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Investigation of Quenching on Microstructure and Mechanical Properties of Mild Steel

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ABSTRACT
This study examines how different bath temperatures, specifically Selected Vegetable oil, water, palm kernel oil, engine oil, and diesel, affect the cooling rates, mechanical properties, and microstructure of quenched steel samples. Quenching is a widely used heat treatment process employed in steel machine components to improve their mechanical properties and increase their longevity. During quenching, heat is rapidly transferred from the hot metal component to the quenchant, resulting in a rapid decrease in temperature and inducing phase transformation in the metal. In this research, the steel samples were heated to an austenitizing temperature of 730°C, and alternative quenching methods were applied alongside water. The steel was then quickly quenched in oil for 15 minutes; followed by testing the mechanical properties, including hardness, impact strength, and tensile strength. Additionally, the microstructure of the specimens was analyzed. The findings reveal that the sample quenched in oil exhibited the highest value of 64.32 Joules showing its ability to absorb a significant amount of energy before fracture, while the water quenched sample had the lowest impact energy value of 57.94 Joules. On the other hand, water quenched sample has exhibited the highest hardness value of 78.2 HBN indicating its greater resistance to indentation leaving vegetable oil quenched sample with the lowest value of 62.8 N/mm^2. In term of tensile strength, engine oil quenched sample with a value of 62.52 N/mm^2 lead every other samples while water sample had the lowest value of 39.08N/mm^2.The findings demonstrate that these cooling rates effectively enhance the mechanical strength of the quenched carbon steel, although there are some limitations in terms of flexibility. The results highlight that the quenched steel exhibits an exceptional combination of tensile strength, impact strength, and hardness, making it highly suitable for structural applications.
Keywords: Quenching, Cooling rates, Mechanical properties, Microstructure, Austenizing temperature, Steel and strength

I. INTRODUCTION

Mild steel, known for its affordability and availability, is widely used in various applications. It typically contains a carbon content ranging from 0.16% to 0.29% and has a melting point of around 1450°C [1]. Achieving desired properties in steels and aluminum alloys often requires the process of quenching. However, the absence of active cooling methods limits the heat transfer rate through the fluid film boundary, necessitating the use of agitation or forced circulation of the quenchant [2].

Heat treatments are complex processes with multiple parameters that influence the behavior of treated components, including mild steel specimens. The choice of quenching medium, its temperature, and whether it is non-metallic or metallic are crucial factors in predicting the behavior and properties of treated components [3]. Studies have shown that adding small amounts of silicon and magnesium can further improve the properties of plain carbon steel, making it more suitable for industrial applications due to its ease of machining and cost-effectiveness [3,4].. Mild steel can be classified based on its carbon content, with low carbon steel containing less than 0.25%, medium carbon steel ranging from 0.25% to 0.65%, and high carbon steel typically ranging from 0.65% to 1.5% [5]. Increasing the carbon concentration in austenite enhances the hardness and mechanical properties of plain carbon steels, especially after quenching during the hardening heat treatment process [6]

In various engineering applications, the design of components using steel requires an understanding of design requirements and material properties. Recent research has focused on high-strength steels, high-speed steels, and tempered and quenched micro-alloyed steels, which are expected to be highly valuable materials in the future [7]. Tempered and quenched steel sheets are commonly used in the automotive industry for structural members, impact resistance systems, and power transmission [8]. Components require high hardness to withstand heavy-duty processes. Hardening involves heating the alloy to a high temperature, holding it there, and rapidly cooling it using a medium such as oil, water, or salt bath. This process increases the hardness of the metal and alloy through phase transformation, resulting in the formation of non-equilibrium products[9]. The presence of martensite, a hard micro-constituent formed through the low-temperature transformation of austenite, contributes to the increased hardness of rapidly cooled steels [10]. While mineral oil is commonly used as a quenching medium for alloy steels due to its excellent cooling capacity, concerns have arisen regarding its toxicity, high cost, and non-biodegradability. As a result, alternative options such as polymers and aqueous solutions have been considered. Recently, non-toxic cooking oils that are locally available, relatively inexpensive, and environmentally friendly, have gained attention as potential quenching media [11].

Microstructures play a significant role in determining the physical properties of materials. By examining the microstructure of a material, insights can be gained into its surface structure and properties. In this study, the effects of heat treatment on the corrosion and mechanical properties of quenched mild steel were investigated. Different heat treatment processes were applied to a mild steel specimen, followed by quenching with various media including water, diesel, vegetable oil, kernel oil, and engine oil. The influence of temperature, time, and transformation during the quenching process was examined [12]. The primary objective of the study was to assess the mechanical characteristics of quenched mild steel with different cooling media. Specific objectives included determining the chemical properties necessary for industrial processes, performing heat treatment using an electric furnace, conducting quenching with various liquid mediums, analyzing the microstructure of the heat-treated mild steel, evaluating other mechanical properties, and assessing the impact of heat treatment on microstructure [13].

The aim of this research is to investigate the effect of hardening, a form of heat treatment, on the microstructure of mild steel in order to enhance its hardness, toughness, ductility, and strength [14, 15]. Mild steel is increasingly used in major industrial operations due to its engineering considerations, but it is susceptible to corrosion when exposed to acidic media solutions. Additionally, mild steel has relatively low tensile strength compared to other metals, making it prone to breaking under tension [16]. The carbon content of mild steel is typically lower, usually less than 1% by mass, while other steels may contain higher carbon content, up to 15% or more [17]. Quenching high-carbon steel enhances its hardness but also makes it brittle until annealed with heat [18].

In summary, mild steel is an affordable and readily available material with suitable properties for various applications. Quenching plays a crucial role in achieving desired properties in steels and aluminum alloys, and selecting the appropriate parameters in heat treatments is important in predicting the behavior of treated components. Recent research has focused on high-strength steels and tempered and quenched micro-alloyed steels, while alternative quenching media such as non-toxic cooking oils have been considered. The microstructure of a material greatly influences its physical properties. The current study investigates the effects of heat treatment on the corrosion and mechanical properties of quenched mild steel, aiming to enhance its hardness, toughness, ductility, and strength. Mild steel's susceptibility to corrosion and relatively low tensile strength are areas of concern that can be addressed through heat treatment processes.

II. LITERATURE REVIEW

The process of quenching, which involves rapidly cooling metals or alloys, is used to prevent significant changes in their microstructure by inhibiting diffusion at lower temperatures [6]. Different quenching media, such as liquids (e.g., water, oil) and gases (e.g., Elkatatny), are employed, and computational fluid dynamics (CFD) is used to simulate high-pressure gas quenching processes and predict temperature distribution. Totten et al. studied heat transfer stages in quenching hot objects in fluids like oil or water, including the formation of vapor blankets and nucleate boiling. Finite element software to analyze the quenching process of a heavy rail and obtain time-varying temperature fields and emphasized the importance of quenchants providing sufficient intensity for martensitic transformation in rapid quenching[8]..Liquid quenchants, such as water and brine, are commonly used for rapid cooling, leading to the formation of a hard martensitic microstructure that enhances toughness and strength after tempering [11]. .However, water quenching can cause cracking and distortion, while brine is corrosive. Oil quenching avoids these issues but may not provide sufficient cooling rate, especially for larger cross-sections. To overcome these limitations, polymeric solutions, including glycol-based quenchants, have been introduced as substitutes. Various commercial polymer quenchants, including glycol-based ones, are now widely utilized. Previous studies have focused on measuring deformation and residual stress using different methods for simple geometries and conventional transient stress analysis. Researchers have presented methods for solving thermo-elastic problems and investigating thermal stress problems using finite element analysis. Heat treatment, a process used to modify the chemical and physical properties of materials, is commonly applied in metallurgy and other material production processes [19]. It involves controlled heating or cooling, often to extreme temperatures, to achieve desired outcomes such as softening or hardening. Heat treatment techniques include case hardening, annealing, precipitation strengthening, carburizing, normalizing, tempering, and quenching. Incidental heating and cooling also occur during manufacturing processes. The objective of heat treating carbon steel is to modify its mechanical properties while minimizing the impact on thermal and electrical conductivity. The techniques used involve a trade-off between ductility and increased strength. Austenite phase plays a crucial role in most heat treatments for steels. The rate of cooling through the eutectoid temperature affects carbon diffusion and the resulting microstructure. Rapid cooling leads to finely dispersed iron carbide and a fine-grained pearlite structure, while slower cooling results in coarser pearlite. Different types of steel exhibit various microstructures, such as lamellar pearlite, predominantly pearlite, and eutectoid pearlite. Quenching is a crucial process in material science, particularly in the hardening of steel, as it prevents undesirable phase transformations and enhances hardness [15]. Steel can be rapidly cooled through its eutectoid point, resulting in a martensite transformation. Alloying elements and high-speed steel influence the eutectoid temperature and the overall quenching process, providing enhanced properties such as abrasion resistance and hardness. Heat treatment processes, including quenching, offer a wide range of modifications to physical and chemical properties without material removal. Common heat treatment processes involve changes in physical properties like quenching, tempering, aging, annealing, and normalizing is presented in Figure 1, showing the temperatures and carbon range for certain types of heat treatments.

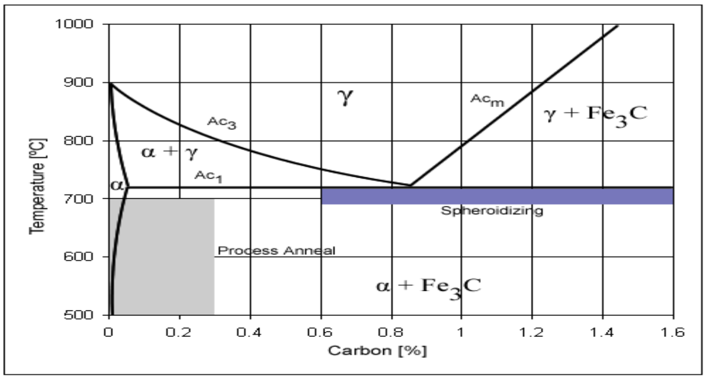


Figure 1: Iron-carbon phase diagram [1, 20].

The impact of time and temperature on heat treatment requires precise control and accurate manipulation of temperatures, duration, and cooling rates [12]. Most heat treatments involve heating the alloy beyond a specific transformation temperature, known as the arrest temperature, except for stress relieving, tempering, and aging. At the arrest temperature, the metal undergoes hysteresis, where heat energy is solely utilized for crystal changes, resulting in a brief stabilization of temperature before further rising. To achieve transformation, the alloy must be heated above its critical temperature and held there for a sufficient duration to ensure complete penetration and solid solution formation. For instance, steel has an austenizing temperature (A3) and an austenite-to-pearlite transformation temperature (A1), with heating just above the upper critical temperature to prevent excessive grain growth and enhance mechanical properties. Controlling grain size is essential to reduce the risk of breakage during the hardening process. The time-temperature transformation of diffusion is influenced by time, as cooling reduces precipitation to lower temperatures. Rapid cooling can suppress transformation, leading to the formation of various microstructures consisting of ferrite and cementite. The cooling rate controls grain growth and can produce partially martensitic microstructures. In the martensite transformation, time does not significantly affect the process. Cooling to the martensite transformation temperature (Ms) results in a rapid transformation speed. The size of austenite grains affects nucleation rate, but temperature and cooling rate primarily govern grain size and microstructure. Slow cooling of austenite forms large ferrite crystals with spherical cementite inclusions, known as "spheroid." Coarse pearlite forms with slightly faster cooling, while fine pearlite and bainite result from even faster cooling. In nonferrous alloys, heating to form a solution is followed by rapid cooling to induce martensite transformation, leading to supersaturation and work hardening [1].

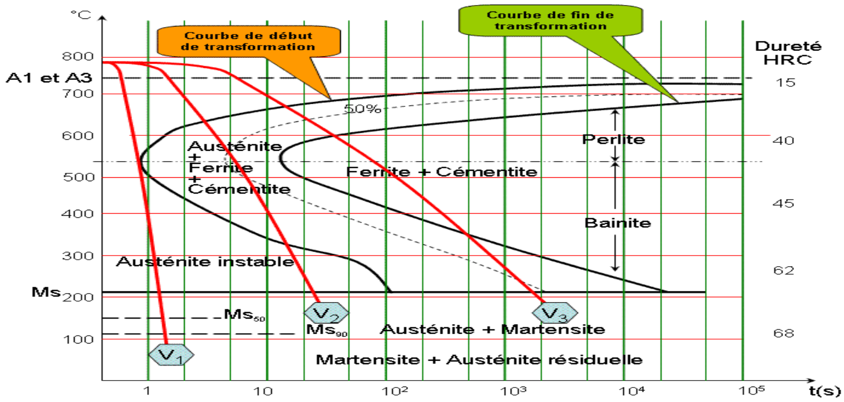


Figure. 2: Time-temperature transformation (TTT) diagram for steel[1, 21]..

III. MATERIALS AND METHOD

In this study, 35 mm diameter mild steel bars were selected as the material for investigation. The mild steel samples were collected and prepared for hardness, impact, tensile, and metallographic examinations. The chemical composition of the mild steel was determined through spectrometric analysis, revealing a carbon content of 0.471%. To begin the experiment, the mild steel material was initially heated to a temperature exceeding 730°C. After soaking for 15 minutes, the material was machined according to the specifications required for the tensile, impact, and hardness tests.

The quenching process involved the use of two different quenchants, namely kernel oil and engine oil, which were contained in separate cylindrical base tanks with an extended height of 2000 mm. Once the samples were machined, they were placed in an electric furnace and heated to a temperature above 750°C. Using tongs, the specimens were rapidly transferred from the furnace to the respective quenchants. Four samples were prepared for each quenchant, as they were intended for various mechanical property tests, including impact, hardness, tensile strength, and microstructure analysis.

Different dimensions were used for the samples depending on the specific test. For the hardness test, the samples had a diameter of 25 mm and a height of 20 mm. The ultimate tensile stress test specimens had dimensions of 10 mm by 7 mm (diameter by length). Impact tests were conducted using samples with dimensions of 10 mm by 10 mm by 60 mm. Additional samples with dimensions of 20 mm by 20 mm were prepared for microstructure analysis. These procedures were repeated for each of the five different quenchants used. During the quenching process, the quenching time for each quenchant was recorded, taking into consideration the varying impact on the annealed specimens due to the different viscosities of the quenchants. Subsequently, the mechanical properties of the specimens, including strength, hardness (evaluated using the Vickers hardness test), ductility, ultimate tensile strength, and impact resistance, were tested. Furthermore, the microstructure of the specimens was observed and documented for analysis. Overall, this study involved the quenching of mild steel samples using different quenchants, followed by the evaluation of their mechanical properties and microstructure. The results obtained from these tests will contribute to a better understanding of the effects of quenching on the material and provide insights for its practical applications.

MECHANICAL PROPERTIES

Hardness Test Measurement

In the measurement of hardness, a Brinell hardness testing machine was utilized in the research as shown in Figure 4. The test specimen was placed on the machine's anvil, and a manual load was applied, resulting in the creation of a circular depression on the surface of the sample. The diameter of this impression or indentation was then measured. Subsequently, the load was released, and the impression was examined using a low-power microscope equipped with a calibrated lens. The hardness of the specimen as presented in Figure 3, indicated by the Brinell number, was determined using [22] formula:

$$HBN = 2P / [\pi(D - \sqrt{D^2 - d^2})] \quad (1)$$

In the formula, P represents the applied force in newtons (N), D represents the diameter of the indenter in millimeters (mm), and d represents the diameter of the indentation in millimeters (mm). In this study, the diameter of the indenter (D) is equal to 28 mm, while the length of the specimen is 25 mm.

Figure 3: Hardness Testing Specimen

Figure. 4: Brinell hardness Testing Machine

The tensile properties of the quenched steel specimen were evaluated using a tensometer [23]. Prior to conducting the specimen test as shown in Figure 5, the initial gauge length (lo) of 100 mm and diameter (d) of 10 mm were measured. The maximum load applied during the test was used to calculate the yield strength and tensile strength of the specimen. The following parameters were employed in the calculations:

Yield strength: $\sigma y = Py / Ao$ (2)

where σy represents the yield strength in N/mm², Py is the yield load in Newton (N), and Ao is the original cross-sectional area in mm². The tensile from [24; 25]

Tensile strength or ultimate tensile strength: $\sigma max = Pmax / Ao$ (3)

where σmax represents the tensile strength in N/mm², Pmax is the maximum load in Newton (N), and Ao is equal to 78.54 mm².

In this study, σmax is equal to 754.40 N/mm², and the maximum load is 1453.54 N.

To calculate the percentage elongation, the measurement of the final gauge length (Lf) and the smallest diameter of the local neck were taken into account. The percentage elongation was calculated using the following formula:

% elongation = $(Lf - lo) / lo \times 100$ (4)

where lo represents the initial gauge length in mm, and Lf is the final gauge length in mm.

By applying these formulas from [26] and measurements, the tensile properties of the quenched steel specimen can be determined, providing insights into its mechanical behavior and strength.

Figure 5: Tensile Test Specimen

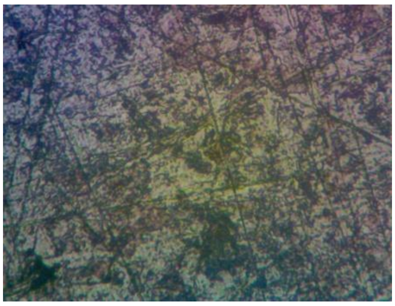
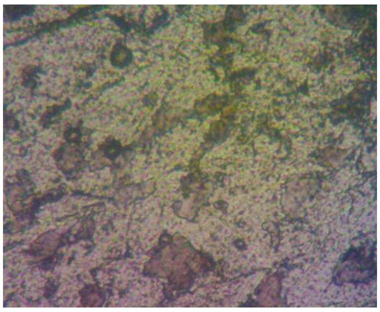
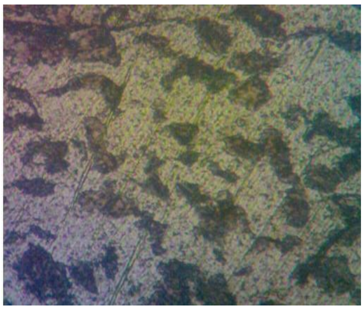
The impact tests of the quenched steel sample were carried out using an Avery Denson impact testing machine (Figure 6). The specimens were positioned horizontally, with the V-notch facing away from the striking end. To initiate the test, the trigger was released, causing the pendulum to strike the specimen. The pendulum had an initial potential energy of 0J. The amount of energy absorbed by the specimen before fracture occurred was directly measured using the gauge on the testing machine. During the impact test, the pendulum's energy was transferred to the specimen upon impact, resulting in deformation and fracture. The gauge on the testing machine accurately measured the energy absorbed by the specimen, providing valuable information about its impact resistance and toughness. By conducting impact tests, the behavior of the quenched steel sample under sudden and high-intensity loading conditions can be evaluated. The results obtained from these tests enable a better understanding of the material's ability to withstand impact forces and its overall structural integrity in impact-prone applications.

Figure 6: Hounsfield Izod Impact Machine

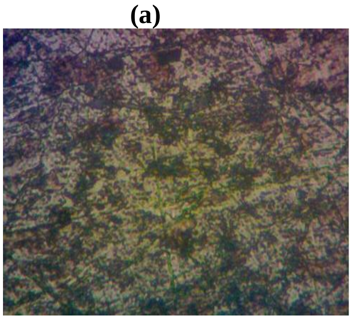
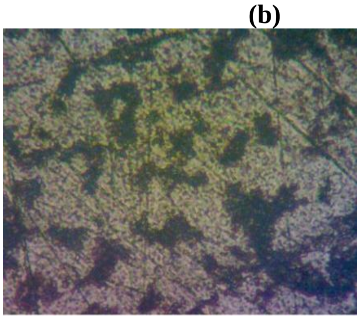
IV. RESULT AND DISCUSSION

Quenching Analysis of Mild Steel

To assess the effectiveness of quenching, metallographic analysis was conducted on both the received and quenched specimens with a carbon content of 0.509%. The microstructure of the as-received sample revealed a transformation into martensite and retained austenite due to the increased carbon content. Additionally, the carbon contributed to solid solution strengthening. In Figure 7a, the as-received specimen predominantly consisted of martensite and pearlite. The presence of martensite structures, combined with a mixture of pearlite, contributed to an increase in material hardness. Figure 7b exhibited the presence of graphite, primarily in a dark brownish color. The spherical form of the graphite resulted in improved strength compared to lamellar cast iron, but the material hardness was lower due to the absence of cementite in the purely ferritic matrix. The microstructures of the carbon steel samples quenched in different media at 750 °C are shown in Figure 7a, b, c, d and e for Water, Diesel, Vegetable Oil, Palm Kernel and Engine oil respectively.

(a) **(b)** **(c)**

(d) **(e)**

Figure7(a-e): Microstructure View **a)**Water, **b)** Diesel, **c)** Vegetable Oil, **d)** Palm Kernel and **e)** Engine oil

The microstructures of a Ferritic steel with approximately 0.1% carbon content were examined and depicted in Figure 7(a-e). The carbon in the steel predominantly existed as cementite, accompanied by a small amount of pearlite located between the ferritic grains. The ferritic matrix itself exhibited excellent ductility but relatively low hardness.

In Figure7d, a sample that was quenched in palm kernel oil displayed a low proportion of martensite structures (dark) within the ferritic matrix (white). Figure 7e, on the other hand, depicted a sample quenched in engine oil, where full martensite formation (dark) was observed. The specimen quenched in water demonstrated the highest presence of martensite phase along with retained austenite. Furthermore, the plain carbon steel specimen quenched in palm kernel oil exhibited less retained austenite and martensite compared to the other quenching media.

The impact of different quenching media on the mechanical properties of the received and quenched specimens was assessed by comparing the obtained results. It was found that the hardness values of both medium carbon steel specimens increased after quenching in all the media, as indicated by the experimental findings. This suggests that the quenching process effectively enhanced the hardness of the specimens.

Overall, the microstructural analysis and hardness measurements provide insights into the effects of quenching media on the resulting microstructures and mechanical properties of the steel specimens. These findings contribute to a better understanding of the behavior and performance of quenched steels, aiding in the optimization of heat treatment processes for desired material properties.

MECHANICAL PROPERTIES ANALYSIS

Figures 8 to 10 provide the results of the mechanical properties tests conducted on the steel specimens quenched in different media. The impact energy values, hardness test values (measured in HBN - Brinell hardness number), and tensile strength values (multiplied by 10 and measured in N/mm2) are presented for each quenching medium. Comparing the impact energy values, it can be observed that the specimen quenched in Engine Oil exhibited the highest impact energy value of 64.32 Joules, indicating its ability to absorb a significant amount of energy before fracturing. On the other hand, the Water Quenched specimen had the lowest impact energy value of 57.94 Joules. Regarding the hardness test values, the Water Quenched specimen exhibited the highest hardness with a value of 78.3 HBN, indicating greater resistance to indentation. The Diesel Quenched specimen had a lower hardness value of 70.5 HBN, followed by the Palm Kernel Oil Quenched specimen with a value of 72 HBN. The Vegetable Oil Quenched specimen had the lowest hardness value of 62.8 HBN.

In terms of tensile strength, the Engine Oil Quenched specimen demonstrated the highest value of 62.52 N/mm2. The Palm Kernel Oil Quenched specimen had a relatively lower tensile strength value of 50.21 N/mm2, followed by the Diesel Quenched specimen with a value of 49.65 N/mm2. The Water Quenched specimen exhibited the lowest tensile strength value of 39.08 N/mm2.

These results indicate that the choice of quenching medium significantly affects the mechanical properties of the steel. The Engine Oil Quenched specimen displayed the highest impact energy, hardness, and tensile strength values, suggesting improved toughness, hardness, and strength compared to the other specimens. On the other hand, the Water Quenched specimen had lower mechanical properties overall, indicating reduced toughness, hardness, and strength.

The results also highlight the influence of the quenching medium on the steel's properties. The specimens quenched in vegetable oil and palm kernel oil generally exhibited higher mechanical properties compared to those quenched in diesel and water. This suggests that vegetable oil and palm kernel oil may have provided more effective quenching, resulting in improved mechanical properties.

In conclusion, the mechanical properties tests revealed the impact energy, hardness, and tensile strength values of the steel specimens quenched in different media. The Engine Oil Quenched specimen demonstrated superior mechanical properties, while the Water Quenched specimen exhibited lower values overall. These findings emphasize the importance of selecting an appropriate quenching medium to achieve desired mechanical properties in steel.

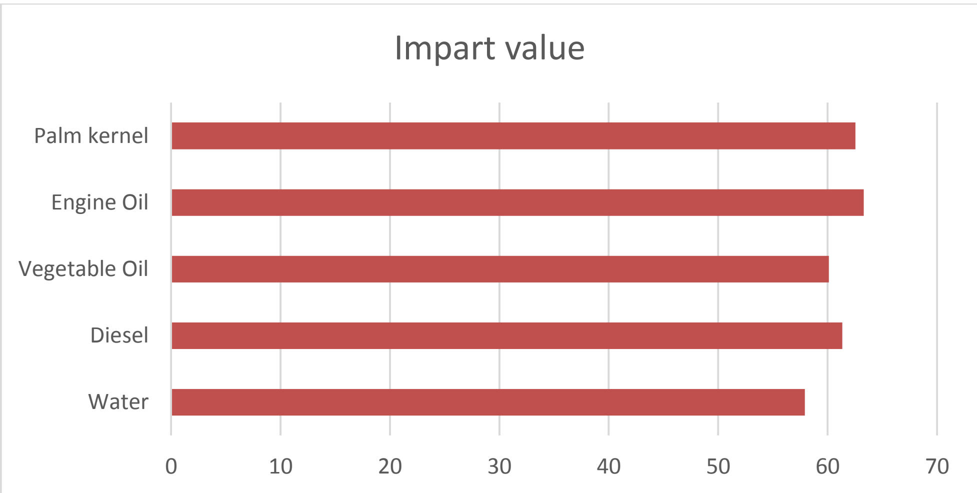


Figure 8: Impact Energy Values of the Carbon Steel Quenched in Different Quenchants.

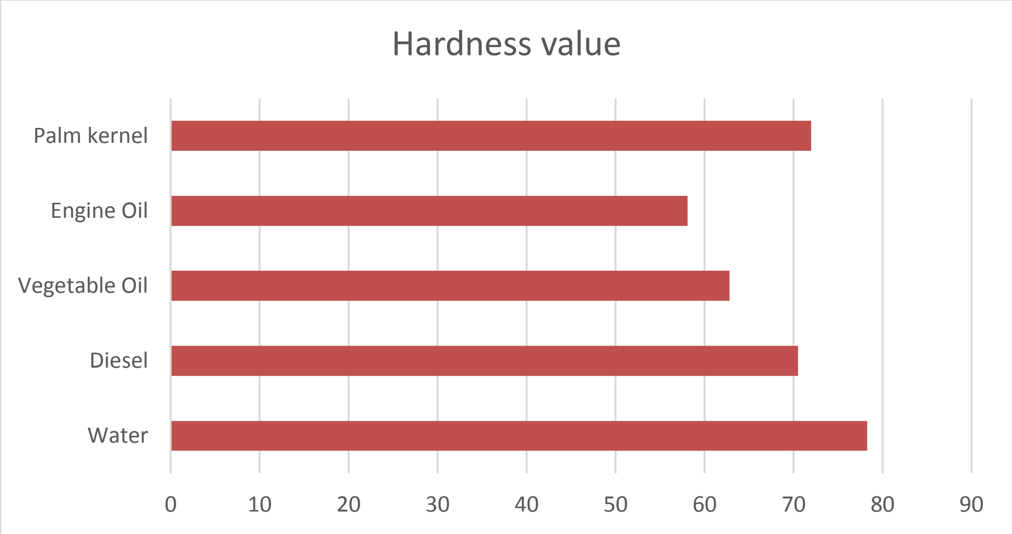


Figure 9: Hardness Values of the Carbon Steel Sample Quenched in Different Quenchants.

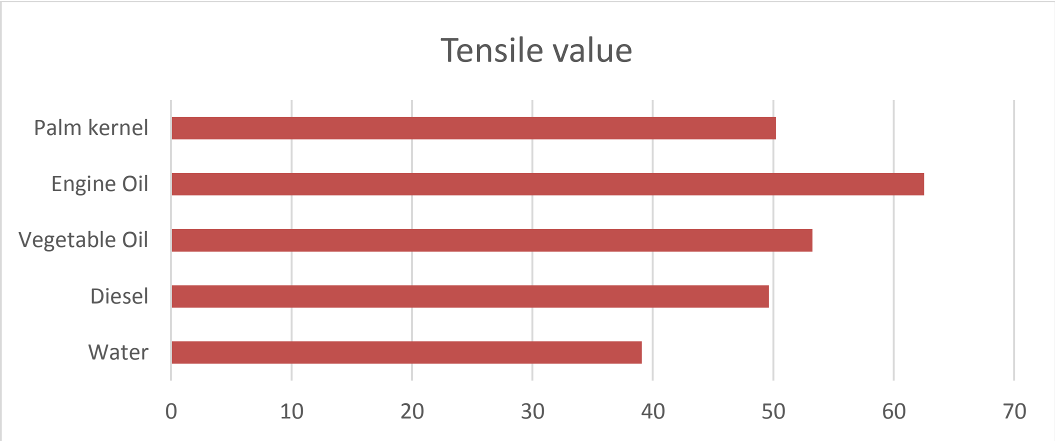


Figure 10: Tensile Strength Values of the Carbon Steel Sample Quenched in Different Quenchants.

V. CONCLUSION AND RECOMMENDATION

Conclusion

1. Ferritic steel exhibited excellent ductility but relatively low hardness due to the presence of cementite and pearlite, making it suitable for applications requiring high deformability but not high hardness.
2. Different quenching media resulted in varying proportions of martensite structures. Palm kernel oil showed low martensite, engine oil exhibited full martensite, and water quenching led to the highest presence of martensite with retained austenite.
3. Quenching increased the hardness of medium carbon steel specimens, enhancing their resistance to indentation. This highlights the effectiveness of the quenching process in improving hardness.
4. Choice of quenching medium significantly impacted mechanical properties. Engine oil-quenched specimens demonstrated higher impact energy, hardness, and tensile strength, indicating improved toughness, hardness, and strength compared to water-quenched specimens with reduced properties.

These conclusions underscore the importance of selecting the appropriate quenching medium for desired microstructures and mechanical properties in steel. Vegetable oil and palm kernel oil showed potential as effective quenching media, resulting in higher mechanical properties. Understanding the influence of quenching media, aids in optimizing heat treatment processes for specific applications that requires specific material characteristics.

Recommendation

Based on the conclusions drawn from the study, the following recommendations can be made:

1. For applications that require high deformability but not high hardness, ferritic steel can be a suitable choice due to its excellent ductility. However, if higher hardness is desired, alternative steel types should be considered.

2. The selection of the quenching medium should be carefully considered to achieve the desired microstructure and mechanical properties. Engine oil and palm kernel oil demonstrated favorable results in terms of martensite formation and mechanical properties. Therefore, these oils can be recommended as effective quenching media for enhancing the mechanical properties of steel.
3. The quenching process should be employed to increase the hardness of medium carbon steel specimens, providing better resistance to indentation. This can be particularly beneficial for applications that require improved hardness and surface durability.
4. In order to optimize the mechanical properties of steel, it is crucial to choose the appropriate quenching medium. Engine oil-quenched specimens exhibited superior impact energy, hardness, and tensile strength compared to water-quenched specimens. Therefore, for applications that demand higher toughness, hardness, and strength, engine oil can be a preferred quenching medium.

Overall, this study emphasizes the significance of considering the quenching medium during heat treatment processes for steel. By understanding the influence of different quenching media on microstructures and mechanical properties, engineers and material scientists can make informed decisions to achieve the desired material characteristics for specific applications. Further research and experimentation can be conducted to explore the potential of other quenching media and optimize heat treatment processes in steel manufacturing.

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