



Evaluation of the Effects of Charcoal Particle Sizes on Carburized Low Carbon Steel

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Abstract

This research investigates how charcoal particle size affects the carburization of mild steel. A total of 32 low-carbon steel specimens (0.219% carbon content) were carburized using charcoal particles of varying sizes: 0.5 mm, 2 mm, 5 mm, and 10 mm. The charcoal used contained 63% fixed carbon. Carburization was carried out at 900°C for 120 minutes in the presence of an energizer, followed by quenching in water. The carburized samples were then subjected to tensile, hardness, and metallographic tests. Results indicate that the specimen treated with 0.5 mm charcoal specimen achieved the highest ultimate tensile strength 956.77 MPa which is 59% higher than the control sample. In contrast, the 10 mm charcoal specimen exhibited the highest hardness (85.23 HRA, 45.4% higher than the control) and modulus of elasticity (205.34 GPa, 2.7% higher). Metallographic analysis revealed that these samples developed a martensitic case with a bainitic core, indicating improved surface hardness and strength due to the larger particle size of charcoal used in the carburizing process.

Keywords: Carburize, particle size, metallographic, hardness, tensile strength.

1.0 Introduction

Engineers typically strive to develop materials that possess both high yield strength and good elongation, even though improving one often diminishes the other. In normalized low-carbon steel, strain ageing can significantly enhance the yield strength potentially matching or exceeding the material's ultimate tensile strength though this improvement comes at the expense of reduced elongation.

Steel which is an alloy primarily composed of iron and carbon, with small amounts of other elements—is classified into low-, medium-, or high-carbon steel based on its carbon content. Through heat treatment processes involving controlled heating and cooling, steel's microstructure can be altered to enhance properties such as tensile strength, hardness, ductility, and yield strength (Hesham, 2014). Mild steel, also referred to as low-carbon steel, typically contains between 0.05% and 0.25% carbon (Devakumar, 2015), making it versatile, relatively strong, easy to fabricate, and affordable. Its widespread use in construction, automotive, machinery, and energy sectors underscores its practical importance (Fayomi, 2021).

However, mild steel has notable shortcomings, including low hardness, insufficient fatigue resistance, reduced toughness at low temperatures, and limited wear and corrosion resistance. To address these limitations, surface-hardening techniques—like carburization—are applied (Modak, 2023). Carburizing involves infusing carbon into the steel's surface, thereby increasing hardness and wear resistance. Among carburizing methods—gas, liquid bath, vacuum, and pack—pack (or solid) carburizing is particularly cost-effective and accessible, especially when charcoal is used as the carbon source (Adedipe, 2023).

This study focuses on pack carburizing mild steel using charcoal of varying particle sizes, in the presence of an energizer, within an electric furnace held at constant temperature and duration. The goal is to determine how charcoal particle size influences the steel's surface hardness and wear resistance. The anticipated outcome is the creation of a hardened outer layer (the case) surrounding a tougher, ductile inner core. Understanding the optimal particle size could guide manufacturers in producing components with enhanced mechanical properties using affordable, locally available materials. Ultimately, this research aims to provide practical recommendations for achieving better performance in applications demanding high surface hardness and durability.

Carbon steel is an iron–carbon alloy with less than 2% carbon though may also contain trace impurities such as silicon, phosphorus, sulfur, and oxygen (Yahya et al., 2013). Mild steel, defined as containing less than 0.25% carbon, falls within this category. Heat treatment comprising controlled heating, soaking, and cooling stages is a

critical manufacturing technique used to tailor material properties such as hardness, strength, toughness, and ductility (Sharma, 1970; George & Totten, 2006).

Heating Stage: the material is heated above its critical temperature.

Soaking Stage: the material is held at this temperature to ensure a uniform temperature throughout.

Cooling Stage: the material is cooled rapidly or slowly, depending on the targeted properties.

Carburizing, a surface-hardening method for mild steel, creates a hard, wear-resistant surface while maintaining a ductile core. Historically performed by packing the steel in charcoal and quenching it thus hardening the surface without compromising core toughness modern techniques like pack, gas, or liquid carburizing offer improved process control (Krauss, 2017). Compared with alternatives like nitriding or quench-and-temper treatments, carburizing operates at lower temperatures, induces less distortion, and allows precise control of case depth and hardness (Fatai *et al.*, 2010).

Research indicates that finer charcoal particles increase carbon diffusion efficiency due to their greater surface area. Surface hardness tends to increase with temperature: fine particles yield hardness up to 551 HV, while coarser particles can reach 682.6 HV. Metallographic analysis shows that ferrite predominates at 800 °C with short hold times, while longer times and higher temperatures promote the formation of pearlite and martensite, which correlate with increased hardness. Thus, carburizing enhances tensile strength, hardness, and wear resistance essential qualities for components subjected to sliding, friction, and dynamic loading (Shackelford, 2015).

This research narrows its focus on the effect of charcoal particle size during pack carburization of mild steel. By comparing different particle sizes along with the use of an energizer this study evaluates mechanical (surface hardness and wear resistance) and microstructural outcomes. The aim is to establish the optimal charcoal particle size that maximizes hardness and durability while preserving core ductility, offering practical insights for manufacturers in resource-limited settings.

2.0 Materials and Methods

2.1 Materials and Equipment

The material used for this work are included: Mild steel, charcoal, BaCO₃ CaCO₃ energizers, sieve, stone grinder, tube furnace, oven, gride paper and carbide cutting tool.

2.2 Methods

The charcoal was prepared using the principle of proximity and standard mesh size. It was milled manually to obtain ranges of sizes from 10mm, 5mm, 2mm and 0.5mm with the help of the standard mesh sizes. The mesh sieve where arrange by sizes from bottom to top of ranging 0.4mm, 0.5mm, 1mm, 2mm, 4mm, 5mm, 9mm and 10mm. These enable obtaining mesh sizes of 10mm, 5mm, 2mm, and 0.5mm of charcoal sizes. Sieve of different sizes.

Proximate Analysis: The proximate analysis of the charcoal which involved the determination of moisture content, volatile matter and ash content were determined according to ASTM D3173, D3175, and D3174 standards. The fixed carbon content was obtained by subtracting the percentage of ash, moisture content and volatile matter from 100.

Other analysis done were compressed density, durability, relaxed density and relaxation ratio.

Composition of energizer and charcoal: Combination composition during carburization for each containment box is as follow

1. Weight of charcoal per carburization 300g
2. Weight of CaCO₃ 10% of 300g charcoal = 30g
3. Weight of BaCO₃ 3% of 300g charcoal = 9g

Sample Preparation: The samples were prepared in a serial manner for mechanical test starting from cutting operation and turning operation followed by carburization.

The mild steel samples were loaded into the carburization container housing charcoal and energizes and carburized with charcoal particle sizes of 0.5, 2, and 10mm with the same quantity of energizers, temperature, and time. The carburizing temperature for this sample was 900°C and soaked for 2hrs and cooled in water.

Mechanical Test: The mechanical test perform on the carburized steel samples were tensile test and hardness test. The tensile test was conducted in accordance to ASTM E8 and a Rockwell hardness test was used in accordance to ASTM E18. The metallographic samples were prepared by cutting, sequential polishing with 220–1200 grit papers, etching, microscopic analysis, and repeated for the specimens.

3.0 Results and Discussion

3.1 Chemical Composition of Specimen

Table 1 presents the result of analysis of the composition of the steel specimen use for this investigation as receive from Ratnakar Hayin Dogo Kaduna state.

Table 1 Chemical Composition of Specimen

Element	Composition (%)	Element	Composition (%)
C	0.219	W	<0.010
Si	0.51	Pb	<0.0030
Mn	1.15	Mg	<0.0010
P	0.0064	B	<0.0005
S	0.0039	Sn	0.0051
Cr	0.019	Zn	0.0038
Ni	0.042	As	0.0072
Mo	0.0098	Bi	0.0041
Al	0.015	Ca	0.0029
Cu	0.115	Ce	0.0034
Co	0.017	Zr	0.0020
Ti	0.029	La	0.0021
Nb	<0.0040	Fe	97.8
V	<0.0010		

(Yahya *et al* 2013), classified steel whose carbon content is less than 0.25% as mild [low carbon] steel. Hence the sample composition 0.219% carbon, satisfies the minimum percentage requirement for a low carbon steel.

3.2 Proximate Analysis of the Charcoal

Table 2 presents the result of proximate analysis of the charcoal content, used for the carburization process.

Table 2 Composition of Charcoal

No	Element Symbol	Charcoal (%)
1	Ash content	5.5
2	Volatile matter	29.2
3	Moisture content	2.5
4	Fixed Carbon, C	62.8

The charcoal obtained from the market was subjected to approximate analyses to ascertain its carbon content and other approximate compositions. The result showed a carbon content of 62.8% which satisfies the carbon range of 50%-95% for pack carburization according to Salawu et al 2019.

3.3 Mechanical Test

Figure 1 presents the result of the tensile test for the samples as a function of charcoal particle size. Figure 2 presents the modulus of elasticity test for the samples as a function of charcoal particle size. Figure 3 presents the result of hardness test of the samples as a function of charcoal particle size.

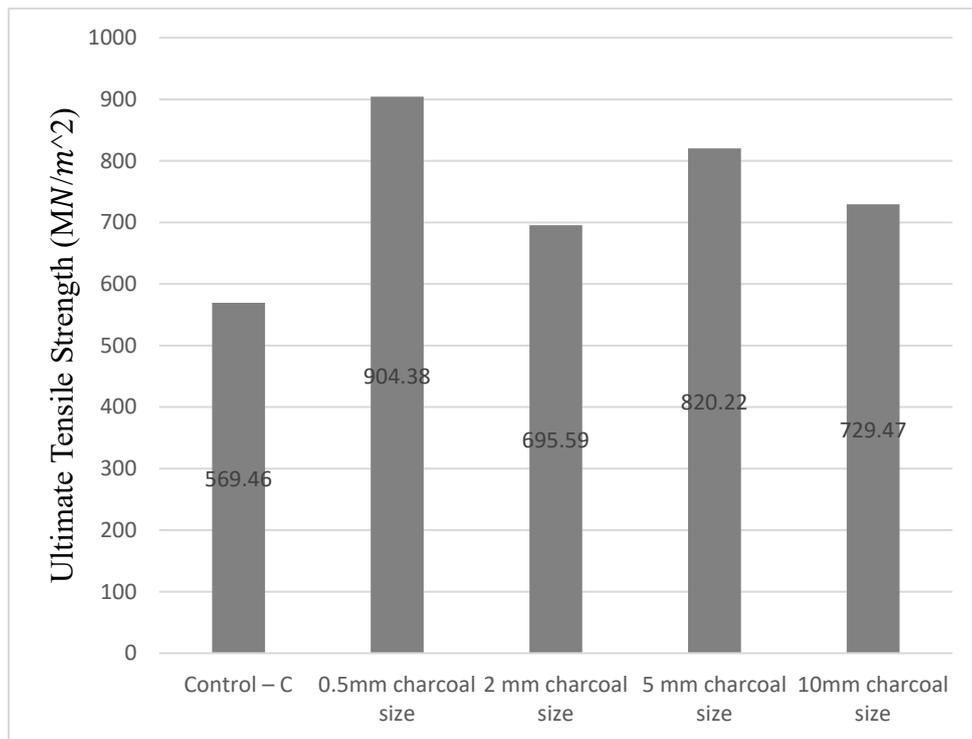


Figure 1. Ultimate tensile strength (UTS) [(GN/mm) ^2]

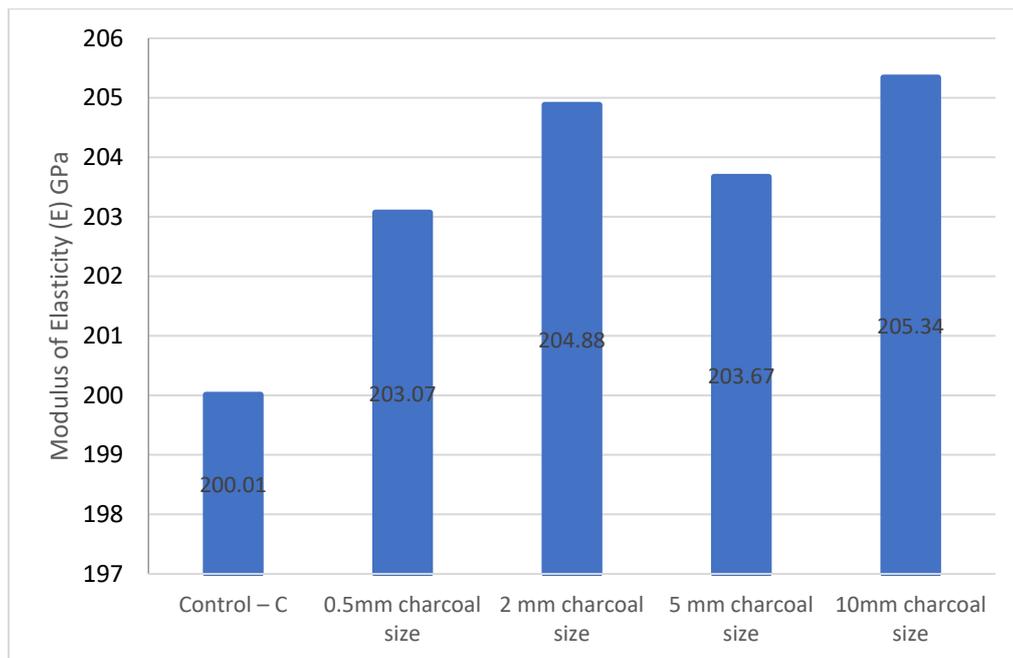


Figure 2. Modulus of elasticity (E)

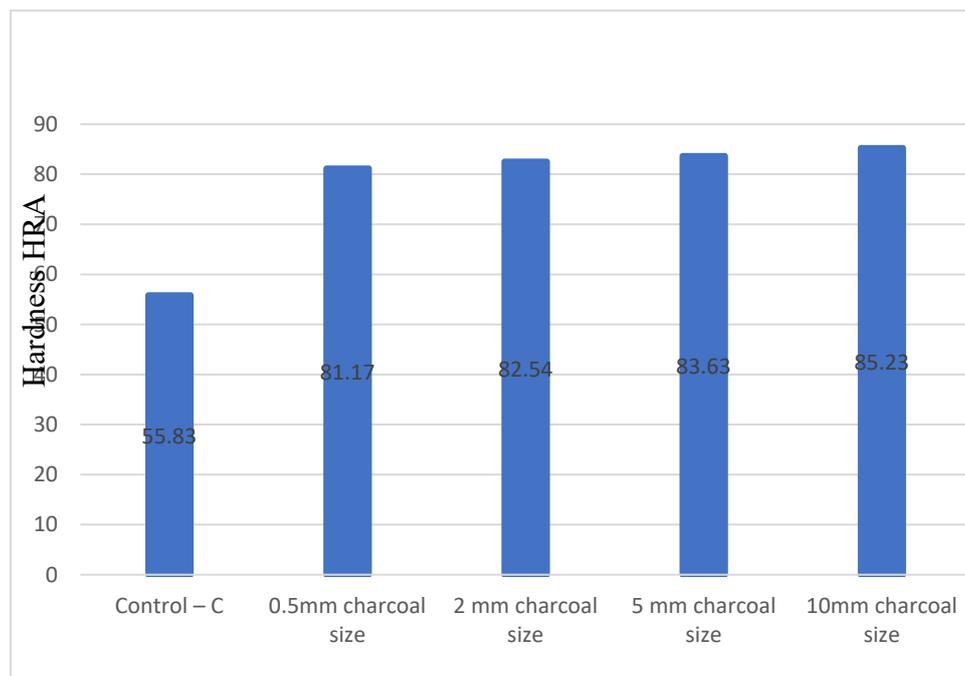


Figure 3. Hardness test value for rough surface

The influence of charcoal particle size on carbon diffusion is a critical factor in determining the mechanical properties of carburized mild steel. The 0.5 mm charcoal specimen achieved the highest ultimate tensile strength 956.77 MPa which is 59% higher than the control sample with 604.61 MPa. This is attributed to the larger surface area of smaller particles, which enhances carbon release and diffusion rates, as described by Fick's first law of diffusion ($J = -D \partial C / \partial x$, where J is the diffusion flux, D is the diffusion coefficient, and $\partial C / \partial x$ is the concentration gradient). The high surface area of 0.5 mm particles increases the carbon concentration gradient at the steel surface, promoting rapid diffusion and forming a high-carbon martensitic case upon quenching (Adly *et al.*, 2020; Ngafwan *et al.*, 2021). This result in a significant strengthening effect, ideal for applications requiring high tensile strength, such as structural components.

In contrast, the 10 mm charcoal specimen exhibited the highest hardness (85.23 HRA, 45.4% higher than the control) and modulus of elasticity (205.34 GPa, 2.7% higher), as shown in Figure 2 and 3. Larger particles likely provide a more stable and sustained carbon supply, maintaining a consistent carbon potential throughout the 120-minute carburization process. This stability may lead to a deeper carburized layer, as larger particles reduce the risk of carbon depletion compared to finer particles, which may exhaust their carbon content more quickly (Adebayo *et al.*, 2023). The deeper case depth enhances hardness and stiffness, making the 10 mm specimen suitable for wear-resistant applications like gears and bearings. The trade-off between tensile strength (maximized at 0.5 mm) and hardness/stiffness (maximized at 10 mm) suggests that particle size can be tailored to specific performance requirements, offering flexibility for industrial applications.

3.4 Metallography Test

Plate 1 presents the result of the metallography test carried out for the control specimen.

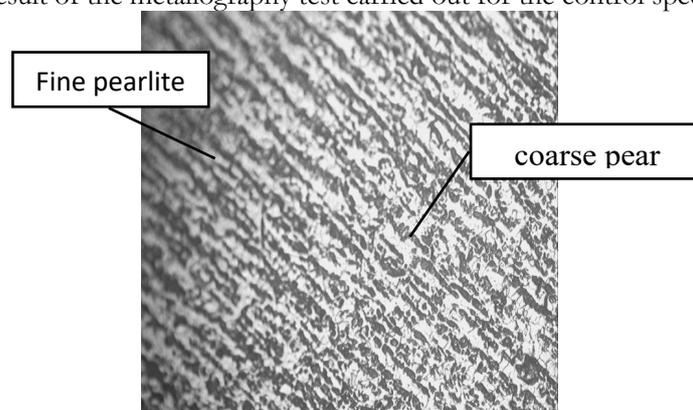


Plate 1: Control specimen

The metallography test shows the coarse pearlite microstructure due to slow cooling in the furnace during annealing.

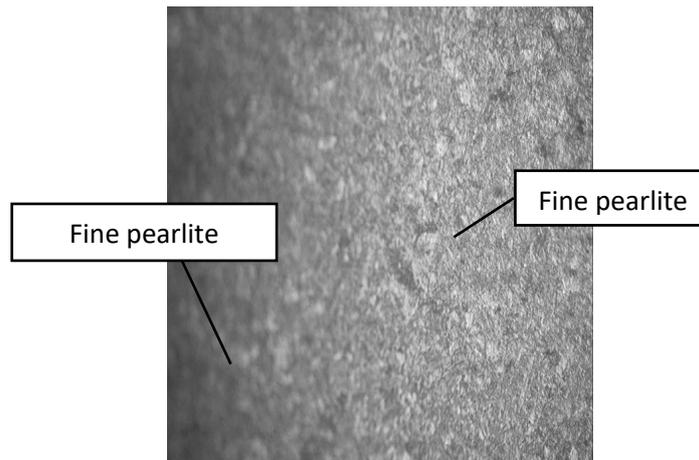


Plate 2 Charcoal size of 0.5mm

Plate 2 shows the structure of mild steel carburized with 0.5mm charcoal particle size. This indicates two structural regions of low concentration of martensite close to the surface and high concentration of fine pearlite at the center.

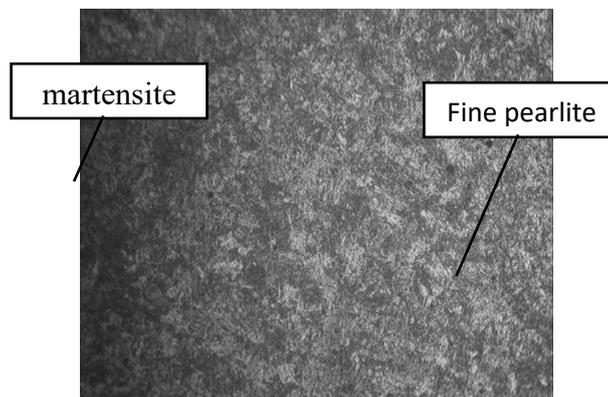


Plate 3 Charcoal size of 2mm

Plate 3 shows the structure of mild steel carburized with 2mm charcoal particle size. This indicates two structural regions which shows high concentration of martensite close to the surface and low concentration of fine pearlite at the center

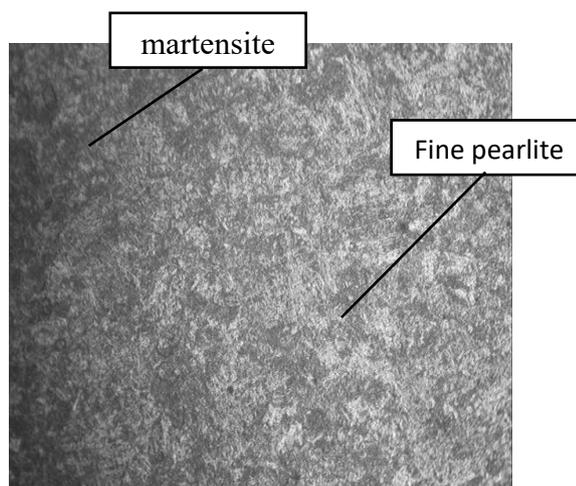


Plate 4 Charcoal size of 5mm

Plate 4 shows the structure of mild steel carburized with 5mm charcoal particle size. This indicates two structural regions which shows low concentration of martensite close to the surface and high concentration of fine pearlite at the center.

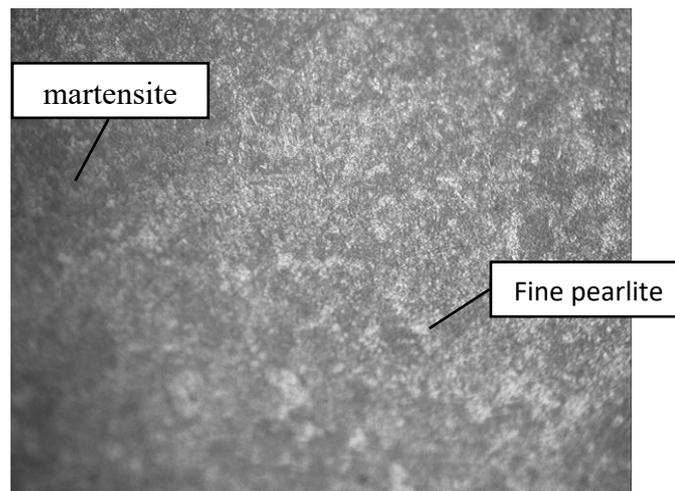


Plate 5: Charcoal size of 10mm

Plate 5 shows the structure of mild steel carburized with 10mm charcoal particle size. This indicates two structural regions which shows low concentration of martensite close to the surface and high concentration of fine pearlite at the center.

As it is seen from the metallography, the control specimen's coarse pearlite microstructure results from slow cooling during annealing, promoting ferrite and pearlite formation, which corresponds to its low hardness (55.83 HRA) and moderate strength (604.61 MPa) (Krauss, 2017). Carburized specimens subjected to water quenching, exhibited a martensitic case due to rapid cooling through the eutectoid temperature (727°C), which suppresses pearlite formation and induces a body-centered tetragonal (BCT) martensite structure (Oluwole *et al.*, 2022).

The 0.5 mm specimen showed low martensite concentration with and high fine pearlite indicating rapid carbon diffusion but limited case depth due to the high surface area of fine particles. This aligns with the high UTS (956.77 MPa), as the surface martensite enhances strength, while the pearlite retains ductility (Adly *et al.*, 2020). The 2 mm specimen displayed a higher martensite concentration near the surface, suggesting a balance between diffusion rate and case depth, resulting in moderate improvements in both strength (812.67 MPa) and hardness (78.50 HRA). The 5 mm and 10 mm specimens exhibited lower surface martensite but a bainitic core, particularly in the 10 mm specimen. Bainite, a mixture of ferrite and cementite, enhances core toughness, while the martensitic case ensures high surface hardness (81.17 HRA), making the 10 mm specimen ideal for applications requiring both wear resistance and impact resistance Agustinus *et al* 2020.

4.0 Conclusion

Based on the results of the experiment, the following conclusions were drawn:

- The elemental analysis of the test specimen shows a composition of 97.8% iron (Fe) and 0.219% carbon (C), placing it within the carbon content range of mild steel (0.04–0.25% C).
- The proximate analysis of the charcoal indicates a fixed carbon content of 63%, which exceeds the minimum requirement of 50% for effective carburization, confirming its suitability for the process. Carburizing mild steel with 10 mm charcoal particle size significantly enhances its mechanical properties. The modulus of elasticity increased to 205.34 GPa, which is above the typical range for mild steel (180–200 GPa). Additionally, the hardness reached 81.17 HRA, which is a 45.4% increase compared to standard mild steel. Microstructural examination revealed a higher concentration of martensite in the carburized specimen, indicating an increase in carbon content due to successful absorption during the carburization process.
- The results demonstrate that carburizing mild steel with larger charcoal particle sizes (specifically 10 mm) effectively enhances both mechanical and structural properties. Therefore, carburization using larger charcoal sizes is recommended for improving the performance of mild steel.
- It is recommended to use charcoal with a particle size of 10 mm for the carburization of mild steel to achieve improved mechanical properties such as increased hardness and elasticity. Further research can explore the effect of varying carburization durations and temperatures to optimize the process for industrial applications.

References

- [1] C. C. Liu, X. J. Xu, and Z. Liu, "A FEM modeling of quenching and tempering and its application in industrial engineering," *Finite Elements in Analysis and Design*, vol. 39, no. 11, pp. 1053–1070, 2003.
- [2] D. M. Ward, "Influence of carburization on the properties of furnace tube alloys," in *Corrosion and Mechanical Stress at High Temperatures*, V. Guttman and M. Merz, Eds., London, UK: Applied Science Publishers, 1981, pp. 71–83.
- [3] D. H. Xu and Z. B. Kuang, "A study on the distribution of residual stress due to surface induction hardening," *International Journal of Engineering Materials and Technology*, vol. 118, no. 2, pp. 571–575, 1996.
- [4] G. P. Shewmon, *Diffusion in Solids*, Tokyo, Japan: McGraw Hill, 1963.
- [5] H. C. Child, *Surface Hardening of Steels*, Oxford, UK: Oxford Univ. Press, 1980.
- [6] J.-B. Leblond, "Mathematical modeling of transformation plasticity in steels II: Coupling with strain hardening phenomena," *International Journal of Plasticity*, vol. 5, no. 6, pp. 573–591, 1989.
- [7] K. F. Wang, S. Chandrasekar, and H. T. Y. Yang, "Experimental and computational study of the quenching of carbon steel," *International Journal of Manufacturing Science and Engineering*, vol. 119, no. 3, pp. 257–265, 1997.
- [8] M. B. Prime, V. C. Prantil, P. Rangaswamy, and F. P. García, "Residual stress measurement and prediction in a hardened steel ring," in *Materials Science Forum: Residual Stress ECRS 5*, A. J. Böttger, R. Delhez, and E. J. Mittemeijer, Eds. Stamford, CT, USA: Thomson Scientific, 2006, pp. 223–228.
- [9] R. Hochman and J. Burson, *The Fundamentals of Metal Ducting*, New York, NY, USA: API Div. of Refining, 1966, p. 331.
- [10] S. Denis, "Coupled temperature stress, phase transformation calculation model numerical illustration of the internal stresses evolution during cooling of a eutectoid carbon steel cylinder," *Metallurgical Transactions A*, vol. 18A, pp. 1203–1287, 1987.
- [11] T. V. Rajan, C. P. Sharma, and A. Sharma, *Heat Treatment Principles and Techniques*, New Delhi, India: Prentice Hall, 1994.