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# Effect of carbonization on the mechanical properties of mild steel utilizing oak charcoal as a carbon source

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## HIGHLIGHTS

- This study investigates how carburization temperature and soaking time affect mild steel mechanical properties.
- Inexpensive, locally produced oak charcoal was utilized as a carbon source.
- Mild steel cannot be hardened through quenching due to low carbon content.

## ARTICLE INFO

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## ABSTRACT

Carburizing is a process that improves the mechanical properties of low-carbon steel, particularly its surface hardness. Introducing carbon into the steel's surface enhances the creation of a durable and resistant outer layer. The technique is especially useful for low-carbon steel because it cannot be hardened by quenching and tempering. This work investigates the effects of solid carburizing on the mechanical properties of mild steel. Oak charcoal was used as a carbon source due to its local availability and low cost. The study examined how solid carburization affects the microstructure and mechanical characteristics of mild steel. Mild steel samples were carburized at 830, 880, and 930 °C temperatures for 30, 50, and 75 minutes. These samples underwent Rockwell hardness, impact, and tensile strength testing. The research investigated the influence of the carburization process, carburization temperature, oak charcoal as a carbon source, and soaking period on the mechanical properties of mild steel. It compared the mechanical properties of mild steel before and after carburization. The treated and untreated samples had different ultimate stress values. The untreated specimens had a value of 629 MPa, whereas the hardened specimens had a value of 1030 MPa. The specimens carburized at 930 °C and submerged for 75 minutes displayed the best mechanical characteristics. Oak charcoal is suitable since the research found that it considerably increases mild steel component surface hardness. This technology is cost-effective and efficient, making it a good choice when other carbon sources are scarce or costly.

## 1. Introduction

The service condition of steel gears, shafts, cams, pinions, and piston pins requires a robust, wear-resistant shell with a shock-resistant core. Low-carbon steel may be case-hardened by heat treatment to increase its characteristics. Due to its low carbon content, it requires surface treatment to fulfill high-carbon steel standards and is unsuitable for many end products. Hardened exteriors withstand abrasion, while soft interiors resist impacts [1]. The best and most popular way to case harden low-carbon steel is carburizing. Heat treatment (hardening and tempering) gives carburized machine components their intended microstructure and characteristics. Case hardening technologies provide a hard exterior and a softer interior, which is crucial for modern engineering. High-quality alloy steels combine core strength and toughness with exceptional surface hardness to create a composite structure that can bear significant stress. Cheaply produced, low-priced carbon steel may achieve low or moderate core characteristics and high surface hardness for many applications [2]. Heat treatment plays a crucial role in producing machinery and equipment, as it helps meet operational requirements and demands during their use. Carburization is done to increase the carbon content to manufacture mild steel components with a low carbon content. This is because the carbon content of such components is limited [3,4]. When mild steel and carbon-rich materials are heated together until they turn red, carbon atoms penetrate to form a harder surface structure. Carburizing is a process that involves adding carbon to the outer layer of steel components to increase their strength and durability. This is done by increasing the carbon content in the outer layer of the steel to increase its hardness. Analysis showed that longer holding durations and higher surface carbon



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content increased fatigue strength. They found that carbon atom migration to the outer layer created a martensitic phase. The steel's carburized zone enlarged, and the carbon content deepened as treatment progressed [5–9]. Carbon concentration varies in wood, coal, bones, sugar cane, and charcoal; during solid carburization, carbon is added to steel at high temperatures. Thus, more carbon sources yield more carbon on the steel surface. Wood charcoal increased its hardness and tensile strength more than coal. Hardness increased with longer carburizing [10–14]. In this investigation, a variation of quenching media was employed to cool pack carburization after treatment. This study seeks a cooling medium for pack carburizing quenching to improve low-carbon steel durability. Darmo and colleagues tested the water, 10% NaCl, and 10% cane molasses as cooling mediums. These media were tested to discover a dependable carburizing quenching method. Increasing mild steel durability was the goal. All chilling techniques improved steel's mechanical properties, carbon content, and microstructure [15]. Quenching quickly cools metal to attain mechanical characteristics. Steel is strengthened and hardened by heat treatment. To convert austenite into martensite, it is heated to 845-870 °C and quickly cooled. During steel quenching, the cooling medium viscosity affects microstructure and hardness. This research cools with oil, but the industry has also quenched with water, salty water, and oil. Slower heat absorption improves heat absorption in lower-viscosity oil [16]. This study enhanced low-carbon steel's mechanical properties using water instead of expensive cooling chemicals. Oak charcoal was employed as the carbon source during carburization due to its local availability and cost-effectiveness. The present study focuses on using local carbon sources and tap water in solid carburize to modify the mechanical characteristics of mild steel to meet this research need.

## 2. Research methodology

### 2.1 Material

The present experiment used mild steel; its chemical composition is shown in Table 1. The carbon source used was oak charcoal, which was sourced from a local farm in Sitak town, Sulaymaniyah, Iraq.

**Table 1:** The chemistry components of steel employed

| Elements | Fe | C | Mn | P | Si | Cr | W | Mo | Cu | Ni |
|---|---|---|---|---|---|---|---|---|---|---|
| Content Wt.% | 98.2 | 0.264 | 0.546 | 0.013 | 0.134 | 0.145 | 0.0039 | 0.021 | 0.456 | 0.121 |

### 2.2 Preparing samples for testing

The mild steel sample used met the dimensional requirements specified by the tensile experiment based on DIN 50125 for typical tensile, impact, and hardness samples.

### 2.3 Solid carburizing and tempering

Various test specimens were mixed with powdered oak charcoal inside a tightly sealed steel container. The container was then inserted into the Muffle Electric Furnace, namely the 1500 variant produced in China. Figure 1 shows the furnace in the heat treatment laboratory of Sulaimani Polytechnic University's Technical College of Engineering. The furnace had been set to reach and maintain certain temperatures (830, 880, and 930 °C) for different durations (25, 50, and 75 minutes). When the temperature was determined and the required immersion period was completed, tap water rapidly cooled specimens. Subsequently, they were subjected to tempering at 510 °C for 75 minutes.

### 2.4 Chemical and microstructure analysis

The composition of raw materials and pack carburizing results were assessed using the Optical Emission Spectrometer method according to ASTM E415. In addition, microstructure alterations were analyzed using a 3% Nital HNO3 solution and a Euromex PB-4161 optical microscope, as seen in Figure 2.


**Figure 1:** Barnstead Small Electric Benchtop Muffle Furnace

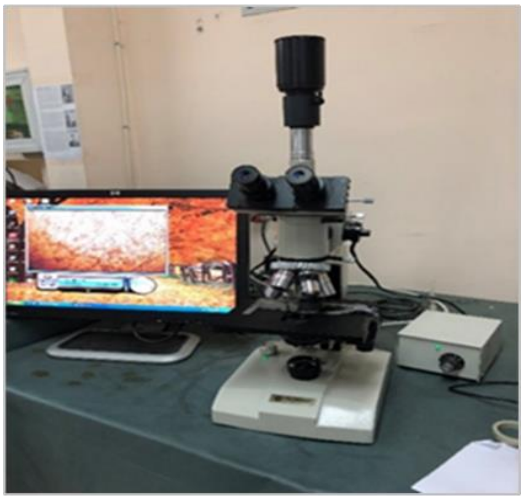

**Figure 2:** EUROMEXPB-4161Metallurgical Microscope

## 2.5 Tensile test

Tensile tests were performed on samples using the WP310 tensile testing apparatus manufactured by Gunt Company in Hamburg, Germany, by the DIN 50125 standard. The experiments were conducted in the Technical College of Engineering material laboratory at Sulaimani Polytechnic University. The specimens complied with the criteria outlined in DIN 50125. Figure 3 shows a tensile specimen with a diameter of 6 mm, a test length of 30 mm, and a total length of 64mm. These products are furnished with an M10 fastening thread.

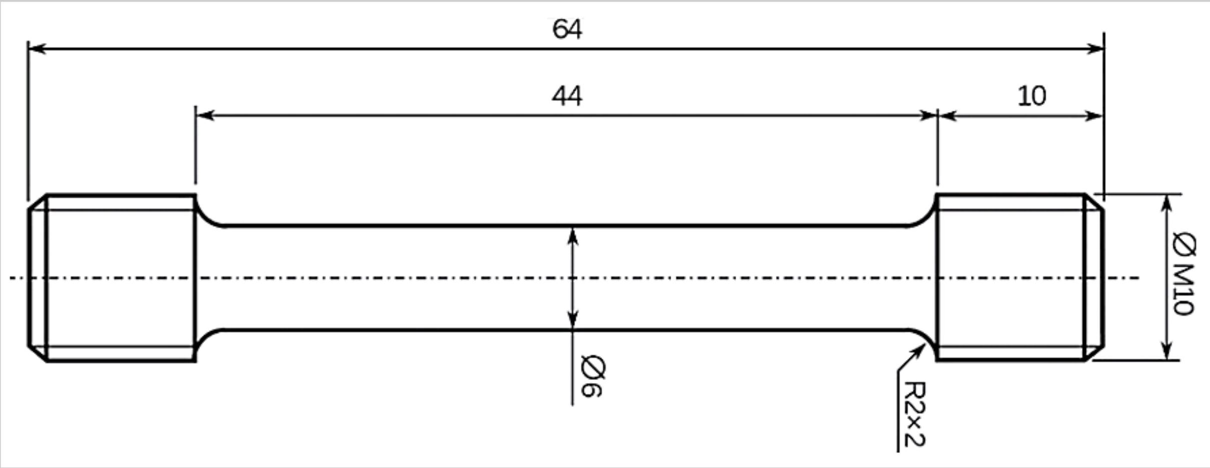


**Figure 3:** Tensile specimen dimensions comply with the requirements of DIN 50125

## 2.6 Hardness test

The carburized samples were subjected to hardness testing using a Chinese Rockwell Hardness machine of type HRS-150 manufactured in 2017, as seen in Figure 4. The test was carried out at the hardness laboratory of Mass Iraq for the Iron and Steel Industry in Sulaymaniyah, Iraq.

**Figure 4:** Rockwell Hardness Tester machine, HRS-150 digital

## 2. 7 Impact test

Impact testing was performed on the carburized V-notch specimens, as seen in Figure 5. The testing was conducted using a Charpy-type apparatus known as WP410, which adheres to the industrial specifications outlined in DIN 148-1.The investigations were carried out in the Technical College of Engineering materials laboratory at Sulaimani Polytechnic University.

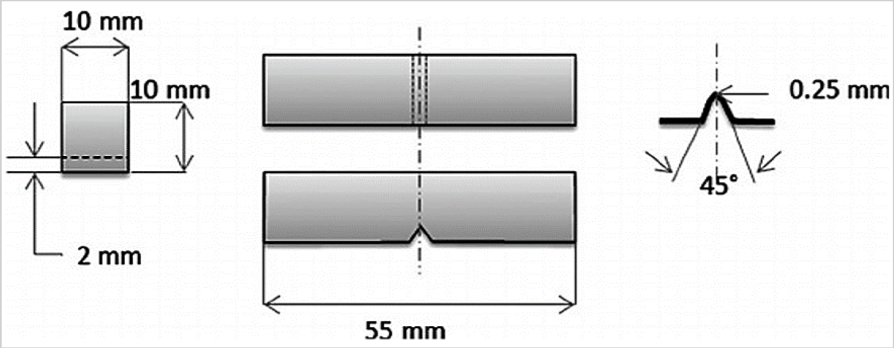


**Figure 5:** The dimensions of the V-notch specimen meet the specifications of DIN 148-1

## 3. Results and discussion

### 3.1 Composition and microstructure

Carburization induces a modification in the chemical makeup of steel, increasing its carbon content. According to Table 2, the carbon concentration rises from 0.264% to 1.86%. The initial indication of successful pack carburizing is achieved with an increase in carbon content. Nevertheless, the carbon content of the material carburized at 830 °C did not see a substantial rise compared to the initial material with a carbon concentration of 0.264%. These findings indicate that the temperature of 830 °C is inadequate for the diffusion of carbon atoms into the material. Conversely, the carbon concentration rises at carburizing temperatures of 880 °C and 930 °C. At a temperature of 930 °C, the carbon concentration on the surface is 1.86 wt%, which is seven times more than the initial specimen's concentration of 0.264 wt%. Figure 6 displays the microstructure of untreated mild steel, typically consisting of a pearlite structure contained within a ferrite matrix. The mild steel specimen has a low hardness due to its low carbon content (0.264 wt.%, Table 1). Light areas suggest ferrite owing to ferrous interacting with the etching solution.

**Table 2:** The chemical composition before and after carburizing

| | C% | Si% | Mn% | Cr% | Ni% | Mo% | Cu% | Fe |
|---|---|---|---|---|---|---|---|---|
| Raw material | 0.264 | 0.134 | 0.546 | 0.145 | 0.121 | 0.0216 | 0.456 | Bal. |
| Carburized 830 °C | 0.319 | 0.134 | 0.546 | 0.145 | 0.121 | 0.0216 | 0.456 | Bal. |
| Carburized 880 ºC | 1.20 | 0.135 | 0.5465 | .0.145 | 0.1212 | 0.0217 | 0.323 | Bal. |
| Carburized 930 °C | 1.86 | 0.1344 | 0.63 | 0.146 | 0.1213 | 0.0217 | 0.326 | Bal. |

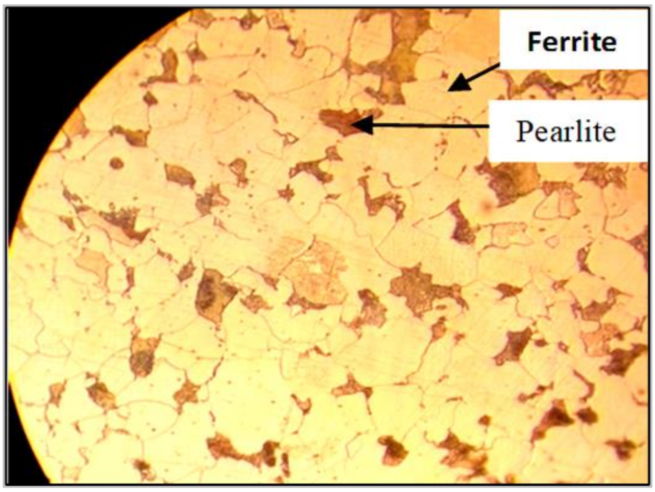


**Figure 6:** Microstructures of raw material (500× magnification)

Low-carbon steel's carbon atoms travel toward the surface after pack carburizing. New phases with surface carbon atoms result. The samples' exterior layer has a martensitic microstructure, and temperature affects the structures and carburization. The sample's microstructure is mostly pearlite with some martensite. Carburized steel microstructure at 830 °C is shown in Figure 7(a). Due to its low carbon content, carburized steel resembles a raw material. These data imply that 830 °C is insufficient for carbon atom diffusion into the material. Figure 7(b and c) shows that the sample's surface has a lot of martensite structure. The presence of martensite phases during quenching may improve surface hardness. Dark dots on specimen 7(c) indicate a lot of cementite ($Fe_3C$) structure. When cementite and ferrite are present, pearlite develops as a lamellar structure. Carbon diffusion rises with temperature and has more pearlite, tempered martensite, and ferrites at grain boundaries. The quenching process also reduces the average grain size, resulting in a more rigid surface for the mild steel specimen, as seen in Figure 7c. Smaller grain sizes are associated with higher hardness ratings.

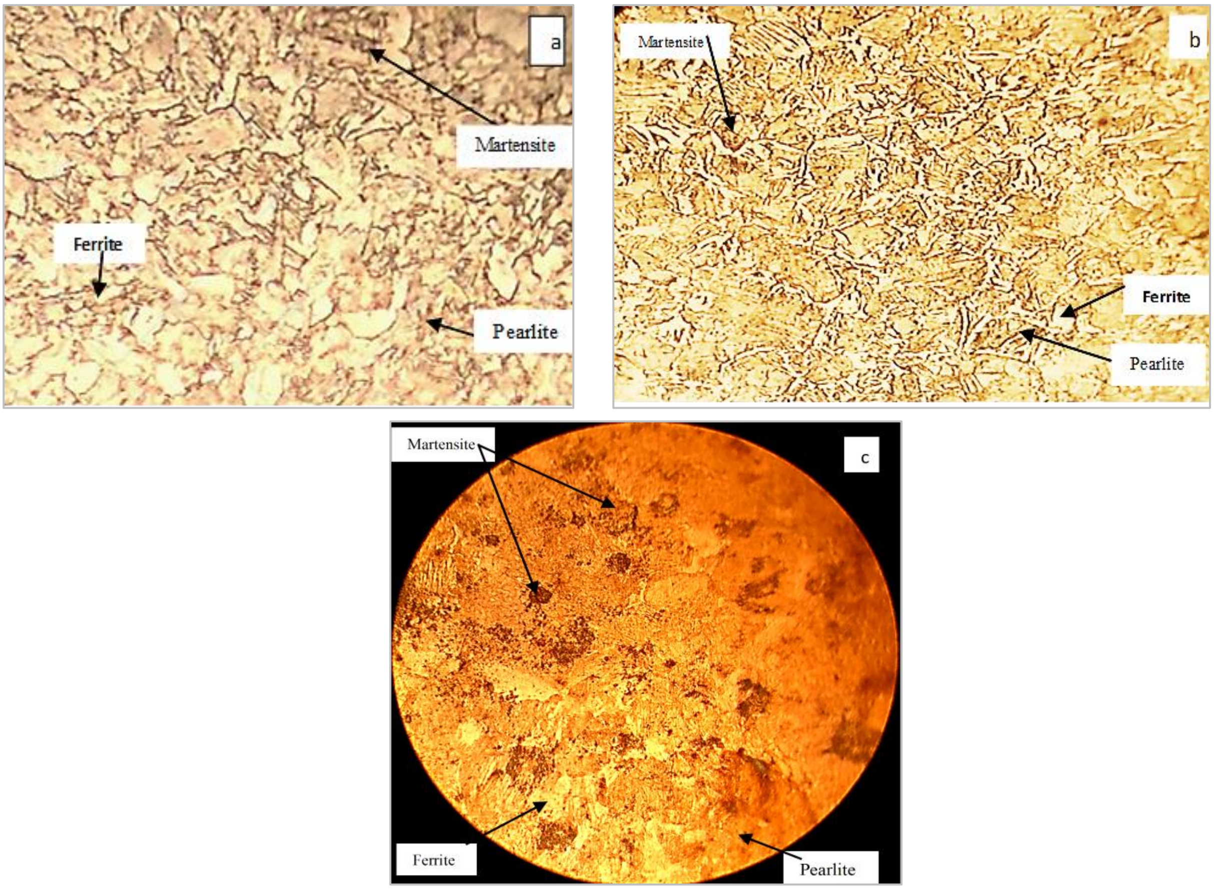


**Figure 7:** Changes in the Microstructure of Carburizing Results:
(a) Carburizing at 830 ºC; (b) Carburizing at 880 ºC
(c) Carburizing at 930 ºC, Magnification 500X; Nital 3%

## 3.2 Surface hardness test

Table 3 compares the hardness test results for untreated and carburized mild steel. Carburization results in a significant increase in the surface hardness of low-carbon steel. Figure 8 demonstrates a clear correlation between the sample's surface hardness, the carburization temperature, and the soaking period. The maximum hardness value of 99.3 $H_{RB}$ is achieved after 75 minutes at 930 °C, but after 75 minutes at 830 °C, the hardness rating drops to a minimum of 88.4 $H_{RB}$. Carburizing is a procedure that entails introducing carbon to the external surface of steel components to enhance their strength and durability [8,15]. As shown in Figure 8, there is a relationship between the hardness values and the carburized temperature. The hardness values exhibit a pronounced upward trend on the graph as the temperature rises, suggesting a more excellent carbon absorption by the outer layer of the carburized sample due to phase change [5]. Consequently, carburizing at 930 °C for 75 minutes yields the best carburizing conditions.

**Table 3:** The test results of the carburized working

| Properties / Temperatures (°C) | Soaking Time (min) | Rockwell Hardness ($H_{RB}$) | Impact (J) | Ultimate stress (MPa) | Eng. Strain (%) | Yield Strength Mpa | Young's modulus (GPa) |
|---|---|---|---|---|---|---|---|
| | 25 | 91.7 | 42 | 731 | 0.198 | 607 | 12.138 |
| 830 | 50 | 93.2 | 43 | 724 | 0.186 | 567 | 16.088 |
| | 75 | 88.4 | 45 | 683 | 0.1894 | 532 | 10.444 |
| | 25 | 92.2 | 40 | 941 | 0.154 | 817 | 28.577 |
| 880 | 50 | 95.3 | 40.9 | 897 | 0.125 | 789 | 20.557 |
| | 75 | 97.5 | 37 | 994 | 0.135 | 886 | 20.243 |
| | 25 | 96.5 | 38 | 985.8 | 0.143 | 845 | 47.568 |
| 930 | 50 | 96.9 | 41.2 | 918 | 0.119 | 778 | 62.194 |
| | 75 | 99.3 | 36 | 1030 | 0.113 | 890 | 57.350 |
| Untreated | | 74.5 | 56.4 | 629 | 0.256 | 501 | 9.231 |

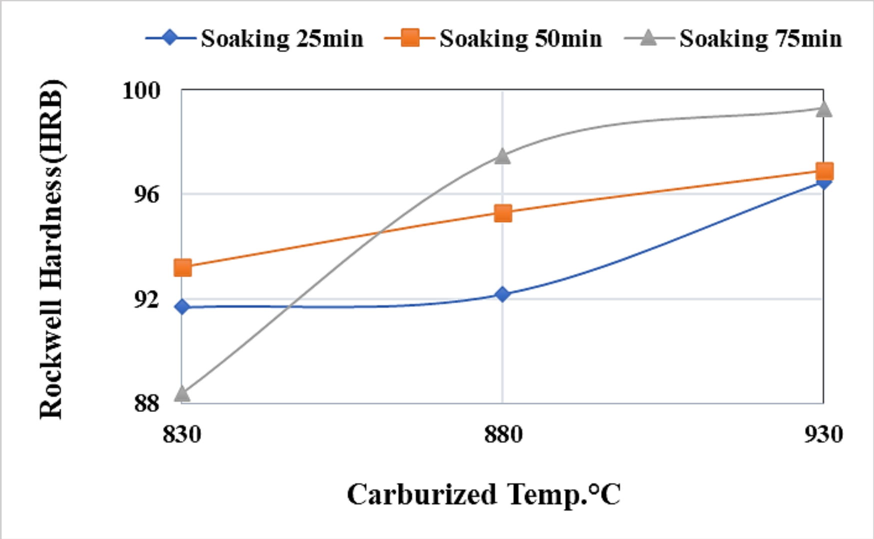


**Figure 8:** The influence of carburized temperature and soaking duration on hardness

## 3.3 Ultimate tensile strength

Figure 9 illustrates a direct relationship between the carbonization temperature and the tensile strength of each sample. Subjecting the sample to a temperature of 830 °C for 75 minutes reduces tensile strength to 683 MPa. In contrast, the untreated sample has a tensile strength of 629 MPa. The disparity between those numbers is not substantial. A possible reason for this phenomenon is that a temperature of 830 °C is insufficient to induce carbonization; the carbon diffusion process appears not active enough. Figure 10 indicates that the tensile strength of carburized steel remains unaffected by the soaking period at 830 °C, compared to 880 °C and 930 °C. However, as the carburizing temperature increased, the ultimate stress of the samples immersed for 75 minutes improved. A similar finding was reported by [3,5]. The highest tensile strength value, 1030 MPa, was achieved at a carburizing temperature of 930 °C with a soaking time of 75 minutes. Therefore, carburizing is a process that involves adding carbon to the outer layer of steel components to increase their strength and durability [9,15] . Consequently, the carburized samples have a higher ultimate tensile strength than the raw material.

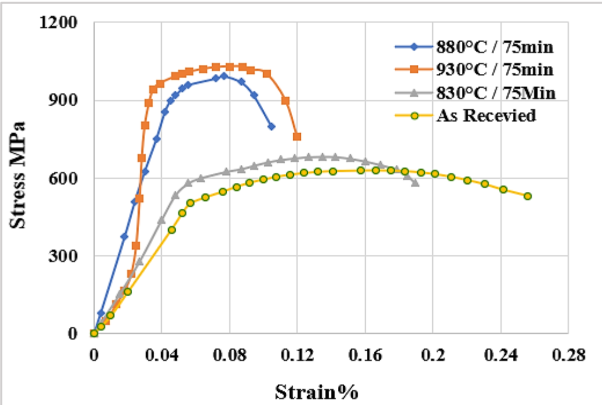


**Figure 9:** Illustrates how carburization temperature and soaking duration affect tensile strength when compared to the original sample

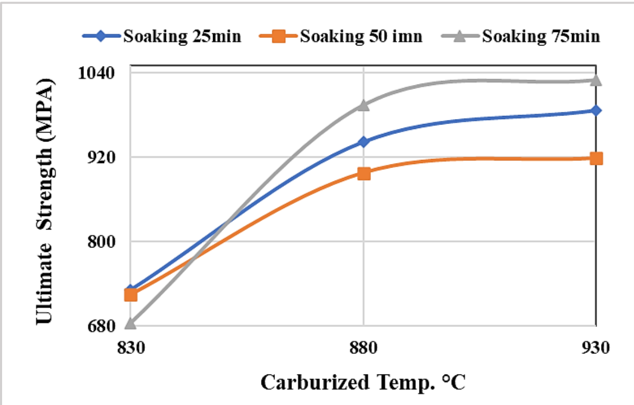


**Figure 10:** Shows the influence of carburized temperature and soaking duration on tensile strength

## 3.4 Absorbed (impact) energy

Figure 11 depicts an inverse correlation between temperature, time, and impact energy for carburized materials subjected to different temperatures and durations. The impact energy decreases to 36.0 J after 75 minutes at a temperature of 930 °C, indicating a significant relationship between carburization temperatures and impact energy. The impact energy of the 75-minute samples was decreased compared to the 50 and 25-minute samples, perhaps due to the prolonged immersion duration. The impact energy remained unchanged after exposing the material to carbonization at 830 °C for different durations. The carbon diffusion process may lack sufficient activity to increase the properties of the carbonized material, or the temperature of 830 °C may not be enough to achieve carbonization. The carburized samples exhibited a minimum impact energy of 36.0 J, whereas the non-carburized samples showed a higher value of 56.5 J. The data suggest that carburizing mild steel enhances its quality.

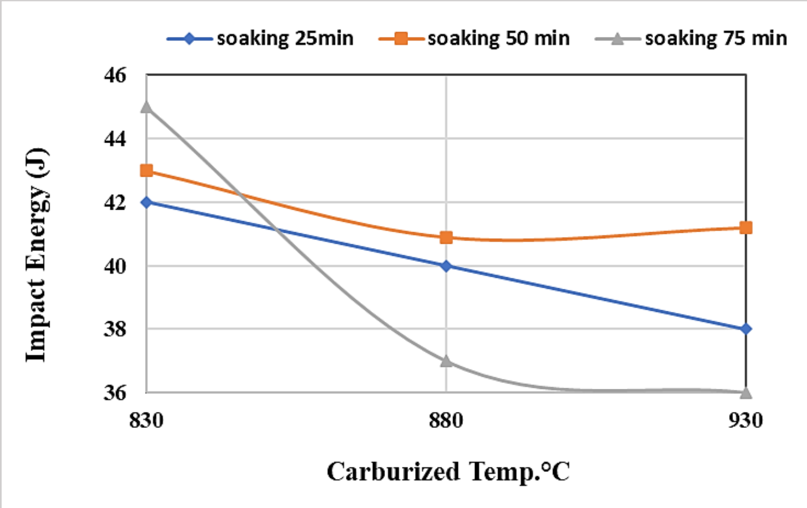


**Figure 11:** The influence of carburized temperature and soaking time on impact energy

## 3.5 Engineering Strain

Figure 12 demonstrates no disparity in the engineering strain between the treated and untreated samples after 75 minutes of carburizing at a temperature of 830 °C. However, when exposed to temperatures of 880 °C and 930 °C for an equal duration, the tensile strength substantially rose to 1030 MPa, while the engineering strain value decreased to a minimum of 0.113 from 0.256 in the untreated sample. As the surface hardness of the carburized samples rises, their malleability decreases. Figure 9 demonstrates a linear reduction in strain as the carburizing temperature increases when samples are immersed at various temperatures for 50 and 75 minutes. In addition, specimens immersed for 25 minutes at a temperature of 830 °C had a maximum strain of 0.198. A possible reason for this phenomenon is that a temperature of 830 °C is insufficient to induce carbonization [15]. When oak is used as a carbonaceous substrate for the production of carburized steel, the strain value in the initial material reduces from 0.3273 to 0.113. Based on the experimental findings, a holding duration of 75 minutes is the best choice to achieve the minimum engineering strain at all 3 carburized temperatures [5] .

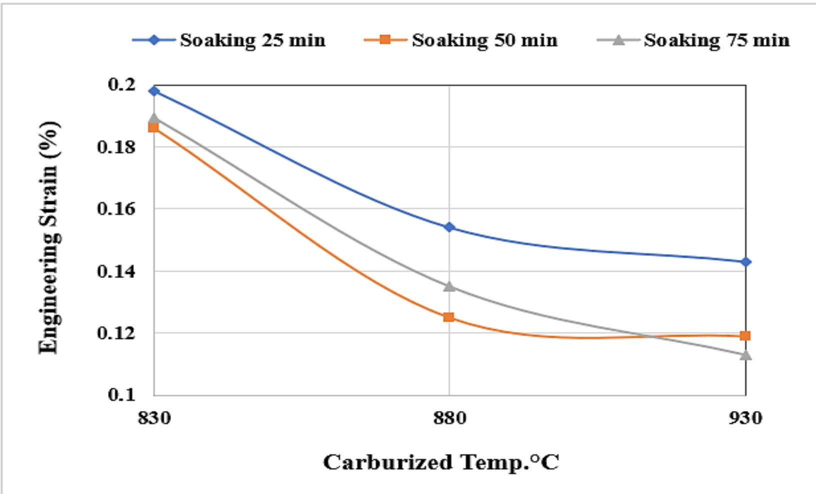


**Figure 12:** Shows the influence of carburized temperature and soaking duration on strain values

## 3.6 Modulus of elasticity

Figure 13 depicts the results of the carburization process on specimens that were immersed for different periods and at various temperatures. The modulus of elasticity exhibits an upward trend with increasing temperature compared to its untreated state, ultimately peaking at 62.194 GPa during a 50-minute immersion at 930 °C. More extended immersion periods had little impact on stiffness as strain values decreased after 75 minutes of soaking, reaching a minimum of 10.444 GPa at a temperature of 830 °C. Carburized low-carbon steels exhibit a significant improvement in ultimate strength and modulus of elasticity compared to raw material but experience a decrease in elongation. These results corroborate the research conducted by D N K Negara and Widiyarta [5]. The reference is from the paper by Baali et al., [8]. Hence, the most effective carburizing parameters were attained with carburizing at 930 °C for durations of 75 and 50 minutes. According to the findings, the specimens' elasticity and tensile strength exhibit an upward trend as the carburization temperature increases. Consequently, the modulus of elasticity rises.

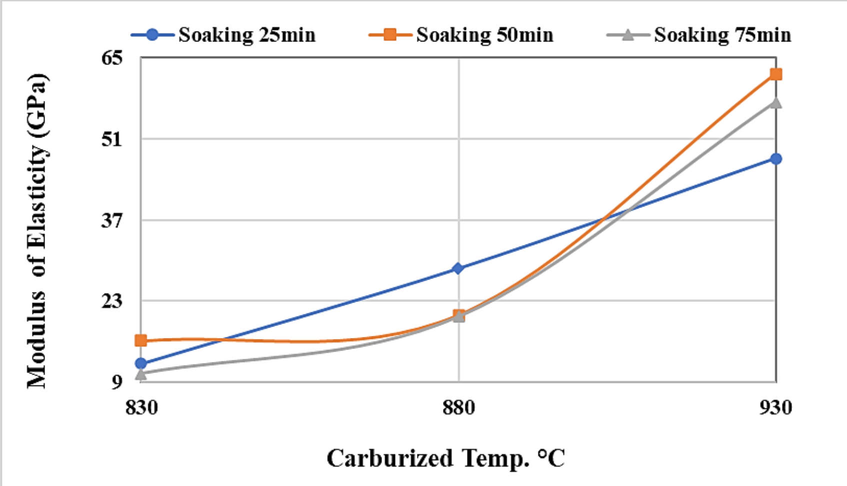


**Figure 13:** Influence of carburizing temperature and duration on the elastic modulus of the specimen

## 4. Conclusion

The project intends to investigate how carbonization affects the mechanical characteristics of mild steel. Tap water is our main cooling medium, and oak charcoal is our local carbon source. The effects of carburizing temperature and soaking time on mild steel mechanical characteristics were also studied. Conclusions from the study:

1) The temperature and duration of the carburizing process significantly influence the crystalline structure of the carburized layer. This results in a transformation from ferrite and pearlite to martensite and new iron carbides $Fe_3C$ in the outer layer.
2) The carburizing process directly impacts the chemical makeup of the steel, resulting in an observable rise in the carbon percentage.
3) The hardness value of mild steel increases with higher carburization temperature. The maximum hardness of 99.7 $H_{RB}$ is achieved at 930 °C.
4) The tensile strength increases with higher carburization temperature, with the highest value at 930°C and the lowest for raw material, ranging from 1030 to 629 MPa.
5) As the carburization temperature rises, the toughness of mild steel that has undergone carburization decreases. The minimum toughness value of 36 J is achieved at 30 °C.
6) The sample's tensile strength dropped to 683 MPa after 75 minutes at 830 °C. The untreated sample has 629 MPa. So, no substantial difference exists between the two numbers. Possible explanation 830 °C isn't a sufficient temperature to cause carbonization.

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### Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

### Conflicts of interest

The authors declare that there is no conflict of interest.

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