International Journal of
Metallurgy and Alloys

ISSN: 2456-5113
Volume 10, Issue 2, 2024
July-December
DOI (Journal): 10.37628/IJMA

https://journalspub.com/journal/ijma/

Research IJMA

Influence of Different Quenching Media on the Mechanical Properties of Mild Steel – A Case Study of Coconut Oil, Mineral Oil, Jatropha Oil, and Water

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Abstract

This study elucidates how local cooling agents, such as coconut oil and jatropha oil, influence the mechanical characteristics of heat-treated mild steel. Tensile testing, Brinell hardness testing, and microstructural analysis were conducted on both heat-treated and untreated samples. The results show observable differences in the heat-treated materials' mechanical characteristics. Specifically, the yield strength increased across all quenched media, while the ultimate tensile strength decreased for samples cooled with coconut oil (594.865 MPa) and water (585.292 MPa) compared to untreated samples. Various quenching media yield diverse microstructures that directly impact mechanical properties. Enhanced ductility was observed in most heat-treated samples, except for those cooled with water (20.22), which exhibited decreased ductility compared to untreated samples. Additionally, hardness improved in all heat-treated samples, except for those cooled with water (57.218 BHN), which showed decreased hardness compared to untreated samples. Moreover, microstructural analysis was solely conducted on the untreated sample, laying the groundwork for future experimental analysis.

Keywords: Local cooling agents, mechanical properties, microstructural analysis, mild steel, quenching media

INTRODUCTION

The alteration of a material's grain size during heat treatment arises from re-crystallization, a process wherein new, defect-free, equiaxed grains form below a certain temperature threshold known as the re-crystallization temperature. Mild steel typically undergoes re-crystallization between 400 and 700°C, fostering the formation of fresh grains.

Mild steels find extensive utility across diverse industrial sectors owing to their cost-effectiveness and ease of fabrication. These steels are categorized based on their carbon content, with carbon being the primary alloying element. Medium carbon steels, characterized by carbon content ranging from 0.25% to 0.65%, and low carbon steels, with less than 0.25% carbon content, constitute common classifications. Meanwhile, high-carbon steels typically contain carbon levels within 0.65% –1.5% [1].

Increasing the amount of carbon dissolved in austenite before quenching during the hardening heat treatment improves the mechanical characteristics of plain carbon steels, such as hardness, brittleness, and wear resistance. The conversion of austenite to martensite is frequently cited as the cause of this improvement. Therefore,

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Received Date: October 25, 2024
Accepted Date: October 30, 2024
Published Date: December 21, 2024

Citation: E. O. Ajoge, Musa James. Influence of Different Quenching Media on the Mechanical Properties of Mild Steel – A Case Study of Coconut Oil, Mineral Oil, Jatropha Oil, and Water. International Journal of Metallurgy and Alloys. 2024; 10(2): 1–8p.

using the right quenching procedures can increase the mechanical strength of medium carbon steel.

However, the primary determinants guiding the selection of quenching media are the specific heat treatment, steel composition, and dimensions and shapes of the components [2].

The application of steels in engineering necessitates a comprehensive comprehension of material properties and design requisites. Over recent decades, ongoing research has focused on a category of steel known as high-strength steel. Consequently, quenched and tempered micro-alloyed steel emerge as prime candidates for next-generation high-strength steel sheets [3]. These steels, featuring a good balance of strength and toughness, are commonly employed in the automotive industry for structural elements, power transmission, and impact resistance systems.

Certain engineering components demand high hardness for effective performance in heavy-duty processes. To achieve these goals, metallic or alloy components undergo hardening, a type of heat treatment [4]. According to Hassan et al. (2009) [5, 6], this procedure comprises heating the metal alloy to a high enough temperature and then quickly cooling it in a medium like water, oil, or a salt bath. Rapid cooling causes phase change, which increases hardness and produces non-equilibrium products [1]. The primary phase undergoing transformation is austenite, with martensite emerging as the hard micro-constituent in steel. This rapid cooling process, known as quenching, occurs in a quenchant medium, such as water, oil, or salt bath [5]. Quenching plays a vital role in tailoring the desired properties of numerous steel and aluminum alloys [7, 8]. Agitation or forced circulation of the quenchant is often necessary to expedite cooling times, as natural convection and quenchant vaporization can limit heat transfer rates without agitation. The selection of appropriate parameters, including the quenching medium, temperature, and agitation state, significantly influences the outcome of the heat treatment process [9]. Consequently, designing quenching processes that maximize material properties while minimizing residual stresses and deformations is imperative [10].

Despite recent advancements in steel heat treatment practices and understanding, the method of hardening steel through quenching in a liquid bath has remained unchanged for a century [11]. Water and mineral oil have been the predominant quenching media over the years, but the contemporary focus now shifts toward mitigating warping and breakage after quenching, particularly when comparing water and oil for the same application [12]. Additionally, modern steel heat treating literature lists various quenchants, each possessing unique qualities suited to specific applications.

While mineral oils exhibit excellent cooling capacities for most alloy steels, they are relatively costly, toxic, and nonbiodegradable [13]. Consequently, considerable research has explored substituting mineral oils with aqueous solutions of chemicals and polymers. The use of locally accessible cooking oils as quenching media has grown in popularity recently because of its affordability, non-toxicity, and environmental friendliness [14].

This study aims to assess the mechanical properties of tempered mild steel samples quenched solely in coconut oil and Jatropha oil, comparing the results with those quenched in water and mineral oil (SAE 40), respectively. Water serves as a benchmark cooling medium due to its high cooling capacity, with considerations extending to safety, management, economy, and environmental impact [15]. These mechanical properties encompass not only tensile strength, impact strength, and hardness but also percentage elongation and yield strength of the material.

MATERIALS AND METHOD

The materials used for this project are: mild steel, coconut oil, and jatropha oil. The mild steel rod of dimension 14 mm diameter was locally sourced at Tony Steel Limited, Lagere, Ile-Ife, Nigeria. The cooling media (coconut oil and jatropha oil) was sourced from Oja Titun market in Ile-Ife, Nigeria.

Material preparation and Heat Treatment

The mild steel rod was cut into smaller rods and machined into the desired dimension according to the ASTM E-8 specification for tensile operations as shown in Figure 1. Fifteen standard stud-like specimens were produced for the tensile test and hardness test. Three specimens were retained which serves as the control sample. While the other specimens are being heat treated, after which quenching took place in triple duplicates of the specimens using coconut oil, mineral oil, jatropha oil, and water as their quenching media. Table 1 shows the chemical composition of mild steel.

Figure 1. Mild Steel samples after tempered and quenched in different cooling media ready for tensile testing.

Table 1. Chemical composition of the mild steel.

C – 0.33%	Mn – 0.93%	P – 0.007%	S – 0.001%
Si – 0.3%	Nickel – 0.84%	Cr – 0.99%	Mb – 0.4%
V – 0.005%	Cu – 0.14%	Al – 0.026%	Ti – 0.003%
Ca – 0.001%	Co – 0.013%	Hppm – 1.0%	Fe – 96.014%

Material Preparation and Heat Treatment

The samples were heat-treated in a furnace at the foundry workshop, Obafemi Awolowo University, Ile-Ife (Figure 2). This was done at a temperature of 900°C for 6 hours in the heat treatment furnace.

Figure 2. Heat treatment furnace.

The heat-treated samples were taken out and quenched in triplicate pieces, it was quenched in coconut oil, jatropha oil, mineral oil, and water till room temperature. The specimens were therefore removed and cleaned properly before being sent to the laboratory for testing. The possibility of using bio-oils as quenchants which is a good alternative of mineral oil in each case [16].

Mechanical Testing

The tensile strength characteristics of the control sample and the heat-treated mild steel samples were determined using the Instron Universal Testing Machine at the Centre for Energy and Research Development, Obafemi Awolowo University, Ile-Ife. The samples were subjected to constant loading and extension rate till the samples failed by breaking. The yield strength, ultimate tensile strength, extension, percentage elongation, and stress induced were carefully studied on the display screen. The broken samples due to induced stress are kept for further tests (Figure 3).

Figure 3. Samples after tensile test was carried out.

Also, Hardness test was carried out on the control sample and the heat-treated ones using Brinell hardness method to determine their hardness property. An average of the three samples readings was used to determine the hardness value.

Microstructural Examination

The microstructural examination of the samples after undergoing mechanical test was done using an electron microscope. The samples were cleaned to remove every loose grit, the samples were then ground to obtain a smooth surface finishing with emery paper to reduce the coarseness attached to the rotating disc machine. Aluminum oxide was used to polish the mild steel. Etching was also carried out using Methylated spirit to help clean the water molecules from the surface of the samples and hydrochloric acid solution as to improve the acid-surface contact, the samples were then cleaned in ethanol. This was followed by drying in warm air and photographically recorded with a magnification of 500 using an electron microscope.

RESULTS AND DISCUSSION

The stress-strain curves of the tensile test carried out on the samples which are quenched in different cooling media were plotted using results obtained from the Instron Universal Testing machine (Table 2 and Figures 4–8).

Table 2. Samples which are quenched in different cooling media.

Samples	**Quenching Media**
A	Coconut oil.
B	Jatropha oil.
C	Mineral oil.
D	Water.

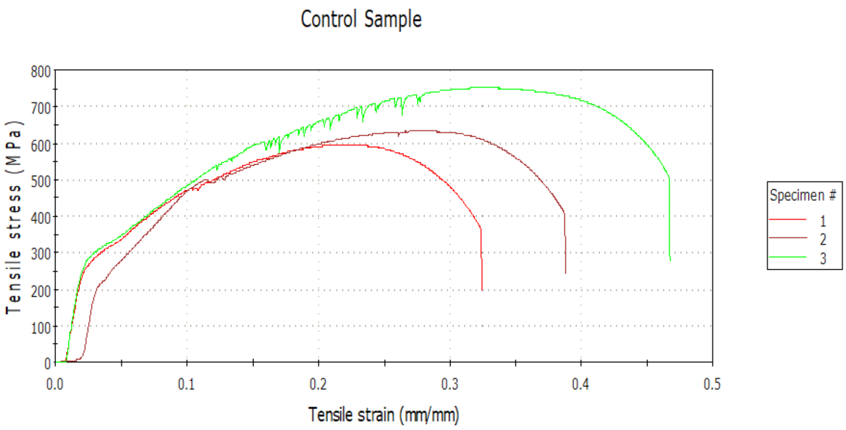

Figure 4. Stress-Strain flow curve of the steel (as received) sample.

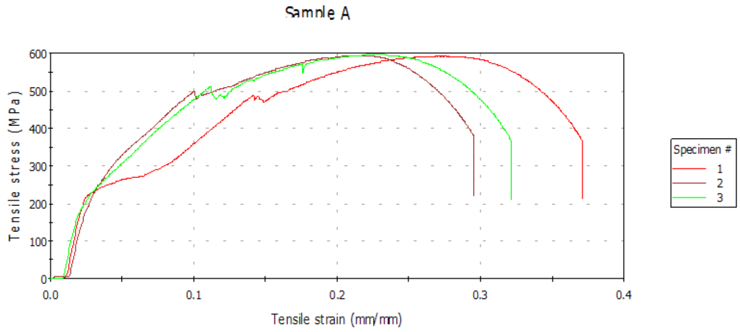

Figure 5. Stress-Strain flow curve of the steel sample heat-treated and quenched in Coconut oil.

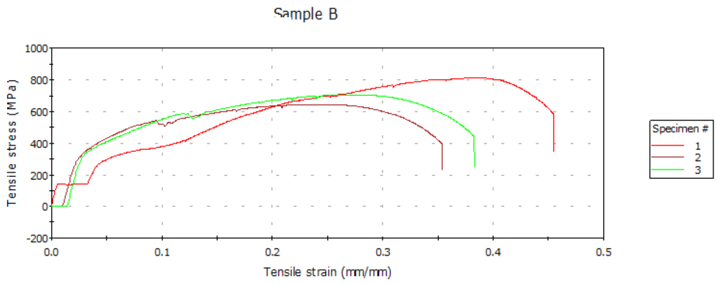

Figure 6. Stress-Strain flow curve of the steel sample heat-treated and quenched in Jatropha oil.

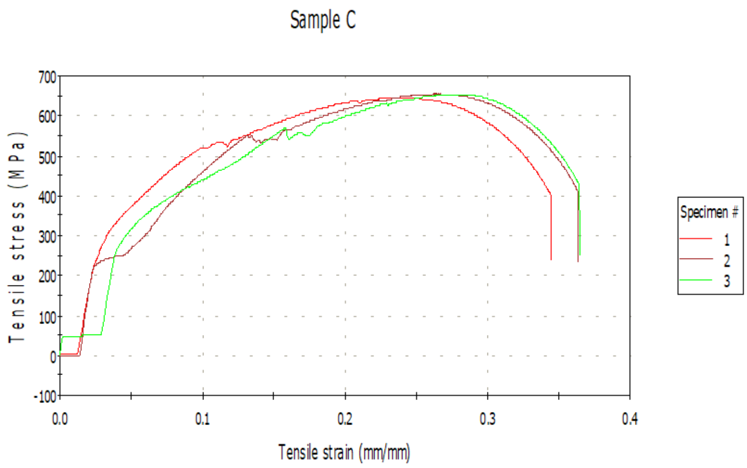

Figure 7. Stress-Strain flow curve of the steel sample heat-treated and quenched in Mineral oil.

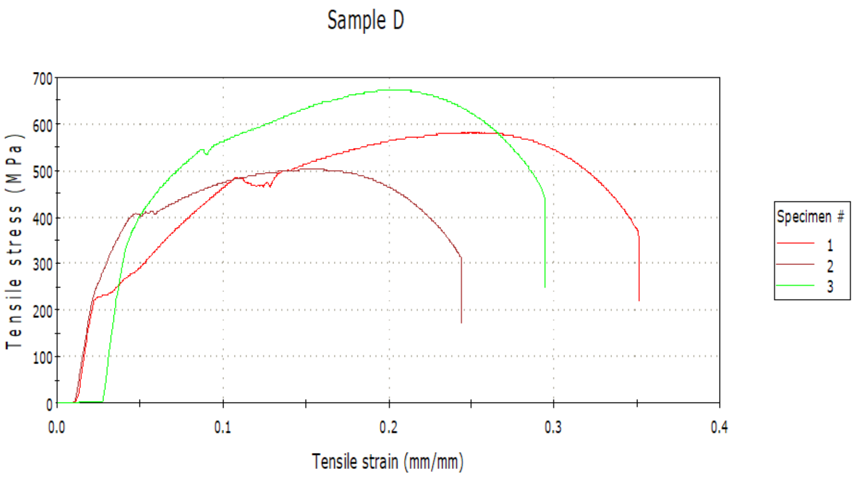

Figure 8. Stress-Strain flow curve of the steel sample heat-treated and quenched in Water.

For the sake of determining the responses of the samples to mechanical tests. The yield strength, percentage elongation, and ultimate tensile strength which were evaluated from the stress-strain curves and plotted against different quenching media used. The results are depicted in Tables 3 and 4, and Figures 9 and 10. From the tables and figures, it can be observed that the cooling process of the heat-treated mild steel samples in different media has varying effects on the hardness, strengths, and percentage elongations of the samples.

Mathematical analysis with software was done on the values obtained due to the tensile tests, which are portrayed in Tables 3 and 4.

Table 3. Mechanical properties data of the mild steel quenched in coconut oil, jatropha oil, mineral oil, and water after inter-critical annealing heat treatment process.

Sample	**Impact (J/mm^2)**	**Hardness (BHN)**	**Energy Absorbed (J)**
Control	216.6713	58.8616	121.6280
Coconut oil	167.1316	59.0546	87.7616
Jatropha oil	246.5408	75.3283	131.1839
Mineral oil	199.6405	65.8095	104.8148
Water	154.1459	57.2179	80.6099

Table 4. Mechanical properties of the control sample and other samples quenched in coconut oil, jatropha oil, mineral oil, and water after inter-critical annealing heat treatment.

Sample	**Yield (MPa)**	**UTS (MPa)**	**Young Modulus (MPa)**	**Extension (mm)**	**Elongation (%)**
Control	433.0981	660.0379	21661.8515	6.6251	22.08
Coconut oil	461.1762	594.8649	17969.8898	7.1835	23.95
Jatropha oil	482.3944	722.7371	25164.0574	8.9502	29.83
Mineral oil	493.4004	651.2133	23483.9320	7.8196	26.07
Water	456.4031	585.2917	26083.1512	6.0668	20.22

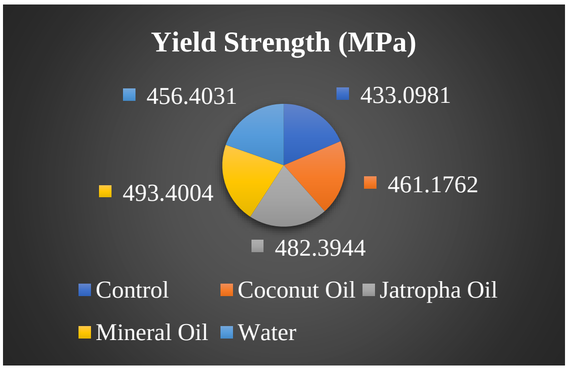

Figure 9. Yield Strength statistical representation against various quenching media.

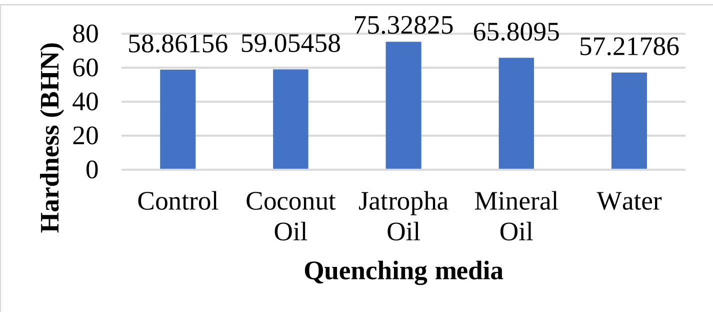

Figure 10. This depicts the variation of the Brinell Hardness number against different quenching media.

CONCLUSIONS

Based on an experimental study that examined the effects of changing the local cooling media on the mechanical characteristics of mild steel samples that had undergone heat treatment. The result of this work was obtained from the mechanical tests (Impact test, hardness test, Tensile test, and microstructural analysis) carried out on the samples which were quenched in different media (coconut oil, mineral oil, jatropha oil, and water). The inferences obtained from the experimental tests are shown below:

1. Quenching the heat-treated mild steel in different media had varying effects on the mechanical properties of the mild steel sample.
2. From the analysis, it can be deduced that the samples quenched in Mineral Oil can withstand more stress during deformation.
3. The Jatropha Oil cooled samples had the best maximum strength to withstand loadings before failure.
4. The highest percentage of elongation occurred in the samples that were quenched in Jatropha Oil is best considered for applications of mild steel necessitating the need for higher ductility.
5. The Jatropha Oil medium was observed to have the highest ultimate tensile strength and yield strength than all other specimens tested irrespective of their cooling media. Hence it is recommended for improving the strength and toughness of mild steel.
6. The heat treatment has a significant effect on the improvement of mechanical properties of steel material and given attention in the quenching medium is “Jatropha medium” for an advanced improvement of mechanical properties.

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