **Tensile Strength:**
    - **Increased Tensile Strength:**
        - The quenching process contributes to a substantial increase in tensile strength. The martensitic structure formed during quenching enhances the material's resistance to deformation under tension.
3. **Impact Resistance:**
    - **Reduced Impact Resistance:**
        - While hardness and tensile strength are improved, the brittleness associated with the martensitic phase decreases the impact resistance of the material. This is a trade-off that needs to be considered based on the specific application requirements.

2.15 HEAT TREATMENT AND TEMPERING

After the quenching process, some low carbon steels undergo a tempering step. Tempering involves reheating the steel to a lower temperature, which imparts a degree of ductility and toughness back into the material. This is particularly important for applications where high impact resistance is required.

2.14.1 APPLICATION CONSIDERATIONS

1. The choice of quenching medium (water, oil, brine) and the cooling rate play a crucial role in determining the final properties of the steel.
2. The specific alloy composition of low carbon steel influences the hardenability, or the depth to which the steel can be effectively hardened.

The quenching process significantly influences the properties of low carbon steel, making it a versatile material with tailored mechanical characteristics. The trade-offs between hardness, tensile strength, and impact resistance highlight the importance of carefully selecting heat treatment parameters based on the intended application of the steel. The choice of quenching medium depends on the specific application requirements. Water may be suitable for applications prioritizing extreme hardness, while oil and brine may be preferred for a balance between hardness and toughness. It's essential to note that the exact effects can vary based on factors such as steel composition, initial microstructure, and quenching process parameters. Individual studies may provide more specific insights and detailed comparisons based on experimental data. The microstructure of steel after quenching is a critical aspect of the heat treatment process and significantly influences the material's mechanical properties. The quenching process involves rapid cooling from elevated temperatures, typically above the critical transformation temperature, leading to a variety of changes in the microstructure. Let's explore the key components of the microstructure, including phases, grain size, and changes that occur under quenching conditions:

2.15 PHASES IN THE MICROSTRUCTURE

1. **Austenite:**
    - **Pre-Quenching:**
        - At high temperatures, steel is typically in the austenitic phase. Austenite is
        - a face-centered cubic (FCC) crystal structure that is relatively soft and ductile.
2. **Martensite:**
    - **After Quenching:**
        - Rapid cooling prevents the normal transformation of austenite into other phases. Instead, it transforms into a hard, tetragonal crystal structure known as martensite.
        - Martensite is characterized by a highly stressed and distorted lattice, leading to increased hardness and brittleness.
3. **Bainite:**
    - **Formation Conditions:**
        - Depending on cooling rates and alloy composition, bainite may also form during quenching. Bainite is a mixture of ferrite and cementite and offers a balance between hardness and toughness.
        - Forms at lower temperatures and slower cooling rates than martensite.

4. **Pearlite:**
    - **Formation Conditions:**
        - In some cases, if the cooling rate is slow enough, pearlite may form. Pearlite is a lamellar structure composed of alternating layers of ferrite and cementite.
        - It provides a softer and more ductile microstructure compared to martensite.

1. **Tempered Martensite:**
    - **Subsequent Heat Treatment:**
        - In some cases, especially when tempering follows quenching, martensite may undergo a secondary heat treatment process.
        - This tempering process reduces internal stresses, slightly increases ductility, and may result in the precipitation of fine carbides.

2.15.2 MICROSTRUCTURE AND MECHANICAL PROPERTIES

1. **Hardness:**
    - Martensite, being a hard and brittle phase, contributes significantly to the increased hardness of the material after quenching.
    - Fine-grained structures also contribute to hardness, as grain boundaries act as barriers to dislocation movement.
2. **Strength:**
    - The presence of martensite and, to some extent, bainite contributes to increased strength due to their hard and crystalline structures.
    - Fine-grained structures generally lead to increased strength.

3. **Toughness:**
    - While martensite provides high hardness, it tends to be brittle and reduces toughness. The formation of bainite and fine-grained structures can help balance hardness with improved toughness.

2.15.1 GRAIN SIZE AND CHANGES UNDER QUENCHING

2. **Grain Size:** Pre-Quenching
        - Before quenching, steel typically has a larger, coarse-grained structure.
    - **After Quenching:**
        - The rapid cooling during quenching promotes the formation of fine-grained structures. The exact grain size depends on factors such as the cooling rate and alloy composition.
        - Fine-grained structures often lead to improved mechanical properties, such as increased hardness and strength.
3. **Changes in Crystal Structure**
    - **Transformation to Martensite:**
        - The primary change under quenching conditions is the transformation of austenite to martensite. This transformation involves displacive lattice rearrangement, resulting in the characteristic needle-like or plate-like martensitic structure.
    - **Distortion and Stresses:**
        - The rapid nature of quenching prevents the diffusion of atoms, leading to a high degree of internal stresses and lattice distortion in martensite.

2.16 EFFECT OF ALLOYS ON HARDENING

Alloying elements play a significant role in influencing the hardening behavior of carbon steel. Two common alloying elements found in carbon steel are manganese (Mn) and silicon (Si). Let's delve into a detailed explanation of how these elements affect the phase transformation kinetics and mechanical properties during the hardening process

The main objectives of heat treatment as follows

1. To increase strength, hardness and wear resistance (bulk hardening, surface hardening)
2. To increase ductility and softness (tempering, re-crystallization annealing) to increase toughness (tempering, re-crystallization annealing)
3. To obtain fine grain size (re-crystallization annealing, full annealing, normalizing)
4. To remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding (stress relief annealing)
5. To improve machinability (full annealing and normalizing)
6. To improve cutting properties of tool steels (hardening and tempering)
7. To improve surface properties (surface hardening, corrosion resistance-stabilizing treatment and high temperature resistance-precipitation hardening, surface treatment)
8. To improve electrical properties (re-crystallization, tempering, age hardening)
9. To improve magnetic properties (hardening, phase transformation)

The effect of manganese (Mn) improves solid solution strengthening, manganese is a strong austenite-forming element and readily dissolves in the ferrite and austenite phases. The addition of manganese promotes the formation of a solid solution in the steel, leading to solid solution strengthening. This enhances the strength and hardness of the material in its as-quenched state. Manganese also tends to retard the formation of cementite (Fe_3C) during the eutectoid reaction, favoring the formation of a finer pearlitic microstructure. This alteration in phase transformation kinetics contributes to improved mechanical properties. Manganese can also enhances hardenability by slowing down the diffusion of carbon during the quenching process. This effect allows for the formation of a more uniform and refined martensitic structure. The presence of manganese contributes to an increase in both strength and toughness. It refines the microstructure, resulting in improved mechanical properties.

Silicon is another element that readily dissolves in the ferrite and austenite phases, contributing to solid solution strengthening. Similar to manganese, silicon strengthens the steel in its as-quenched state by forming a solid solution in the iron matrix. Silicon promotes the formation of ferrite during the cooling process, influencing the phase transformation. This can lead to a microstructure with a higher ferrite content. Silicon enhances hardenability by promoting the formation of fine-grained structures. It aids in achieving a more uniform and finer martensitic structure during quenching. Silicon contributes to improved strength and ductility, particularly in the presence of other alloying elements. It helps in achieving a balance between strength and formability, making the steel suitable for various applications.

The combination of manganese and silicon can have a synergistic effect on the hardening behavior. Together, they contribute to the refinement of microstructures and the improvement of mechanical properties. When properly balanced, the addition of manganese and silicon enhances the overall performance of carbon steel. This includes increased strength, hardness, toughness, and improved machinability. The alloying elements manganese and silicon have a profound impact on the hardening behavior of carbon steel. They influence phase transformation kinetics, alter microstructural characteristics, and play a crucial role in determining the mechanical properties of the material. The careful selection and control of alloying elements allow engineers and metallurgists to tailor the properties of carbon steel for specific applications, striking a balance between strength, hardness, and other desirable characteristics.

The microstructure of steel after quenching is characterized by the presence of martensite, bainite, or pearlite, depending on the cooling rates and alloy composition. The balance between hardness, strength, and toughness can be tailored through careful control of the quenching process and subsequent heat treatments. The fine-grained structures formed during quenching contribute significantly to the improved mechanical properties of the material.

2.17 MODELLING AND SIMULATIONS

Modeling and simulation studies play a crucial role in predicting the hardening behavior of low carbon steel under various conditions. These studies leverage computational tools to simulate the complex thermomechanical processes involved in heat treatment. Here are some commonly used models and simulations along with a discussion on their accuracy and limitations

2.17.1 Phase Field Models: Phase field models simulate the evolution of microstructure during phase transformations in materials. These models can predict the formation of different phases like martensite, pearlite, and bainite during quenching and tempering processes.

- **Accuracy:** Phase field models provide a detailed representation of microstructure evolution and are capable of capturing complex phase interactions.
- **Limitations:** Computational cost and resource requirements can be significant. Accuracy depends on the fidelity of the chosen parameters and the underlying assumptions of the model.

2.17.2 CALPHAD (Calculation of Phase Diagrams) Method: CALPHAD is a thermodynamic method that utilizes phase diagrams to predict the phase composition of alloys at different temperatures and compositions. CALPHAD can predict phase transformations during heat treatment based on thermodynamic principles.

- **Accuracy:** CALPHAD is generally accurate for predicting phase stability and composition under equilibrium conditions.
- **Limitations:** It may not capture kinetic effects during rapid cooling or the evolution of non-equilibrium microstructures.

2.17.3 Kinetic Monte Carlo (KMC) Simulations: KMC simulations model the stochastic evolution of a system by simulating individual atomic events. KMC can predict the kinetics of phase transformations during heat treatment.

- **Accuracy:** KMC simulations are effective in capturing kinetic aspects of phase transformations, such as nucleation and growth.

- **Limitations:** The accuracy depends on the representation of atomic events and may require extensive computational resources.

2.17.4 Finite Element Method (FEM) Simulations: FEM simulations model the thermomechanical behavior of materials, including heat transfer, phase transformation, and stress-strain relationships. FEM can predict temperature distributions and phase evolution during heat treatment.

- **Accuracy:** FEM simulations can provide accurate predictions when calibrated with experimental data.
- **Limitations:** Accurate representation of material properties and boundary conditions is crucial. Calibration is often required for complex systems.

2.17.5 Artificial Neural Networks (ANNs): ANNs are machine learning models that can learn complex relationships between input and output data. ANNs can be trained to predict hardening behavior based on input parameters.

- **Accuracy:** ANNs can capture non-linear relationships and patterns in data.
- **Limitations:** Limited interpret-ability, reliance on training data quality, and potential challenges in generalization to new conditions.

2.17.6 OVERALL CONSIDERATIONS

1. **Accuracy Verification:**
    - The accuracy of these models is often validated against experimental data, and the reliability of predictions depends on the quality of input parameters and the fidelity of the model assumptions.

2. **Computational Resources:**
    - High-fidelity models may require substantial computational resources, limiting their applicability in certain situations.
3. **Experimental Validation:** Despite advancements in modeling, experimental validation is essential to ensure the reliability of predictions under real-world conditions.
4. **Integration of Models:** Combining different modeling approaches, such as coupling thermodynamic models with kinetic simulations, can provide a more comprehensive understanding of the hardening behavior.

The quenching process is crucial for achieving desired properties in steel and aluminum alloys. Proper cooling through agitation of the quenchant is necessary, with parameters like quenching medium, temperature, and state playing significant roles. Low carbon steels, categorized by their carbon content, are widely used in industries due to their affordability and ease of fabrication. Enhanced hardness and mechanical properties result from increased carbon concentration, which occurs during hardening heat treatment through the transformation of austenite into martensite. The choice of quenching medium depends on the heat treatment method, steel composition, and part size and shape.

Extensive research has focused on high-strength steels, particularly quenched and tempered micro-alloyed steels, which are poised to become the preferred materials for next-generation high-strength steel sheets. These steels offer a favorable combination of strength and toughness, finding applications in automotive structural components, power transmission, and impact resistance systems. A comprehensive understanding of material properties and design requirements is crucial when selecting steels for engineering components.

Paris and Erdogan (1963) proposed a relationship between crack growth and stress intensity factor "K" at the crack tip to monitor crack growth. This relationship is expressed as = ( )dnda =K(C), where C and m are material properties.

Heat treatment is primarily conducted to address the need for new designs and materials capable of better withstanding fracturing. Key heat treatment methods include annealing, normalizing, hardening, and tempering, each altering the mechanical and microstructural properties of materials to suit specific purposes (Dell, 1989).

Nam and Bae (1999) suggested that annealing leads to the softening of the microstructure, occasionally accompanied by recrystallization and recovery. They also noted changes in carbide morphology during heat treatment. Heat treating steel enhances its machinability, ductility, hardness, tensile strength, impact resistance, and corrosion resistance. Low carbon steel, obtained from Universal Steels Rolling Mill in Lagos, Nigeria, finds wide applications in oil and gas pipelines, power plant components, armored structures, and building construction. However, no characterization of this steel under heat treatment has been conducted. This research aims to evaluate selected mechanical properties and examine the microstructure of low carbon steel when subjected to annealing, normalizing, hardening, and tempering. The study also seeks to compare these properties and recommend the appropriate heat treatment method based on the prioritized mechanical property.

Sung S Kang et al. (2011) evaluated a low carbon cast steel alloy designed for offshore structures under different heat treatment cycles. They studied the effect of austenitizing time on austenite grain size and conducted tempering experiments at various temperatures and cooling rates. Increasing the austenitizing time initially decreased the austenite grain size until it reached a minimum value, followed by an increase. Higher tempering temperatures led to decreased yield and tensile strengths but improved ductility properties. Yield and tensile strengths were unaffected by cooling rate from the tempering temperature, whereas ductility properties were slightly affected. A significant improvement in toughness to fracture occurred with increasing tempering temperature. Cooling rate notably affected impact energy for samples tempered at 650°C, with the highest value achieved at a cooling rate of 50°C/s.

Ahaneku I. E, Kamal A. R , Ogunjirin O. A. (2012) investigated the effects of heat treatment on the properties of mild Steel using different quenchants. This study was conducted in order to improve the mechanical properties of mild steel materials used as bolts and studs in coupling agricultural machinery following their frequent failure in service. Heat treatment at 9000 C for four hours was done and six specimens of each were then quenched with different media used as the major source of strength enhancement. The universal testing machine (UTM) was utilized for the various mechanical tests. The results of the tests showed positive changes in the strength properties of the mild steel material, in terms of high tensile strength, toughness, ductility and hardness. Water quenched specimen has the highest tensile strength (497.76N/mm2), hardness value (138.27), toughness (168.38) and bending at yield (749.49N/mm2). It also recorded the lowest ductility of 28.36% when compared with ductility values for other quenchants. These desirable qualities are needed for durability in service, especially for rugged agricultural operations like tillage. Water proved to be the best quenchant for achieving these desirable qualities among the quenching media used. The findings from the study showed that water quenched specimens proved superior to other specimens quenched in air, furnace and oil, respectively with respect to high strength properties, Brinell hardness, toughness and yield point. Water being relatively more readily available than other quenchants except air, easy to use and safe to handle is preferred. It is therefore concluded that from the standpoint of strength and economy that water quenching should be used for heat-treating mild steel components for coupling agricultural machinery.

According to Hassan, S. B, Agboola. J.B, Aigbodion, V.S. and Williams E.. J (2013) the hardening characteristics of medium carbon steel and ductile cast iron using neem oil as quenching medium has been investigated. The samples were quenched to room temperature in Neem oil. To compare the effectiveness of the neem oil samples were also quenched in water and SAE engine oil the commercial quenchants. The microstructures and mechanical properties of the quenched samples were used to determine the quench severity of the neem oil. The result shows that hardness value of the medium carbon steel increased from 18.30HVN in the as-cast condition to 21.60, 20.30and 20.70HVN while that of ductile cast iron samples increased from 18.90HVN in the as-cast condition to 22.65, 20.30 and 21.30HVN for water, neem oil and SAE40 engine oil respectively. The as-received steel sample gave the highest impact strength value and water quenched sample gave the least impact strength. The impact strength of the medium carbon steel samples is 50.84, 41.35, 30.50 and 45.15 Joule and that of ductile iron is 2.71, 1.02, 0.68 and 1.70 Joule for as-cast condition, neem oil, water and SAE 40 engine oil quenched respectively. The microstructure of the samples quenched in the Neem oil revealed the formation of martensite. Hence, neem oil can be used where cooling severity less than that of water but greater than SAE 40 engine oil is required for hardening of low carbon steels and ductile cast iron.

The effectiveness of the neem oil as quenching medium in the hardening process of low carbon steel and ductile cast iron has been quantitatively assessed using hardness values and impact energy in particular. From the results obtained in this study, the following conclusions can be drawn; 1. Neem oil have a hardness value less than that of water but higher hardness value than that of SAE40 engine oil. Hence, Neem oil can be used where cooling severity less than water but greater than SAE 40 engine oil is required for hardening of low carbon steel and ductile cast iron. 2. Neem oil can be used to improve the toughness of these samples since it has higher impact energy values than water which is the common quenching medium.

Adeleke A.A., Ikubanni P.P, Adediran, Agboola O.O.et al (2014) studied the tensile strength and micro-structural behaviour of medium carbon steel quenched in pap water, coconut water and spent engine oil (SPE). On the strength and microstructural behavior of medium carbon steel was studied. Prepared samples were first heat-treated in a muffle furnace to temperature of 840 and normalized in order to reduce the stresses that might have been induced during machining operations. The prepared samples were later heated to 730 , 760 and 790 and soaked for 30, 45 and 60 minutes, respectively using a muffle furnace and then quenched in different media. The control sample was only heated to 840 and normalized. A testometric M500-50AT model machine was used for the tensile test. M100 optical metallurgical microscope was used for the microstructural examination. An improved yield (YS) and ultimate tensile (UTS) strengths were observed in all the samples quenched in different media against the as-received samples. As-received samples tend to yield earlier at offset strain of about 0.07% which implies a drop in yield and ultimate tensile strength. SPE-quenched samples have better YS, UTS and percentage elongation than others. Quenched samples, irrespective of the heating temperature and soaking time has martensitic islands in matrix of ferrite phases. The quenching media proved effective in their application as quenching media.

Elsevier, (2014) Tempering of martensitic steels involves the segregation of carbon, the precipitation of carbides, the decomposition of retained austenite, and the recovery and recrystallization of the martensitic structure. As is known, the tempering process of low carbon steel includes two processes. One is the softening process that is caused by the recovery of lath martensite and dislocation substructure, the other is the strengthening process caused by the decomposition of austenite, the exsolution of supersaturated carbon and the precipitation of the second phase. The tensile strength of the steel depends mainly on the microstructure of the steel, with the increasing of the tempering temperature, on one hand the content of austenite is decreased, and on the other hand the carbide or metallic compounds in the steel lead to a second-phase precipitation strengthening. As a result, the strength and the hardness increased, while the impact energy and the elongation decreased. However, with the increasing of tempering temperature, the recovery of the martensite matrix enlarged and the generation of precipitated particles took a lot of solute atoms and reduced the atomic pinning action, which led to the elimination of internal stress, the decrease in the dislocation density and the decline in yield strength.

Agunsoye J. O, . Fakolujo O. A, . Oladele I. O et. Al (2015) used water, oil, and air as quenching media and evaluated the microstructure, hardness, and tensile properties of the steel. The results showed that water quenching produced the highest hardness values and fine-grained microstructure, while air quenching produced the lowest hardness values and a coarse-grained microstructure. Oil quenching resulted in intermediate values for both hardness and grain size. The study concluded that the choice of quenching media significantly influenced the microstructure and mechanical properties of medium carbon steel.

In a quest for the development of a quenching medium with good economics like water, but having less severity of quench and yet producing appreciable hardening. an investigation of the hardening characteristics of medium carbon steel quenched in agitated water based eggshell powder by Aliu S.A, Orumwense F.F.O and Ogidiga O.L (2015) the potential of agitated waterbased eggshell powder as a quenching medium for hardening medium carbon steel (SAE-AISI 1045) was investigated. 25wt% eggshell The water-based eggshell powder quenchant was used in un-agitated and agitated conditions in hardening medium carbon steel. The hardening characteristics of the medium carbon steel quenched in water-based eggshell powder quenchant were compared to those obtained with water and engine oil (SAE40) as quenchants. The quenched steel samples in agitated waterbased eggshell powder quenchant showed higher tensile strength and hardness values compared to water and engine oil (SAE 40) and produced toughness values in between that of engine oil (SAE 40) and water. The microstructures of the quenched samples revealed complete transformation of the austenite into martensite.

Analysis on of mechanical properties of low carbon steel by carburization process Bello Imamudeen1, Mahmut A Savas (2015) showed that heat treatment and carburization has been acknowledged by some means of improving the various properties of metals and alloys. In this investigation the mechanical and wear behaviors of AISI 1020 carbon steels carburized at different temperature range of 850, 900 and 950^0 C have been studied and it is found that the simple heat treatment greatly improves the hardness, tensile strength and wears resistance of the AISI 1020 carbon steels. The aim has been to examine the effects of these different carburization temperatures and conditions on the mechanical and wear properties of the carburized AISI 1020 carbon steels. For above purpose firstly the AISI 1020 carbon steels are carburized under the different temperature range as stated above and then it is tempered at 200^0 C for half an hour after this the carburized and tempered AISI 1020 carbon steels are subjected for different kind of test such as hardness test, tensile test and the toughness test. The results of these experiment shows that the process of carburization greatly improves the mechanical and wear properties like hardness, tensile strength and wear resistance and these properties increases with increase in the carburization temperature but apart from this the toughness property decreases and it is further decreases with increase in carburization temperature. The experimental results also shows that the AISI 1020 carbon steels carburized under different temperature range as stated above, with in which the AISI 1020 carbon steels carburized at the temperature of 950^0 C gives the best results for the different kinds of mechanical and wear properties because at this temperature it gives highest tensile strength, hardness and wear resistance, so it must be preferred for the required applications

One researcher (Gábor Kerekes, 2016) presented overview of possibility of use bio-oils as quenchant. The results showed that bio-oils can be a real alternatives of mineral oils in a given case of course. The thermo-kinetic parameters of sunflower, soybean and corn oils were same or better than the investigated mineral quenching oil. (Gábor Kerekes, 2016) Due to demerits of water and oil we have tried to study the effect of various quenching media like brine (37% salt + water), vegetable oil (cotton seed oil), water, oil-in-water emulsion transfer rate extraction from the hot-metal during the cooling

Mordyuk B.N et al, (2016) The effects of severe plastic deformation induced by ultrasonic impact treatment (UIT) and the electric discharge surface alloying (EDSA) with chromium on the stress-controlled fatigue response of low carbon steel 20GL are studied. The surface microrelief and integrity were analyzed using light microscopy and scanning electron microscopy (SEM). The structural formations in the sub-surface layers were characterized by means of X-ray diffraction analysis and transmission electron microscopy (TEM). The steel specimens underwent UIT, and complex UIT+EDSA and UIT+EDSA+UIT processes demonstrate the fatigue strength magnitudes increased respectively by ~15, ~5 and ~30% on the base of 10^7cycles in comparison with that for the pristine specimen. SEM analysis of fracture surfaces reveals the subsurface crack nucleation in the UIT-processed specimens instead of superficial crack initiation observed in the pristine and EDSA-processed ones. TEM studies demonstrate that a dislocation-cell structure forms in ferrite grains and partial dissolution of cementite occurs in pearlite grains both at the surface after UIT and in the layer at a depth of 15-25 μm after the UIT+EDSA+UIT process. The enhanced fatigue strength and prolonged lifetime of the low-carbon steel specimens after UIT and UIT+EDSA+UIT processes are concluded to be associated with the subsurface crack nucleation achieved by the following factors: (i) minimized surface roughness and improved integrity of the modified layer; (ii) compressive residual stresses; and (iii) surface hardening coupled with the alloying by chromium and with the formation of the dislocation-cell structure containing the cell walls impenetrable to moving dislocations at cyclic loading.

Adeyemi E O, Folorunso O.E et. al (2017) studied the effect of different quenching media, including water, brine, and oil, on the mechanical properties of medium carbon steel. Results showed that the hardness, strength, and toughness of the steel varied with the type of quenching media.

B.L. Ferguson, Z. Li, A.M. Freborg (2017) investigated on how to achieve high strength and toughness by heat treatment is a primary advantage of steel alloys. However, the development of internal stress and geometric distortion accompanies these hardening processes. Simulation of heat treatment processes must include the evolution of microstructural phases in order to calculate the mechanical behavior of the composite microstructure as the alloy changes phase. This paper discusses an optimization method to derive the phase transformation kinetics parameters from dilatometry experiments. A discussion of a method based on the lattice parameters of individual phases and a method based on a lever rule for building the bridge between phase transformations and dilatometry strains is offered. The determination of kinetics parameters using an optimization algorithm was implemented into a commercial heat treatment simulation software package, dante®. Using Pyrowear 53 steel as an example, the kinetics parameters were fit for various carbon contents. The heat treatment process steps for a 3-D test bar model with a notch on the top surface were simulated, with steps including furnace heat up, carburization, air transfer from the furnace to quench tank, quenching in heated oil, cryogenic treatment, and tempering. Because of a high amount of retained austenite after oil quenching, a cryogenic treatment is used to complete the martensite transformation in the high carbon case of the test bar. After the deep freeze, the test bar was tempered. The predicted distortion and residual stresses were verified by the experimental testing.

Steel is a ferrous metal classified based on their percentage of carbon. The Carbon content ranges from 0.15-1.5%. Although the number of steel specifications runs into thousands, low carbon steel accounts for more than 90% of the total steel output. Fracturing of materials and effort to prevent it, cost the US industry about $119 billion a year, 90% of the failure of components in a material is caused by stress application. This poses a great threat to the people, environment and economy at large.

Jianling Li, Wenjuan Sun, Xiuli Gao (2017) research paper explores the impact of different quenching media on the mechanical and microstructural properties of austenitic stainless steel. The authors used water, oil and air as quenching media and evaluated the microstructure, corrosion resistance, and mechanical properties of steel. The results of the experiments show that different quenching media have a significant impact on the mechanical and microstructural properties of the austenitic stainless steel. Specifically, quenching in oil and the polyalkylene glycol-based liquid results in lower hardness, lower tensile strength, and higher elongation compared to quenching in water and air. The authors also observe that quenching in oil and the polyalkylene glycol-based liquid results in larger grain sizes and more retained austenite, while quenching in water and air produces finer grain sizes and more martensitic transformation.

Adeyemi E O, Folorunso O.E et. al (2017) studied the effect of different quenching media, including water, brine, and oil, on the mechanical properties of medium carbon steel. Results showed that the hardness, strength, and toughness of the steel varied with the type of quenching media.

Zhang et al (2018) observed twin structured lath martensite, nano-sized precipitates, and ferrite along grain boundaries in the microstructure of quenched 0.2 wt% carbon steel. The crystallographic orientation of nano-sized precipitates with ferrite was observed to be similar to primitive hexagonal ω phase in titanium, and other body-centered cubic alloys [4]. Miernik et al obtained an optimum combination of strength and toughness by austenitizing at 900 °C, cooling to a suitable temperature in $\alpha + \gamma$ region and hardening in water. Similarly, Kanwal et al achieved significant hardness and strength compared to non-heat treated steel by oil and water quenching. Subsequent tempering slightly improves the elongation and impact toughness at a little expense of both the hardness and the strength. 13%Cr stainless steel has been found to exhibit considerable pitting potential compared to tempered steel. With the increase of tempering temperature, a significant reduction in pitting potential has been observed. Aforementioned results encourage, exploring the effect of quenching tempering heat treatment processes on microstructure, mechanical, and electrochemical properties of low carbon steel.

SreeBhavani. G, Charan, Naga Malleswara Rao (2018) investigated the effect of heat treatment to increase the hardness of low carbon steels which cannot be hardened in cold working. When heat treatment is chosen to increase the hardness in case of low carbon steels, only the Hardening operation is considered. In this work, different types of quenching media was selected to investigate their influence on hardness at different quenching temperatures.The prime object of this investigation is to illustrate the effect of heat treatment on low carbon steel (AISI 1020) to expose its mechanical property(hardness) and microstructural (microstructures) properties. Tests were carried out to determine the effects of heat treatment on the hardness of locally available mild steel using different quenchants. The findings from the study showed that water quenched specimens proved superior to other specimens quenched in air, Brine solution, Coconut oil, Neem oil, 2-T oil. Water being relatively more readily available than other quenchants except air, easy to use and safe to handle is preferred. It is therefore concluded that from the standpoint of strength and economy that water quenching should be used for heat-treating mild steel components. Water quench includes its oxidizing nature,its corrosivity and the tendency to eingxcessive distortion and cracking in case of low carbon steels. But it may also be concluded that, vegetable oil e.g., Coconut oil also imparted high hardness to the mild steel components almost equal to that of water and better texture too. Coconut oil and brine may be used in place of water where high hardness is required with less distortion. With these quenchants, there may be a less chance of formation of cracks in low carbon steels. The advantages of using air are that distortion is negligible and that the steel can easily be straightened during cooling process.One drawback here is that the surface may be oxidized by this type of cooling.

Fadare D A., Akanbi O.Y., Bodunrin.M.O. et. al (2019) investigated the effect of different quenching media on the microstructure and mechanical properties of AISI 1039 steel. Water quenching produced the highest hardness and strength values, while oil quenching resulted in the highest ductility. The authors concluded that the choice of quenching media plays a crucial role in determining the mechanical properties of steel.

Motalleb, Md. Abdul (2019) also studied the way heat treatment improve the mechanical properties of low carbon steel for manufacturing of spindle of jute spinning mill. Heating or cooling of a metal can change its microstructure, which causes variations in the mechanical and physical properties and affects the behavior of the metal in processing and operation. There are different spare parts used for different purposes collected from foreign countries in spinning mills where available machines are used in Bangladesh. Spindle is an important part of spinning mills. The spindle used in jute spinning mill required high strength and high hardness. The imported spindle is made of EN-31 metal which is basically a high carbon low alloy steel. This type of raw materials or steel is not available. The locally available raw materials are low carbon steel from which spindle can be made through property development by heat treatment. However, to achieve desired hardness and strength it is difficult to get the spindle without bending in heat treatment due to the length of spindle is too high to its diameter. Time and temperature of carburizing, quenching is the very sensitive issue to get a sound job with desire properties. In this research, heat treatment of low carbon steel is performed to improved desired properties. Quenching temperature, time and medium is considered in heat treatment process. Finally the spindle was prepared through heat treatment with desired properties comprising in a practical field of spinning mill. All the process was explained clearly for the preparation of spindle for spinning mill from locally available low carbon steel. This study also presents a numerical analysis by finite element method (FEM) using ANSYS software to model the spindle and simulate the deformation and fracture condition by applying static and dynamic load. The results show that the general behavior of the finite element method represented by the load-deflection curves. The designed spindle is subjected in various conditional loads and compared with practical field. The practical fracture behavior and bending behavior is same as simulation. As a result it is easy to design any other spare parts of industry which is imported from foreign countries. From this study it can be observed that it is possible to prepare spindle for Sacolowel ring twisting machine used in jute spinning mill from locally available low carbon steel which saves huge amount of money and time rather than collected from foreign countries.

CCBhavesh r. rana, Kamlesh m. rana, Vandana j. rao (2020) studied the effect of various quenching media on hardening behavior of en 9 steel. Media like Water, Veg. oil, Industrial oil, Brine, Rolling mill coolant, Hybrid polymer solution) on hardening behavior of EN 9 steel. EN 9 steel is also designated as C55 DIN, AISI 1055 and SAE 1055. It is mainly consist of C (0.54%), Mn (0.73%), Si (0.21%), S & P (0.015% max.). EN 9 is widely use in automobile sector as clutch plates, Break Parts, agricultural equipment & sometimes use as a structural engineering material. Different quenching media offers different type of micro structure. Normal quenching media used in industries are water, brine, oil etc. present research work involves the idea to optimization of mechanical/metallurgical properties of EN 9 steel by altering the quenching media. To consider effect of both conventional and non-conventional quenching media, present study involves use of water, brine, and industrial oil as conventional quenching media & vegetable oil, rolling mill coolant emulsion and polymer solution as non-conventional quenching media. By altering quenching media microstructural changes occurs which directly affect the mechanical properties of EN 9 steel. Normally martensite, retained austenite & ferrite; their amount and location can control the hardness, tensile strength, yield strength and ductility of EN 9 steel. Brine solution offers best mechanical properties among all the other quenchants. Brine solution effect reflects in the form of lath martensite plates and retained austenite plus ferrite phase in the microstructure

Muhammad ArslanHafeez et al, (2020) used the nanoindentation technique is widely used to measure the micro-scale mechanical properties of various materials. Herein, the nanoindentation-based micro-mechanical and electrochemical properties of low-carbon steel were investigated after quench hardening and tempering processes. The steel was produced on a laboratory scale and subjected to quench hardening separately in two different media-water and brine (10 wt% NaCl)-and subsequent moderate temperature tempering. Microstructure analysis revealed that the lath martensite phase formed after all heat treatments, having different carbon percentages ranging from

0.26% to 0.58%. A ferrite phase was also observed in the microstructure in three different morphologies, i.e., allotriomorphic ferrite, idiomorphic ferrite, and Widmanstätten ferrite. Nanoindentation analysis showed that the brine quench hardening process provided a maximum twofold improvement in indentation hardness and a 51% improvement in stiffness with a 30% reduction in reduced elastic modulus compared with as-received steel. Electrochemical performance was also evaluated in a 1% HNO3 solution. The water quench-hardened and tempered sample exhibited the highest corrosion resistance, whereas the brine quench-hardened sample exhibited the lowest corrosion resistance among all heat-treated samples.

Haitai Xiao et al, (2020) Surface hardening improves the strength of low-carbon steel without interfering with the toughness of its core. In this study, we focused on the microstructure in the surface layer (0–200 µm) of our low-carbon steel, where we discovered an unexpectedly high level of hardness. We confirmed the presence of not only upper bainite and acicular ferrite but also lath martensite in the hard surface layer. In area of 0–50 µm, a mixed microstructure of lath martensite and B1 upper bainite was formed as a result of high cooling rate (about 50–100 K/s). In area of 50–200 µm, a mixed microstructure of acicular ferrite and B2 upper bainite was formed. The average nanohardness of the martensite was as high as 9.87 ± 0.51 GPa, which was equivalent to the level reported for steel with twenty times the carbon content. The ultrafine laths with an average width of 128 nm was considered to be a key cause of high nanohardness. The average nanohardness of the ferrites was much lower than for martensite: 4.18 ± 0.39 GPa for upper bainite and 2.93 ± 0.30 GPa for acicular ferrite. Yield strength, likewise, was much higher for martensite (2378 ± 123 MPa) than for upper bainite (1007 ± 94 MPa) or acicular ferrite (706 ± 72 MPa). The high yield strength value of martensite gave the surface layer an exceptional resistance to abrasion to a degree that would be unachievable without additional heat treatment in other steels with similar carbon content.

J Mater Sci, (2020) The advanced electron backscatter diffraction (EBSD) technique was used to examine the microstructure of a widely used A517GrQ low-carbon low-alloy steel after different heat treatments. Three distinguishable microstructures were studied. Slow cooling in the furnace after austenitization led to the formation of a granular structure that consisted of massive ferrite and randomly distributed M–A constituents. Medium rate cooling in air produced granular bainite that was composed of lath ferrite, and M–A constituents were distributed between the laths. Lath martensite was formed by fast cooling into ice brine. EBSD analysis revealed that, in one austenite grain, the massive ferrite in the granular structure and the lath ferrite in the granular bainite were predominately separated by high-angle boundaries, whilst the ferrite lath in the martensite were separated by low-angle boundaries. The specimens with granular bainite formed by medium rate cooling had higher strength (both yield strength and tensile strength), and also almost 5 times higher Charpy impact energy than that of the specimens containing granular structure obtained at the slow cooling. The strength of the specimens with lath martensite after quenching into ice brine was slightly higher than the granular bainite but were associated with much lower Charpy impact energy. The present work indicates that it is critical to control the cooling rate after austenitization in order to simultaneously achieve high strength and high toughness of low-carbon low-alloy steels.

J Mater Sci, (2021) Heavy plate steels with bainitic microstructures are widely used in industry due to their good combination of strength and toughness. However, obtaining optimal mechanical properties is often challenging due to the complex bainitic microstructures and multiple phase constitutions caused by different cooling rates through the plate thickness. Here, both conventional and advanced microstructural characterization techniques which bridge the meso- and atomicscales were applied to investigate how microstructure/mechanical propertyrelationships of a low-carbon low-alloyed steel are affected by phase transformations during continuous cooling. Mechanical tests show that the yield strength increases monotonically when cooling rates increase up to 90 K/s. The present study shows that this is associated with a decrease in the volume fraction of polygonal ferrite (PF) and a refinement of the substructure of degenerated upper bainite (DUB). The fine DUB substructures feature C-rich retained austenite/martensite-austenite (RA/M-A) constitutes which decorate the elongated micrograin boundaries in ferrite. A further increase in strength is observed when needle-shaped cementite precipitates form during water quenching within elongated micrograins. Pure martensite islands on the elongated micrograin boundaries lead to a decreased ductility.

Nwigwe, Mater J. et al (2021) believed is so important because it is the most widely used alloy and for a very good reason. Steel is majorly an alloy of iron and carbon though not in the exclusion of other alloying elements. Carbon steel is a major type of material that is commonly used in the industrial field for various applications. Carbon steel consists of low carbon, medium carbon and high carbon steel. In this research work, medium carbon steel is being investigated. Literature has proved that medium carbon steel usually fail in the industry due to corrosion and as well as heat treatment which generates gaseous molecules, irregular grain size and internal stresses in the heat affected zone. However, medium carbon steel is an iron alloy with carbon composition more than 0.25% to 0.5%. It is a known fact that medium carbon steel provides an excellent trade-off between strength and ductility, and it is used in many types of steel parts. Iron is relatively soft and the carbon in steel reduces this softness thereby making medium carbon steel harder than the conventional iron. Alloying elements like manganese, chromium, tungsten, and vanadium have always acted as hardening agents when added in steel though the accuracy in the proportion of these elements decides the specific properties that will be achieved in the steel. Medium carbon steel has been virtually and economically used in all aspects of human endeavor such as in oil and gas, manufacturing, construction, medical, transport, textile and aerospace industries etc. The failure of parts produced from engineering materials such as medium carbon steel in various industries by corrosion has become a major problem today. Corrosive processes are mostly directly and indirectly connected to our everyday lives. Corrosion also means the physicochemical degradation of a metal in a given environment, by looking at how it wears away the material, different types of corrosion can be classified. Corrosion problem is observable in numerous places, such as buildings, industries, viaducts, ancient and modern works of art are also not left out. Corrosion can as well emanate from the cross section losses of materials that have lower ductility, yield strength and ultimate strength. It reduces the life span of structures leading into structural vulnerability which usually results to structural failure. Corrosion is responsible for many catastrophes that have bedeviled operational materials in the engineering industries since the history of man.

Tonye Jack, Sandeep Yadav, et al (2021) investigated Microstructural changes on quenched-tempered API 5L X65 pipeline steel. three API 5L X65 pipeline steels were subjected to a variety of quenching rates in brine and oil after heating up to 800°C. Thereafter, tempering was performed at a lower temperature of 550°C. Quenching the steels at a slower rate in oil generated refined microstructures consisting of mostly recovered and recrystallised grains with low dislocation cluster. On the other hand, faster quenching in brine created more deformed microstructures comprising of relatively higher local average misorientation. Such variations in structural properties reduced the hardness values obtained after the separate heat treatment procedures. It is notable that the quenching and tempering approach relieved the high stored energy imparted by the thermomechanical treatment, and helped to retained the key properties required for safe pipeline operation. In addition, the risks of HIC was minimised in the oil quenched pipeline steels.

Niknam, Hassan Rahimi, Mahmoud Abbasi et. al (2023) investigated the effect of different quenching media on the hardness and microstructure of strength components. The authors examined the hardness and microstructure of the steel samples quenched in water, oil, and polymer quenchants, and compared the results with the as-received state of the steel and found a change in the microstructure and strength.

Though prodigious advances have been made recently in steel heat treating practice and in the understanding of the transformations in steel, the process of hardening steel by quenching it in a liquid bath has been in use for 100 of years. The most common used quenching media from years have been water and mineral oil. Though today if oil and water were compared for the same application, attention would probably be focused on cracking during quenching. Any modern text on steel heat treating lists many quenchants in addition to water and oil. Each quenchant has certain characteristics which make it most suitable for specific applications. (Eckel, 1951) .

However, corrosion is the destruction or degradation of a material that results from the reaction of material with its. In another term, corrosion has also been stated as the chemical or electrochemical reaction of a metal with its environment which in some cases can lead to the failure of the entire structural component. Corrosion cause wastage of resources and it is practically not possible to mention a single branch of the national economy of any country, mostly nations that are highly developed technologically, where metals and its alloys are not used as materials in the construction of plants, equipment, machines, processes, transportation, and storage facilities, etc. Corrosion might not have instant negative consequences on the material but it attack the physical appearance, mechanical behavior and strength of the material leading into enormous operational difficulties. The type and level of corrosion in a system relies on the composition and structure of the metal and its service environment. Refinements have been mostly realized through controlling and applying novel casting, thermo mechanical and heat treatment processes to influence the chemical composition of steels. Through this means, reduction of the non-metallic inclusions and porosities, could result to increment in the homogeneity of chemical composition and microstructure, in particular prior austenite grain size, are usually controlled and achieved by casting and thermomechanical processing. As a further matter, a high strength martensitic structure of engineering components is manoeuvred by quenching- hardening and alloying additions. The alloying additions are usually aimed to enhance the hardenability and final mechanical properties of steels. Nevertheless, in alloy steels, a subsequent tempering process is mainly employed to increase the toughness, uniformity of microstructure and mechanical properties and to regulate the amount of retained austenite and carbide precipitates and quenching-defects, and to reduce the amount of hydrogen embrittlement. The two main reasons for the remarkable flexibility of steel are heat alloying and heat treatment. Where heat treatment is a high heating operation applied to metals or their alloys in solid state above their re-crystallization temperature and followed with cooling to impact the required properties to the metal and its alloy suitable for a particular application. Heat treating of metals is a very useful operation in the final fabrication process of most engineering parts. It is used to improve the mechanical properties of the metal alloys through manipulation of its microstructure. In the most essential respects, the product performance

While these models offer valuable insights into the hardening behavior of low carbon steel, their accuracy depends on the specific conditions and assumptions made. A combination of modeling approaches, experimental validation, and a critical assessment of limitations is crucial for obtaining reliable predictions of the material's response to heat treatment.

We report the microstructural, mechanical and electrochemical response of low carbon steel under water and brine quenching, tempering processes to open a new window for the steel manufacturing industry. Light optical and scanning electron microscopes reveal that microstructure of water quenched steel mainly comprised of packets and blocks of supersaturated lath martensite (α′) with allotriomorphic (αal) and idiomorphic (αid) ferrites. Due to the higher cooling rate, brine quenching produced lath martensite with Widmanstätten ferrite (αw) and idiomorphic ferrite (αid). Energy dispersive spectroscopy validated the presence of these phases by their elemental composition. Water quenching provided 41% improved while brine quenching 47% improved tensile strengths. They also produced much higher Rockwell hardness, lower elongations, and lower impact toughness compared to the non-heat treated sample. On the other hand, water and brine quenching, tempering processes caused lattice relaxation of α′ by diffusing the excess carbon to α phases. This microstructural transformation significantly enhanced the elongation and impact toughness values at little expense of tensile strengths and Rockwell hardness.

Electrochemical properties of water, brine quenched and tempered low carbon steel were evaluated in both mild (3% NaCl) and intense (1% HCl) environments. In 3% NaCl solution, the highest corrosion resistance was achieved after water quenching process, while the lowest after water quenching with tempering processes compared toother heat treated samples. On the other hand, the highest corrosion resistance was offered by brine quenched sample and the lowest by brine quenched and tempered sample in an intense 1% HCl solution compared to other heat treated samples.

Polymer quenchant though can provide severity between those of water and oil has the problem of varying concentration during the quenching process and it is also more expensive. Brine produces more quenching severity than water; but it also has a problem of corrosive attack on the components and the equipment used for the quenching.The commonly used quenchants are water, oil, brine, and synthetic solutions. Water though abundant and low cost has the drawback of inducing crack due to its high cooling rate and oil has the problem of not inducing enough hardness.

Low carbon steels having superior elongation and impact toughness can be used in various applications. These applications include automobile component, structural components, pipelines, buildings, bridges, and tin cans. The field of applications of low carbon steels can be further widened by improving their properties. This is possible by controlled thermoplastic treatment, micro-alloying, controlling grain size, controlling austenite recrystallization temperature, developing low-temperature products of austenitic transformation, and quenching, tempering heat treatment processes.

Quenching and tempering processes are most economical, and widely used heat treatment processes. Quenching transforms face-centered cubic austenite structure to body-centered cubic or body-centered tetragonal martensite structure. Due to technological importance and research significance, the transformation has been highly focusing. Generally, lath martensite forms in low carbon steels while lenticular martensite forms in high carbon steels. Additionally, traces of twin structured lath martensite have also been observed in low carbon steels . Various morphologies of lath martensite have been reported in low carbon steels. For example; twinned structured lath martensite formed in 0.2 wt% carbon steel , and elongated martensite in 0.1 wt% carbon steel. Tempering of lath martensite transforms it to tempered martensite and offers optimum an amalgamation of strength and toughness .

In the current work, the effect of water and brine quenching tempering processes on microstructure, mechanical, and electrochemical properties of low carbon steel was investigated. Microstructural features were examined by light optical and scanning electron microscopes. Energy dispersive spectrometer was used to analyze the elemental composition of phases. Mechanical tests including Rockwell hardness, tensile, and Charpy impact tests were also performed. Tafel scan technique was also carried out to analyze the variation in polarization potential and corrosion behavior of quenched and tempered low carbon steel in 3% NaCl solution.Engine oil is required for hardening of low carbon steel and ductile cast iron. 2. Neem oil can be used to improve the toughness of these samples since it has higher impact energy values than water which is the common quenching medium.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Heat Treatment

A procedure called heat treatment is used to improve a material's physical characteristics. A material is usually heated to a desired temperature during a heat treatment procedure, at which point its physical properties alter. After that, it cools at a regulated pace.

The metal must be heated to a specific temperature in order to produce the intended effect. We heated our specimen to 680°C, held it there for a predetermined period of time, and then cooled it. The metal's microstructure, or physical structure, alters when it gets hot, which eventually affects the metal's physical qualities. The term "soak time" refers to the amount of time the metal is heated. A metal's properties are significantly influenced by the duration of its soak time; metal that is soaked for a longer period of time will experience distinct microstructure changes from metal that is soaked for a shorter duration.

fig 3.1 Opened Muffled Furnace

The metal's outcome is also influenced by the cooling procedure that follows the soak period. To ensure that the metal gets the intended outcome, it can be cooled in various medium either, a process known as quenching, or quickly. In order to give a metal or alloy the necessary qualities, a combination of the following factors must be considered: soak temperature, soak time.

M.A. Valdes-Tabernero et al (2019), there is a significant effect of the soaking time on the volume fraction of martensite of the ultrafast heated material.

What qualities are altered depends on the heat treatment method used on the metal during manufacturing; some metals may even undergo more than one treatment. It is quite difficult to determine how long a given step of the process should take for a certain metal or alloy, and what temperatures to heat and cool metals at. Metallurgists, who are material scientists, investigate how heat affects metal and alloys and offer accurate instructions on how to carry out these procedures. To guarantee that their metal components will have the right qualities at the end of the process, manufacturers rely on this knowledge.

3.2 Quenching

Quenching in oil or water is a heat treatment process for metals. Specifically, it focuses on the rapid cooling of a metal to alter the mechanical properties from one solid phase to another solid phase. One example is transitioning from the austenite phase to the martensite phase to increase the hardness of steel for applications such as swords, knives, and other tools.

3.3 Hardening

To harden a metal is to increase its resistance to deformation. Hardness has a relationship to wear resistance, ductility, and strength. While toughness (the capacity to absorb energy and deform plastically before fracture) and ductility (the capacity to deform plastically without fracture) decrease during the hardening process, strength and wear resistance both rise.

3.4 MATERIALS

The main component of low carbon steels is ferrite, which is carbon dissolved in alpha-iron, a cubic crystal with a body core, in a solid solution phase. The softest phase of steel, ferrite, is mostly to blame for low carbon steel's superior machinability over other carbon and alloyed steels. The amount of pearlite that forms in the steel's microstructure rises with the metal's carbon content.

Low-carbon steels are FeC alloys where the C concentration is maintained at equal to or less than 0.25 weight percent so that the maximum C content at the eutectoid temperature is in or near the single-phase α-ferrite (ferromagnetic, bcc) phase field.

3.4.1 TABLE. PERCENTAGE COMPOSITION OF LOW CARBON STEEL

	C % Conc	Si % Conc	Mn % Conc	P % Conc	S % Conc	Cr % Conc	Mo % Conc
1	0.165	0.255	0.642	0.008	0.021	0.025	0.009
2	0.159	0.234	0.635	0.008	0.019	0.025	0.009
3	0.171	0.247	0.634	0.008	0.020	0.025	0.009
Mean	0.165	0,248	0.637	0.008	0.020	0,025	0.009

	Nb % Conc	N % Conc	B % Conc	Al % Conc	Sn % Conc
1	< 0.0002	0.0062	0.0005	0.0074	0.009
2	< 0.0002	0.0060	0.0005	0.0046	0.009
3	< 0.0002	0.0061	0.0004	0.0071	0.009
Mean	<0.00010	0.0061	0.0005	0.0064	0.009

FIG 3.2 Steel

3.4.2 BENCH VICE AND SAW BLADE (CUTTING TOOL)

For cutting of the material to desired length or size we make use of a bench vice used to gain firm grip of the specimen or metal and a Saw blade to cut the material after taking its measured size.

Fig 3.3 Hack Saw

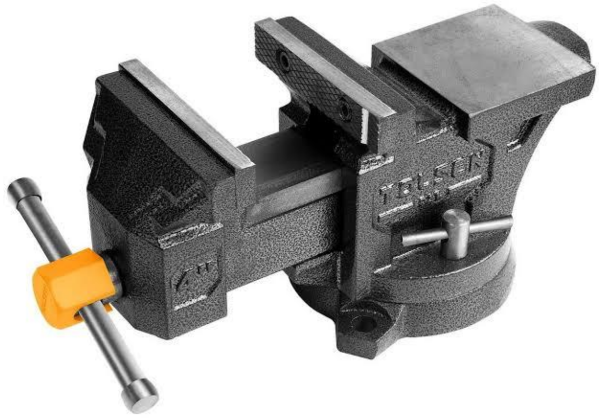

fig3.4 Bench-Vise

3.4.3 Furnace

A furnace is a device that produces and transfers heat to materials in order to alter their chemical and physical properties. Typically, heat is produced by the combustion of solid, liquid, or gaseous fuel, although it can be produced electrically via inductive or resistive heating (also known as Joule heating).

3.4.4 TYPE OF FURNACE USED FOR THE EXPERIMENT

Muffle furnace

A muffle furnace is a laboratory instrument used to heat materials to extremely high temperatures whilst isolating them from fuel and the byproducts of combustion from the heat source. Muffle furnaces allow for the isolation of a material to reduce the risks of cross-contamination and identify specific properties.

fig 3.5 Muffle Furnace

3.4.5 QUENCHING MEDIUMS

1. Distilled water
2. Engine Oil
3. Brine

Water

The primary benefits of water quenching over oil quenching procedures are its speed, cost-effectiveness, and reduced duration. The heated material rapidly cools during the quenching process, yielding the finished product quite quickly.

The final product is often affected by the quick cooling speed by becoming rigid and easily breakable. This could be either a benefit or a drawback, depending on what you hope to achieve. The fact that water quenching is non-flammable, unlike its oil cousin, is one of its main advantages.

Engine Oil

The method of hardening metal alloys with quench oil provides them with the necessary hardening and power without making the final product stiff and brittle, which is why oil quenching is the preferred choice in the metal industry, though it depends on the material.

Because quench oil can be controlled, it is extremely versatile in the metal-working industry. This is because it heats up and cools down at a much slower rate than other liquids, such as water, resulting in greater stability and hardening time.

It is utilized in parts with varying sections or strange forms, in steels with small or large grain size variations, in lean alloy steels, and in steels with variable hardenability when deeper and more uniform hardening is needed.

The use of engine oil for the experiment is comparatively okay in terms of quenching performance. One cool part is that you can use both new and used engine oil for quenching.

Brine Solution

4 Liter of distilled water

100g of NaCl salt.

The quickest cooling method is brine quenching, often known as salt bath quenching. A mixture of water and salt is called brine. For many years, salts have been utilized in the quenching process. They can reduce issues with iron and steel parts and have a broad operating temperature range. For materials with a low ability to harden, this is fantastic.

Oil quenching lacks many of the benefits of salt or brine quenching. In contrast to oil, nonflammable salt might not pose a fire risk. With water, salt is readily removed and cleaned. Certain tools and cleaners are needed for oil washing. It is possible to recover and reuse salt, but it is more difficult to reuse oil. Oil baths are less controllable than salt baths. Controlling temperature, water content, and agitation is simpler. Compared to oil, salt has more quenching properties.

3.4.6 TABLE PROPERTIES OF QUENCHING MEDIUMS

Medium	Color	Boiling point (o c)	Freezing point (o c)	Flash point	pH	Specific gravity
Water	Colorless	100	0	-	7	1
Engine oil	Dark brown	287	-31	246	-	0.9
Brine	Yellowish tint	108.7	-21.1	-	8.5	1.2

3.5 EQUIPMENTS

- Lathe machine,
- Hand grinding deck of abrasive papers and rotary wheel for polishing;
- Metallurgical Microscope,
- Hounsfield Tensile testing machine;
- Izod impact test;
- Digital hardness machine;
- Tanks,
- Tong,
- k-type thermocouple and,
- Arrow 600 variable speed impeller type agitator unit.

Method:

Preparation of specimen:

i. Obtain low carbon steel samples from retail company within markets in Benin City, Edo State. Cut samples to uniform sizes of 25mm by 3mm by 5mm.

ii. Cleaned the sample so as to eliminate any form of contamination.

iii. Heating: Pre-heated the furnace to a temperature of 650°C(to avoid possibility of thermal shock and even distribute heat around the furnace). After was the samples were introduced into the furnace and heated to a temperature of 850°C before the furnace was turned off.

iv. Soaking time: The specimen was held at this temperature (850°C) in the furnace for a duration of 15 minutes so as to achieve the desired internal structural changes. Afterwards the samples was removed quickly with a tong.

v. Quenching: Samples was quenched in the different media. And allowed to cool in these media for some time.

vi. Several test was carried out which includes:

  - Hardness value determination
  - Impact strength determination
  - Tensile strength determination
  - Metallorgraphic examination

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 RESULTS

AS RECEIVED

The received sample contains both the pearlite [dark phase) and the ferrite [white phase], the ferrite and the pearlite phases are almost equal in number.

WATER QUENCHED

When the metal is cooled in water, the hot metal locks the atom in place. The cooling consists of white ferrite grains and dark martensite. This picture also contains some inclusion pigments. The grains size (µm) is lower than the one of oil quenched but greater than Brine quenched.

OIL QUENCHED The structure contains low proportion of martensite plus fine lamellar of ferrite and grain boundary .There are some cementite inclusion in the structure. .The grain size [µm] Is lower than the one in brine quenched but greater than the one in water quenched. The rate of quenching is lower than the one in brine quenched

BRINE

There is a uniform structure of martensite observed and the no of grains size was lower as compared with the oil and water quenched.

Table 4.1.1 Impact and Hardness Test

SAMPLE	IMPACT(JOULES)A	IMPACT (JOULES) B	HARDNESS (BRINELL) BHN A	HARDNESS (BRINELL) BHN B
OIL	53.92	55.76	102.45	104.78
BRINE	43.84	42.56	128.56	130.31
WATER	47.53	45.88	120.67	121.67
AS RECEIVED	61.34		97.57	

Table 4.1.2 Combined Compressive samples

SAMPLE	MAXIMUM COMPRESSIVE STRESS(MPa)	COMPRESSIVE STRAIN AT MAXIMUM COMPRESSIVE STRESS (%)	ENERGY AT MAXIMUM COMPRESSIVE STRESS (J)	COMPRESSIVE LOAD AT MAXIMUM COMPRESSIVE STRESS (N)	COMPRESSIVE EXTENSION AT BREAK (STANDARD) (mm)	ENERGY AT BREAK (STANDARD) (J)
AS RECEIVED	167.11384	17.11938	37.43637	52500.36120	1.71194	37.43637
BRINE	167.11812	17.88281	41.43009	52501.70529	1.78828	41.43009
OIL	167.11496	15.34406	36.09028	52500.71287	1.53441	36.09028
WATER	167.11660	18.70535	31.70535	52501.22845	1.86591	31.17127

From the Table 2.0 above. It can been seen that Brine has the highest maximum compressive strength of 167.118 MPa. .Reason is because it is makes an excellent quenching medium for rapid cooling. The mixture of salt and water prevents the formation of air globules during quenching and during heat transfer, brine has a higher thermal conductivity than pure water. This is follow by water which is

167.116MPa. While As Receive sample has the lowest compressive force. The same trend follow at the compressive strain at maximum stress.

From the Table 3.0 below. It can been seen that Brine has the highest maximum tensile strength of 619.17 MPa follow by Oil which is 535.31. Water has compressive force of 421.12 MPa .The reason why the sudden change may have happened during heat treatment procedure. however , during tensile strain at maximum tensile strength. Oil quench gives a better tensile. Oil quenched has the highest tensile strain at break which is expected from the theoretical stand point.

Table 4.1.3 Results On Different Mediums

SAMPLE	MAXIMUM TENSILE STRESS (Mpa)	TENSILE STRAIN AT MAXIMUM TENSILE STRESS (mm/mm)	ENERGY AT MAXIMUM TENSILE STRESS (J)	TENSILE STRESS AT BREAK (standard)(MPa)	MODULUS (E-MODULUS) (MPa)	TENSILE STRAIN AT BREAK (STANDARD) (mm/mm)
AS RECEIVED	349.30050	0.18000	16.65210	273.48319	4998.80371	0.20417
BRINE	619.17459	0.11184	16.51880	466.22875	17825.63934	0.15051
OIL	535.314165	0.20904	36.09028	341.63056	24729.22440	0.30528
WATER	421.12804	0.08234	8.83899	170.44241	16794.31381	0.10867

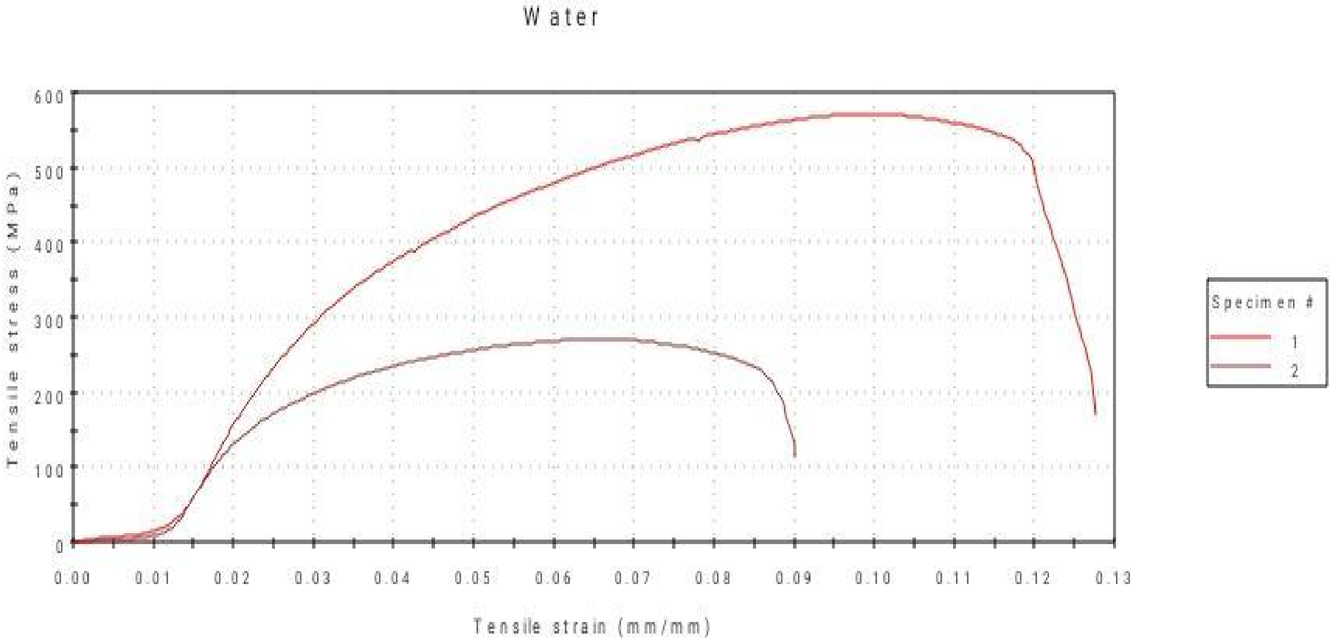

Fig4.1

Table 4.1.4 Maximum Tensile Test Result In Water

Sample	LENGTH (mm)	THICKNESS (mm)	WIDTH (mm)	DIAMETER (mm)	MAXIMUM TENSILE STRESS (MPa)
1	25.00000	3.00000	5.00000		571.00341
2	25.00000	3.00000	5.00000		271.2567
MEAN	25.00000	3.00000	5.00000		421.12804
STANDARD DEVIATION	0.00000	0.00000	0.00000		211.95578

Table 4.1.5 Tensile Test Result In Water

Sample	MODULUS (E- MODULUS) (MPa)	ENERGYB AT YIELD (ZERO SLOPE) (J)
1	178901.4435	13.49864
2	15698.48328	4.17934
MEAN	16794.31381	8.83899
STANDARD DEVIATION	1549.73841	6.58974

Table 4.1.6 Tensile Strength At Break In Water

1	30.00000	4.00000	541.55830
2	30.00000	4.00000	529.07002
MEAN	30.00000	4.00000	535.31416
STANDARD DEVIATION	0.00000	0.00000	0.00000

Table 4.1.7 Tensile Strength At Break In Water

Sample	LOAD AT BREAK (STANDARD) (N)	TENSILE STRAIN AT BREAK (STANDARD) (mm)	TENSILE EXTENSION AT BREAK (STANDARD) (mm)	ENERGY AT BREAK (STANDARD) (J)	TENSILE STRESS AT YEIELD (ZERO SLOPE) (MPa)
1	3165.78299	0.12733	3.18331	18.85601	571.00341
2	1947.48919	0.09000	2.25012	6.43528	271.25267
MEAN	2556.63609	0.10867	2.71672	12.64564	421.12804
STANDARD DEVIATION	861.46380	0.02639	0.65986	8.78278	211.95578

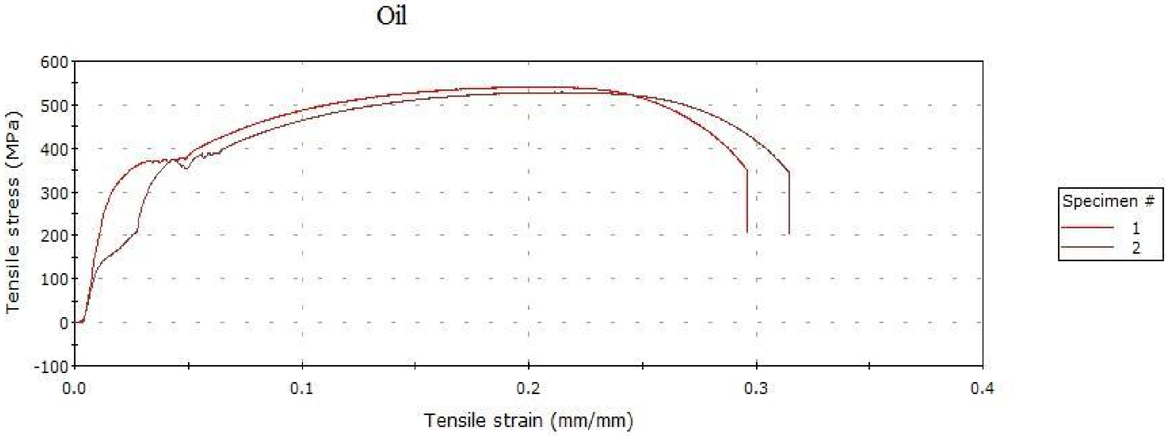

Fig4.2

Table 4.1.8 Maximum Tensile Result In Oil

Sample	LENGTH (mm)	DIAMETER (mm	MAXIMUM TENSILE STRESS (MPa)
1	30.00000	4.00000	541.55830
2	30.00000	4.00000	529.07002
MEAN	30.00000	4.00000	535.31416
STANDARD DEVIATION	0.00000	0.00000	0.00000

Table 4.1.9 Tensile Strength At Break In Oil

Sample	LOAD AT MAXIMUM TENSILE STRESS (N)	TENSILE STRAIN AT MAXIMUM TENSILE STRESS (mm/mm)S	TENSILE EXTENSION AT MAXIMUM TENSILE STRESS (mm	ENERGY AT MAXIMUM TENSILESTRESS (J)	TENSILE STRESS AT BREAK (STANDARD) (MPA)
1	6805. 42216	0.20390	6.11687	34.27113	351.25200
2	6648.48983	0.21417	6.42525	33.90136	332.00913
MEAN	6726.95599	0.20904	6.27106	34.08625	341.63056
STANDARD DEVIATION	110.96791	0.00727	0.21805	0.26147	13.60677

Table 4.1.10 Tensile Strength At Break

Sample	LOAD AT BREAK (STANDARD) (N)	TENSILE STRAIN AT BREAK (STANDARD) (mm)	TENSILE EXTENSION AT BREAK (STANDARD) (mm)	ENERGY AT BREAK (STANDARD) (J)	TENSILE STRESS AT YEIELD (ZERO SLOPE) (MPa)
1	4413.96274	0.29584	8.87512	51.36707	541.55830
2	4172.14967	0.31472	9.44162	52.22660	529.07002
MEAN	4293.05620	0.30528	9.15837	51.79684	535.31416
STANDARD DEVIATION	170.98766	0.01335	0.40058	0.60778	8.83055

Table 4.1.11 Modulus And Yield Strength In Oil

Sample	LOAD YIELD (ZERO SLOPE) (N)	MODULUS (E- MODULUS) (MPa)
1	6805.42216	28886.09314
2	6648.48983	20572.35565
MEAN	6726.95599	24729.22440
STANDARD DEVIATION	110.96791	5878.70015

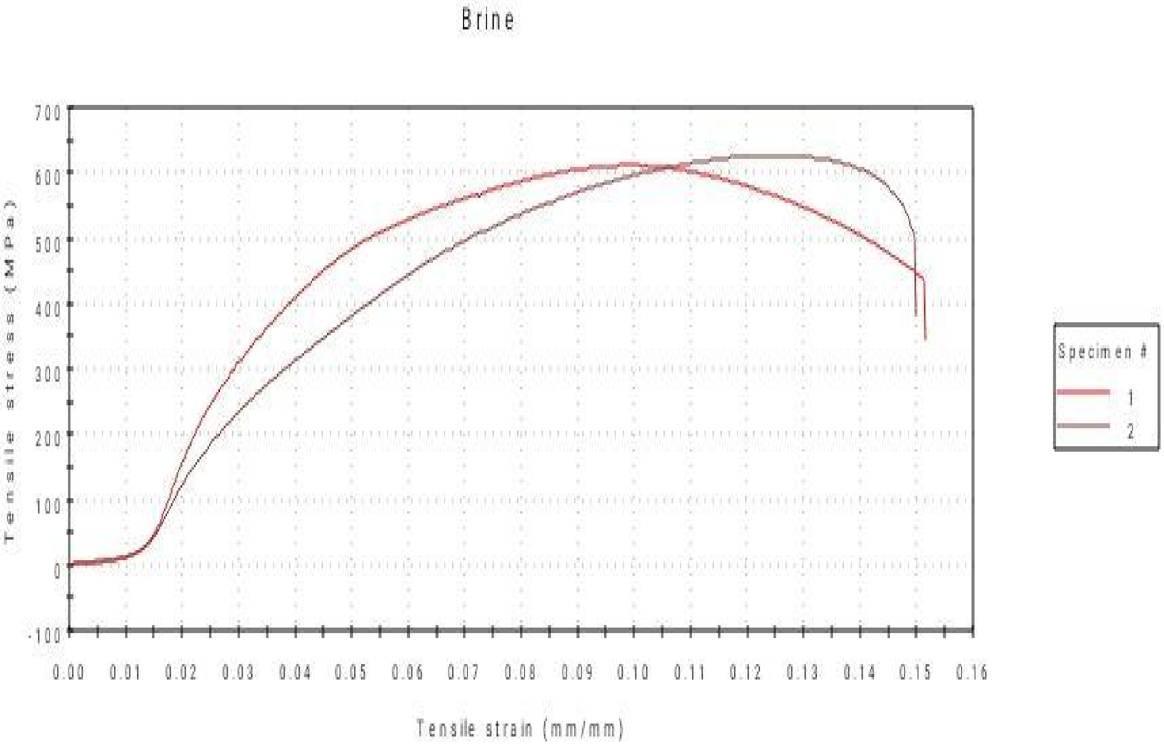

Fig4.3

TABLE 4.1.12 MAXIMUM TENSILE STRESS IN BRINE

Sample	LOAD AT MAXIMUM TENSILE STRESS (N)	TENSILE STRAIN AT MAXIMUM TENSILE STRESS (mm/mm)	TENSILE EXTENSION AT MAXIMUM TENSILE STRESS (mm	ENERGY AT MAXIMUM TENSILESTRESS (J)	TENSILE STRESS AT BREAK (STANDARD) (MPA)
1	9174.63467	0.09867	2.46681	14.50761	434.44231
2	9400.57635	0.12501	3.12525	18.53000	498.01519
MEAN	9287.61885	0.11184	2.79603	16.51880	466.22875
STANDARD DEVIATION	159.74604	0.01862	0.46559	2.84427	44.95281

Table 4.1.13 Maximum Tensile Stress In Brine

Table 4.1.14 Load At Break In Brine

Sample	LOAD AT BREAK (STANDARD) (N)	TENSILE STRAIN AT BREAK (STANDARD) (mm)	TENSILE EXTENSION AT BREAK (STANDARD) (mm)	ENERGY AT BREAK (STANDARD) (J)	TENSILE STRESS AT YEIELD (ZERO SLOPE) (MPa)
1	6516.63467	0.15133	3.78331	25.40881	611.64409
2	7470.22778	0.14968	3.74200	24.09264	626.70509
MEAN	6993.43123	0.15051	3.76266	24.75067	619.17459
STANDARD DEVIATION	674.29215	0.00117	0.02921	0.93060	10.64974

Table 4.1.15 Modulus And Yield At Break In Brine

Sample	MODULUS (E- MODULUS) (MPa)	ENERGYB AT YIELD (ZERO SLOPE) (J)
1	20940.44800	14.50761
2	14710.83069	18.53000
MEAN	17825.63934	16.51880
STANDARD DEVIATION	4405.00464	2.84427

Compression Test

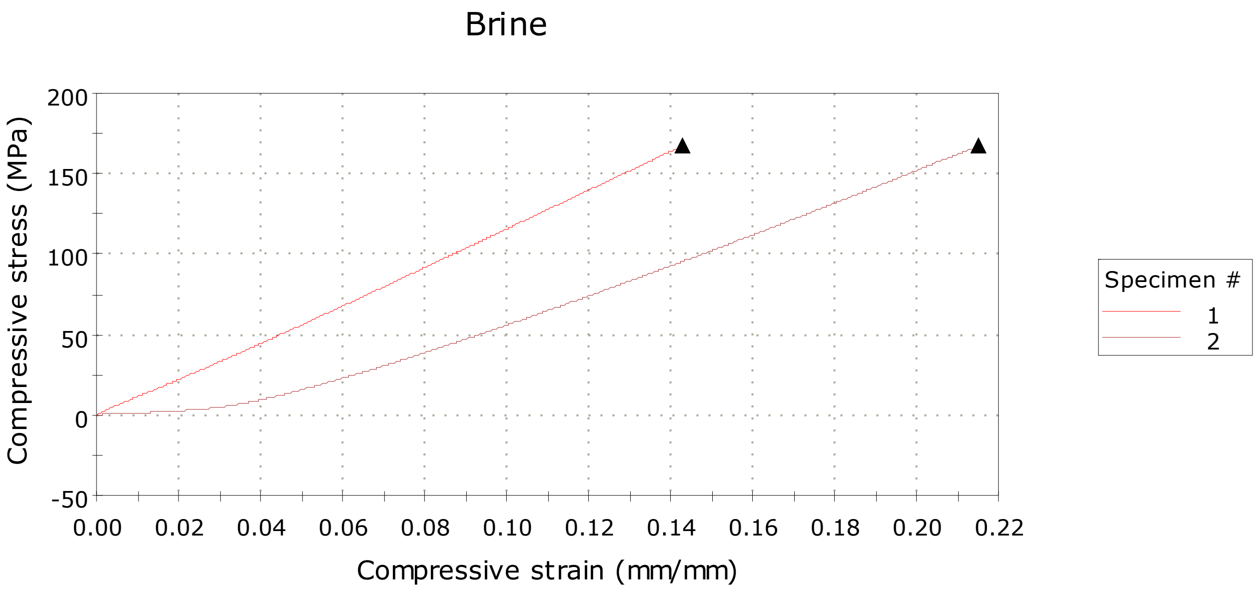

Fig4.4

Table 4.1.16 Anvil

Sample 1 2 MEAN STANDAR DEVIATIC	Anvil height (mm)	Diameter (mm)	Thickness (mm)	Width (mm)
1	10.00000	20.00000		
2	10.00000	20.00000		
Mean	10.00000	20.00000		
Standard Deviation	0.00000	0.00000		

Table 4.1.17 Stress and Strain

Sample	Maximum Compressive stress (MPa)	Compressive strain at Maximum Compressive stress (%)	Energy at Maximum Compressive stress (J)	Compressive load at Maximum Compressive stress (N)
1	167.12022	14.26875	36.77847	52502.36392
2	167.11602	21.49687	46.08172	52501.04666
Mean	167.11812	17.88281	41.43009	52501.70529
Standard Deviation	0.00296	5.11106	6.57839	0.93145

Table 4.1.18 Compression at break

Sample	Compressive extension at Maximum Compressive stress (mm)	Compressive stress at Break (Standard) (MPa)	Compressive load at Break (Standard) (N)	Compressive strain at Break (Standard) (%)
1	1.42687	167.12022	52502.36392	14.26875
2	2.14969	167.11602	52501.04666	21.49687
Mean	1.78828	167.11812	52501.70529	17.88281
Standard Deviation	0.51111	0.00296	0.93145	5.11106

Table 4.1.19a Load at Maximum Compression

Sample	Load at Maximum Compressive stress (N)	Extension at Maximum Compressive stress (mm)	Compressive extension at Break (Standard) (mm)	Load at Break (Standard) (N)
1	-52502.36392	-1.42687	1.42687	-52502.36392
2	-52501.04666	-2.14969	2.14969	-52501.04666
Mean	-52501.70529	-1.78828	1.78828	-52501.70529
Standard Deviation	0.93145	0.51111	0.51111	0.93145

Table 4.1.19b At Break

Sample	Extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Compressive stress at Yield (Zero Slope) (MPa)	Compressive load at Yield (Zero Slope) (N)
1	-1.42687	36.77847	-----	-----
2	-2.14969	46.08172	-----	-----
Mean	-1.78828	41.43009	-----	-----
Standard Deviation	0.51111	6.57839	-----	-----

Table 4.1.20 Modulus

Sample	Modulus (E-modulus) (MPa)
1	-----
2	-----
Mean	-----
Standard Deviation	-----

Table 4.1.21 Fatigue Test Result

NAME	MOMENT KGTCM	GUAGE LENGTH	FINAL LENGTH	INITIAL REVOLUTION	FINAL REVOLUTION	DIAMETER(MM)	MPA STRESS	NO OF CYCLES(THOUDAND)
WATER								
	80	25.2		8058	8058.9	5.1	577.1	0.9
	160	25.2		8058.9	8059.2	5.1	1154.1	0.3
	240	25.2		8059.2	8059.4	5.1	1731.3	0.2

Table 4.1.22 Oil

OIL	MOMENT KGTCM	GUAGE LENGTH	FINAL LENGTH	INITIAL REVOLUTION	FINAL REVOLUTION	DIAMETER(MM)	MPA STRESS	NO OF CYCLES(THOUDAND)
	80	25.2		8069	8070.2	5.1	577.1	1.2
	160	25.2		8071	8071.5	5.1	1154.1	0.5
	240	25.2		8071.5	8071.8	5.1	1731.3	0.3

Table 4.1.23 Brine

BRINE	MOMENT KGTCM	GUAGE LENGTH	FINAL LENGTH	INITIAL REVOLUTION	FINAL REVOLUTION	DIAMETER(MM)	MPA STRESS	NO OF CYCLES(THOUDAND)
	80	25.2		8076.3	8076.9	5.1	577.1	0.6
	160	25.2		8077	8077.2	5.1	1154.1	0.2
	240	25.2		8077.2	8077.3	5.1	1731.3	0.1

Table 4.1.24 Control

CONTROL	MOMENT KGTCM	GUAGE LENGTH	FINAL LENGTH	INITIAL REVOLUTION	FINAL REVOLUTION	DIAMETER(MM)	MPA STRESS	NO OF CYCLES(THOUDAND)
	80	25.2		8078	8078.7	5.1	577.1	0.7
	160	25.2		8079	8079.3	5.1	1154.1	0.3
	240	25.2		8079.3	8079.4	5.1	1731.3	0.1

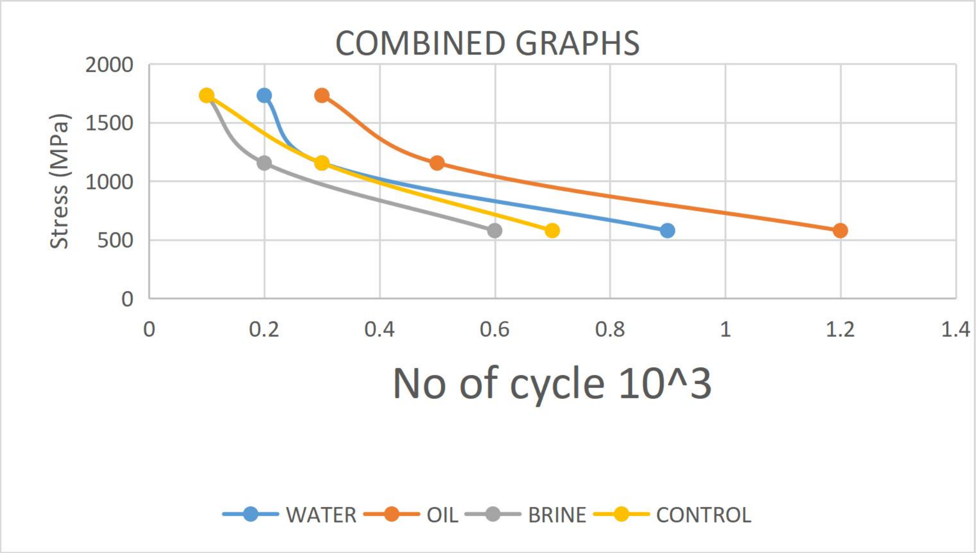

Fig4.5

4.2 FATIGUE EXPLANATIONS

This is a process whereby an already machined sample is fractured to failure by the application of a known value of reversal stresses which could be equal or unequal in magnitude in both directions (positive and negative). The fatigue strength is the maximum stress that can be repeated for a specified number of loading cycles without producing failure.

From the graphs generated , The CONTROL sample has fatigue strength to be 1000MPa. The BRINE samples have fatigue strength to be 1154 MPa, OIL samples fatigue strength to be 1270 MPa while for WATER , it has fatigue strength to be 1200 MPa. This also follow the theoretically explained explanations on Tensile samples.

4.3 METALLOGRAPHIC EXAMINATION

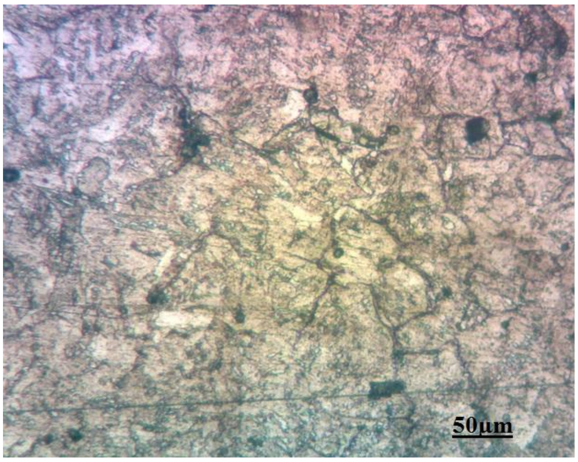

Fig 4.6 Oil

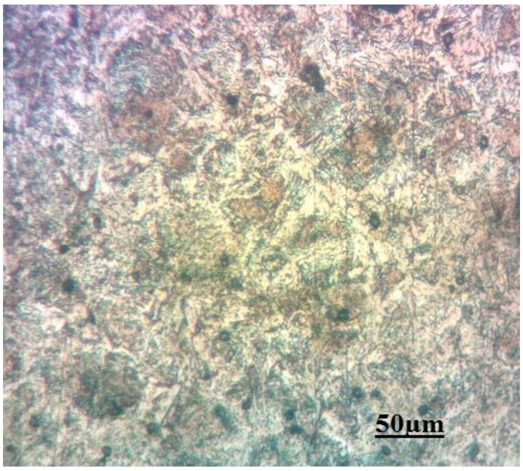

Fig 4.7 Water

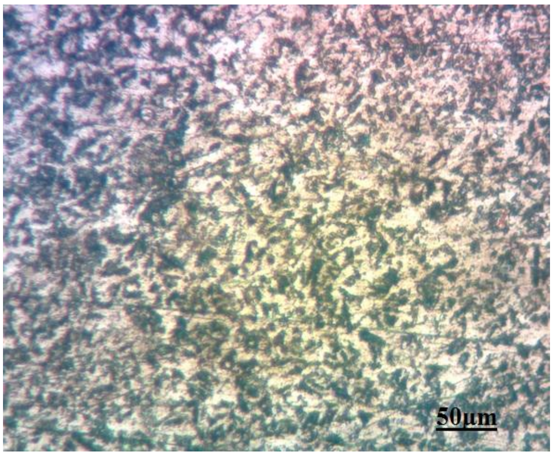

Fig 4.38 Brine

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Based on the results obtained from the experiment we can state conclusively on:

1. Effect on Hardness: Brine quenching resulted in the highest hardness value (129.42 MPa), followed by water (121.17 MPa), and water (103.62 MPa). This indicates that the rate of cooling and the quenching significantly affect the hardness of low carbon steel, with faster cooling rates (as in brine quenching) leading to higher hardness values.

2. Impact Resistance: The impact value, which measures the materials ability to withstand sudden shocks, was highest for oil-quenched steel (54.84 MPa), followed by water (46.71 MPa), and then brine (43.20 MPa). This suggests that oil-quenched steel exhibits better toughness compared to brine and water-quenched steel, likely due to the slower cooling rate and resulting finer microstructure.

3. Tensile Strength: The maximum tensile stress was highest for brine-quenched steel (619.17 MPa), followed by oil-quenched steel (535.31 MPa), and then water-quenched steel (412.13 MPa). This indicates that brine-quenched steel has the highest strength but lower toughness compared to oil- quenched steel.

Therefore, the choice of quenching medium significantly influences the mechanical properties of low carbon steel. Oil quenching provides a balance between hardness and toughness, making it suitable for applications where both properties are important, such as gears and shafts. Brine quenching results in higher hardness and strength but may sacrifice some toughness, making it suitable for applications where high strength is paramount, such as cutting tools. Water quenching, while providing adequate hardness, may not offer the best combination of properties compared to oil and brine quenching.

5.2 RECOMMENDATIONS

The choice of quenching medium for low carbon steel affects its microstructure and properties. Here are some general recommendations for heat treatment after quenching in water, brine, and engine oil;

1. WATER QUENCHING

   a. Rapid cooling leads to a harder but potentially more brittle steel.

   b. Temper immediately after quenching to reduce brittleness.

   c. Temper at temperatures between 350°C to 600°C (660°F to 1110°F) depending on desired properties.

2. BRINE QUENCHING

   a. Brine offers faster cooling rates compared to water, resulting in a harder steel.

   b. Temper as with water quenching, adjusting temperature based on desired hardness and toughness.

3. ENGINE OIL QUENCHING

   a. Engine oil provides slower cooling rates than water or brine, resulting in a tougher but less hard steel.

b. Tempering temperatures are typically lower compared to water or brine quenching, usually between 150°C to 250°C (300°F to 480°F) to maintain toughness while achieving desired hardness.

c. Always ensure to follow specific guidelines and test pieces for optimal results, as the exact parameters may vary depending on the composition and intended application of the steel.

Some constraints to the this work include the time required for heat treatment processes, including quenching and tempering, may be limited, impacting the number of experimental iterations and comprehensive analysis. Availability of equipment for heat treatment processes and mechanical property testing may impose constraints on the scope and depth of the study.

Suggestions for further work should include investigation to include a broader range of quenching mediums beyond water, brine, and engine oil to assess their impact on microstructure and properties of low carbon steel comprehensively. Employ advanced microscopy techniques, such as electron microscopy or X-ray diffraction, to characterize the microstructure of quenched low carbon steel in greater detail. Investigate the effects of thermal cycling, including multiple quenching and tempering cycles, on the mechanical properties and microstructure evolution of low carbon steel for enhanced understanding and optimization.

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