Science, Engineering and Technology Vol. 5, No. 2, pp. 44-52
www.setjournal.com *https://doi.org/10.54327/set2025/v5.i2.277*

Suitability Assessment of Organic Carbon Additives in the Carburization of Low Carbon Steel (AISI 1020) for Engineering Applications

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Abstract

The quest to enhance the mechanical properties of low-carbon steel (LCS) has stimulated the exploration of diverse carburization techniques, with growing attention on organic additives derived from agricultural wastes as sustainable alternatives to conventional materials. This study investigated sheanut shell (SNS) and eggshell (ES) ash as eco-friendly carburizing agents for AISI 1020 steel to improve its performance for engineering applications. The objective was to evaluate their potential in enhancing hardness, strength, impact resistance, and microstructural properties of LCS. Experimental analysis compared carburized and un-carburized (UC) samples, focusing on hardness, tensile strength, impact energy, and microstructural features. The findings showed that carburization significantly increased hardness, with carburized LCS reaching 513 HB compared to 398 HB for UC LCS. However, UC LCS exhibited higher yield strength (221.3 N/mm²) and ultimate tensile strength (241.1 N/mm²), whereas carburized LCS absorbed more fracture energy (63.72 J), reflecting a trade-off between hardness and tensile strength. Microstructural examination revealed improved surface morphology, metallurgical bonding, and higher pearlite concentration due to carbon diffusion, while energy dispersive spectroscopy confirmed elevated carbon content in carburized samples. Structural analysis further identified both crystalline and amorphous carbon phases. The study concludes that SNS and ES ash are effective sustainable carburizing additives capable of enhancing surface properties of LCS, making the material suitable for high-strength and wear-resistant applications. It recommends the wider adoption of these agro-waste additives in industrial carburization processes to reduce reliance on costly conventional materials while promoting sustainable engineering practices.

Keywords: *Carburization process, Low carbon steel, Organic wastes, Mechanical testing, Microstructural analysis.*

1. Introduction

In materials science, there are two primary methods for enhancing the mechanical properties of steel: heat treatment and plastic deformation. When carbon steel is heated to its austenitizing temperature and then rapidly cooled, it forms a martensitic structure, which is significantly harder than the pearlite and ferrite structures. This process is referred to as quenching. AISI 1020 steel, characterized by a low carbon content ranging from 0.20% to 0.30%, is commonly used in various industrial applications such as gear components in plate-bending machines, construction, and automotive industries [1] and [2]. Carburization of AISI 1020 steel is a heat treatment technique that enhances metal hardness by using carbon additives at high temperatures [3], [4]. Traditionally, carburization involves encasing low-carbon wrought iron in charcoal, heating it to a red-hot temperature for several hours, and quenching it in water. This process, which is ideal for LCS applications, creates a hardened surface while retaining a tough inner core [5], [6].

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Received: *4 April 2025*; Revised: *14 May 2025*; Accepted: *26 May 2025*; Published: 3 *September 2025*
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Surface engineering, which is crucial in the automotive and aerospace sectors, aims to enhance component performance by modifying surface characteristics through thermal, mechanical, and thermo-mechanical treatments [7], [8]. Heat treatment of LCS induces significant atomic rearrangements in metals and alloys, affecting their physical, chemical, and mechanical properties. Various carbon sources have been explored for carburizing, including palm kernel shells, cattle bones, oyster shells, melon shells, and polyethylene [9]. Among the carburizing methods, pack carburizing is often chosen because of its simplicity and ability to produce uniform hardness[10], [11] . This method involves heating and cooling the metal in the solid state, altering the grain structure, and enhancing the toughness by controlling the cooling rate. Rapid cooling yields a hard structure, whereas slow cooling results in a softer material [12], [13].

Energizers like Na_2CO_3, $CaCO_3$, or $BaCO_3$ (0–40% of the mixture) are added to materials with low carburizing potential to expedite the process. At high temperatures, $BaCO_3$ decomposes into CO_2 and barium oxide; CO_2 then reacts with the carbon in the carburizer, producing CO, which diffuses into the steel [14], [15], [16]. Quenching the material produces a hardened outer layer, which enhances the hardness and strength of steel. Researchers have extensively studied the impact of organic carbon on iron and steel properties, demonstrating the effectiveness of energizers, such as eggshells, in boosting the carburizing potential [17], [18], [19], [20], [21].

Abdenour (2021) investigated eggshells as enhancers in the carburization of mild steel by leveraging their high calcium carbonate content, such as periwinkle and snail shells [22], [23].. The goal was to demonstrate the effectiveness of eggshells in carburization, especially for applications requiring hard cases, such as gears and spindle shafts.

Nutshells, by-products of nut processing, are typically used as fuel but also serve in plywood as a binder, for plastic, and dye production [24], [25]. Sheanut shell ash (SNSA), derived from burning sheanut shells, is an agro-waste from the shea tree, primarily found in African savannas. Traditionally used for facials and water compaction, sheanut shells have been proposed as sustainable fuel sources [26], [27]. SNSA's modern uses of SNSA include catalyzing biodiesel production and as a partial cement substitute, enhancing mortar and concrete strength with extended curing times. However, a higher SNSA content may reduce compressive strength [28], [29].

Despite the proven potential of agro-wastes, such as date seeds and snail shells, in carburization, studies on SNSA and eggshell ash (ESA) in this application remain limited. This research focuses on exploring the combined effects of SNSA and ESA in enhancing the carburization process of AISI 1020 steel, contributing to sustainable practices, and expanding agro-waste applications in manufacturing, automotive, and agriculture. The objective of this study is to investigate the effectiveness of shea nutshell (SNS) and eggshell (ES) ash as sustainable organic carburizing additives for enhancing the mechanical and microstructural properties of AISI 1020 low-carbon steel. The motivation behind this is to explore environmentally friendly alternatives to conventional carburizing materials by utilizing agricultural waste products, which remain underutilized despite their potential to improve the performance of low-carbon steels in engineering applications.

2. Materials and Experimental Procedures

2.1. Materials

The materials used in this study were AISI 1020 steel, sheanut shells, eggshells, and industrial oil (AMMASCO-SAE 20 W-50), as detailed in Table 1. Sheanut shell was employed for pack carburization, while eggshell served as an energizer, and industrial oil as the quenching medium. Table 1 shows the elemental composition by percentage weight of AISI 1020 steel.

Table 1. Elemental composition of low-carbon steels.

Element	Fe	Si	P	S	Mn	Ca	Cr	V	Ni	Cd	Cu	C
Composition (wt%)	97.32	0.70	0.07	0.10	1.13	0.10	0.20	0.01	0.02	0.19	0.10	0.20

2.2. Experimental Procedures

The experimental procedures involved the preparation of SNS and ES particles, machining of the test samples, and the mechanical and morphological characterization of the samples.

2.2.1. Preparation of the SNS and ES Particles

Both the sheanut shell and eggshell were cleaned separately to eliminate impurities, such as dirt and oil, using detergent, followed by air-drying for 24 h at room temperature. The two organic materials were then crushed using a Denver cone crusher to achieve sizes ranging from 4 to 3 mm. Subsequently, they underwent further size reduction in a roll crusher to reach dimensions between 2 and 1 mm.

2.2.2. Production of the test samples

The resulting product from the roll crusher was ball-milled for two hours. After milling, the product was sieved using a set of sieves with mesh sizes of +710, +500, +355, +250, and +125µm using a sieve shaker for 30 min. The sieved shea nutshell and eggshell particles were individually packed into heat-resistant metal containers (austenitic stainless steel) and calcined in a muffle furnace at 650 °C for carbonization. They were then ground and sieved using a BS sieve analyzer to obtain oversized and undersized particles based on different mesh sizes, and the weights of each were recorded. AISI 1020 steel test samples were machined to standard test sample sizes for tensile, hardness, impact, wear, and microstructure analyses.

2.2.3. Carburization Process

Within a steel pot, the prepared test samples were wrapped in activated carbon made from a 70:30 wt percent mixture of eggshell and shea nutshell ash. The pot was securely sealed with a clay cover to prevent the escape of carbon oxides and to prevent any unwanted furnace gases from infiltrating during the heating process. The furnace temperature was maintained at 850 °C and a loaded steel pot was inserted into the furnace. Upon reaching the desired carburizing temperature of 950 °C, it was maintained for 30 min. These parameters were determined based on preliminary optimization studies to achieve optimal carburization results. Once the time elapsed, the steel pot was extracted from the furnace. Subsequently, the materials were quenched in industrial engine oil at ambient atmospheric temperature as described by Oladosu et al. (2020) and Aramide et al. (2009) [3], [18]. Figure 1 shows the experimental mixture of SNSA and ESA, the carburization charging box, and the induction furnace with the charged box.

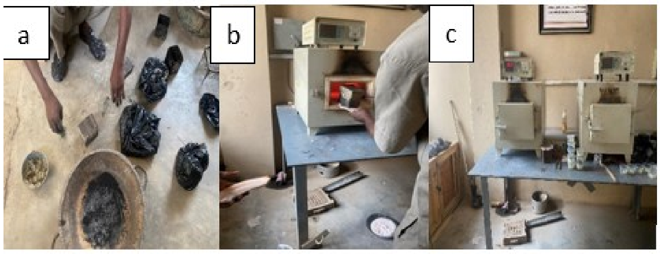


Figure 1. (a) Mixture of Sheanut shell ash and eggshell ash; (b) Charging of Carburized box into the furnace; (c) Induction furnace with Carburizing box.

2.2.4. Characterization

The chemical compositions of the carburized and un-carburized samples, as shown in Table 3, were analyzed using Scanning Electron Microscopy (SEM) equipped with energy dispersive spectroscopy (EDS), conducted with a JOEL JSM 5900LV machine and an Oxford INCATM detector. The phase structures of both the carburizing media and treated specimens were assessed via X-ray diffractometry (XRD) using a MiniFlex300 Rigaku instrument employing Cu Kα radiation within a diffraction angle range of 20–80 °. S. sequently, the microstructures of the specimens were examined using optical microscopy (Olympus BX51M microscope). The microstructures of the samples were further examined using a Metallurgical Microscope Nikon Eclipse LV150 with magnifications ranging from 50 to 1500x [30].

2.2.5. Mechanical Testing

Mechanical assessments were performed on three individual test samples and the mean values were computed for each evaluation. Standardized protocols were adhered to for conducting the mechanical tests, which encompassed the hardness, tensile, and impact energy assessments. The procedures for sample preparation and testing were conducted following previously documented methods [4]. Microhardness testing was performed using a Brinell hardness-testing machine (Model No. 8187-5-LKV Model (B) and Scal-HRF range of 0–60 kgf. Tensile testing was conducted using an electronic universal tensile testing machine (Model WDW-100KN, Jinan Kason Testing Equipment Co., Ltd., China), as shown in Figure 2. Impact energy assessments were carried out using a Chappy Impact testing machine with a 15-25 joules capacity of, Testometric, Model C-300), as shown in Figure 2c.

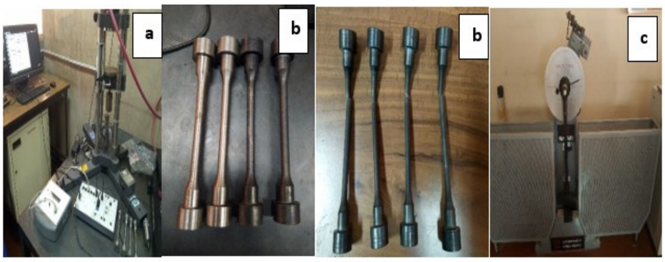


Figure 2. (a) Tensile Test Equipment; (b) Tensile Test Samples; (c) Impact Test Machine.

The hardness gradient, which is essentially the rate of change of hardness per unit distance [4], [1] for the carburized sample, was also determined using Equation 1 [10].

$$\text{Hardness gradient} = \frac{(H1-H2)}{D} \quad (1)$$

H1 and H2 are the two measured hardness values, and D is the distance between the measured points in mm.

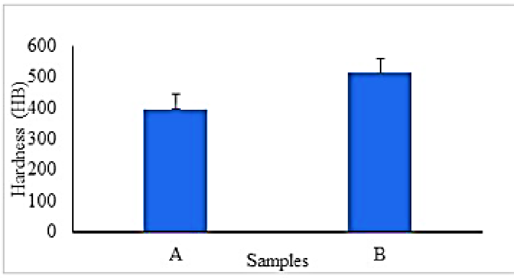
$$\text{Hardness gradient} = \frac{(515-513)}{0.01} = 200 \text{ HB/mm}$$

3. Results and Discussion

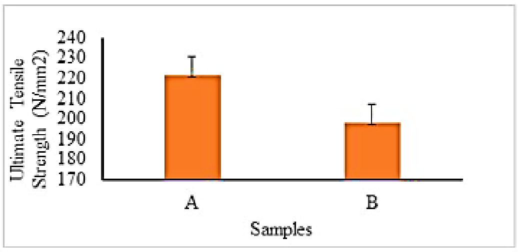
Figure 3 shows the average hardness values, where sample A is the UC and sample B is the carburized LCS across a cross-sectional area of 25 mm in diameter, from the surface to the core, along with the standard deviation. The hardness values were measured in HB (Brinell Hardness). The carburized sample exhibited a significantly higher hardness of 513 HB, and the hardness gradient was found to be 200 HB/mm when compared to the UCS sample, which registered a lower hardness of 398 HB. This hardness test outcome provides evidence that carburized low-carbon steel is inherently stronger than its UC counterpart. This improvement in hardness following carburization aligns with the findings reported by Ihom et al. [8] and Betan et al. [2], who attributed the enhanced hardness to carbon enrichment on the surface of the sample. Figure 3a shows the ductility of the UC material, which is evident from its elongation. LCS are known for their softness and ductility [31]. However, with increasing carbon content resulting from prolonged holding times during carburization, the ductility of the carburized material tends to decrease, as noted by Supriyono (2018) [10].

Figures 3 (b-c) show the ultimate tensile strength (UTS) and yield strength (YS) plots of the UC and carburized LCS samples. The plots reveal that the UC sample exhibited higher UTS and YS values, recording 221.3 N/mm^2 and 241.1 N/mm^{2,} respectively. Conversely, the carburized sample demonstrated lower UTS and YS values, measuring 158.1 N/mm^2 and 197.6 N/mm^{2,} respectively, as shown in Figures 3 b and c. These values are aligned with the standard values for some engineering tools and automobile parts. The tensile strength was reduced because of the reduced ductility and internal stress after carburization, which increased the surface hardness. While carburization enhances surface hardness, which improves wear resistance, it compromises tensile strength due to brittle surface layers, reduced ductility, and internal stresses. This indicates that the carburization of LCS does not lead to strength improvement [9], [32]. This finding aligns with the results reported by Supriyono [10] and Oluwafemi et al. [13], who attributed the increased strength of the control sample (un-carburized) to strain hardening during the forming process to achieve the final shape, which makes it suitable for engineering tools and automobile parts.

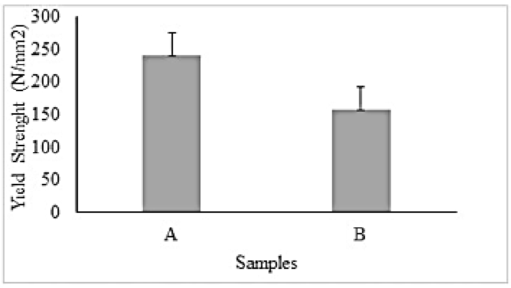
The impact test results, as shown in Figure 3d, indicate that breaking the carburized AISI 1020 steel requires a higher energy input (63.72 J) than breaking the un-carburized AISI 1020 steel, where a lower energy input (61.01 J) is required, as illustrated in Figure 4. This difference can be attributed to the increased hardness of AISI 1020 steel resulting from carburization, rendering the LCS tougher than its UC counterpart, thus requiring more energy to fracture, as confirmed by the results obtained by [33], [34].



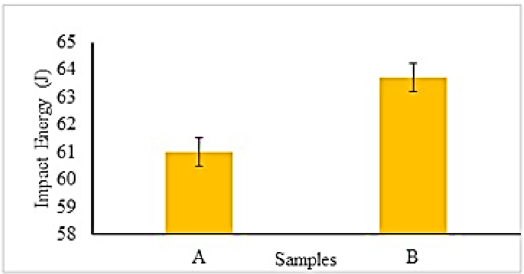
a. Hardness value (HB) of the Un-Carburized and Carburized Samples



b. Ultimate Tensile Strength (UTS) of the Un-Carburized and Carburized Samples



c. Yield Strength (YS) of the Un-Carburized and Carburized Samples



d. Impact Energy of the un-carburized and carburized samples

Figure 3. Average Values for Mechanical Characterization.

Figures 4 and Figure 5 depict the SEM-EDS images showing the morphologies of the UC and CS. The morphology of the carburized sample showed metallurgical enhancement, with carbide dispersion on the resulting surface. The carburization process facilitated the diffusion of carbon atoms into the substrate material, thereby enhancing the surface morphology, which is invariably shown in the results obtained from the hardness, tensile strength, yield strength, and impact energy tests of the samples [14]. EDS analysis, as shown in Tables 2 and Table 3, revealed the presence of various major elements, including Fe, Mg, O, Zn, and C. Iron (Fe) and oxygen (O) constituted the highest elemental contents on the surface. Furthermore, it was observed that the carbon (C) content in the carburized sample increased from 3% to 3.2% following the carburization process, which is consistent with the findings of Ramli et al. [15].

Figure 6 shows the X-ray diffraction (XRD) spectrum of the carburized AISI 1020 steel, which was prepared using a mixture of eggshell powder and SNSA at a ratio of 70:30 wt%, with a carburizing duration of 30 min. These parameters were determined based on preliminary optimization studies to achieve optimal carburization results. The XRD profile exhibited patterns, as shown in Figure 6. A notable peak diffraction variation was observed at various points, indicating the crystalline nature of organic carbon [16]. Examples of such notable peaks include Magnesium, Carbon, Iron, and Oxygen.

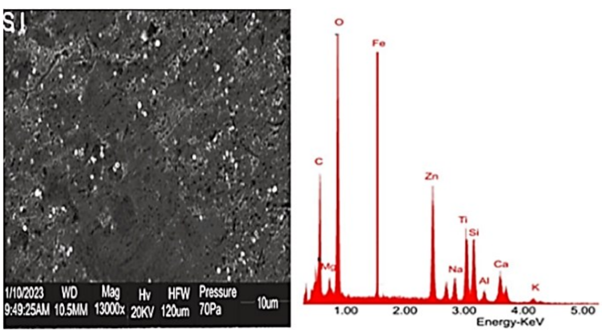


Figure 4. SEM-EDS Morphology of Un-carburized sample.

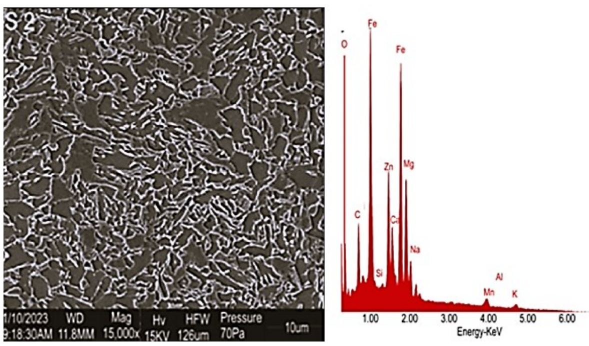


Figure 5. SEM-EDS Morphology of the Carburized sample.

Table 2. Percentage weight composition for Un-carburized Sample.

Elements	C	O	Fe	Ti	Na	Mg	Zn	Ca	Al	Si	K
Wt. (%)	3.00	20.2	54.0	3.24	1.40	2.50	7.00	2.00	1.02	3.22	0.12

Table 3. Percentage weight composition for the Carburized Sample.

Elements	C	O	Fe	Mn	Na	Mg	Zn	Ca	Al	Si	K
Wt. (%)	3.20	20.10	50.00	0.24	1.42	7.02	8.50	2.00	3.30	0.50	0.10

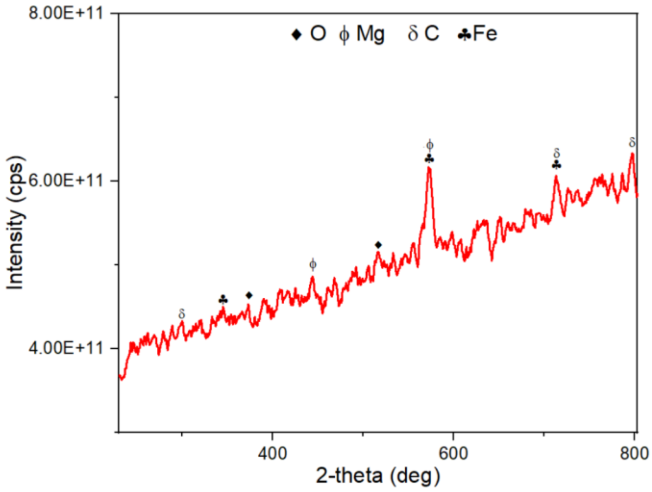


Figure 6. XRD Spectrum of Carburized Sample.

Figure 7 illustrates the microstructural transition from the surface to the core of low-carbon steel before and after carburizing and quenching. The case, showing a mix of dark and bright structures, consists of martensite, while the boundary between the case and the core features of both martensite and ferrite [16], [35].

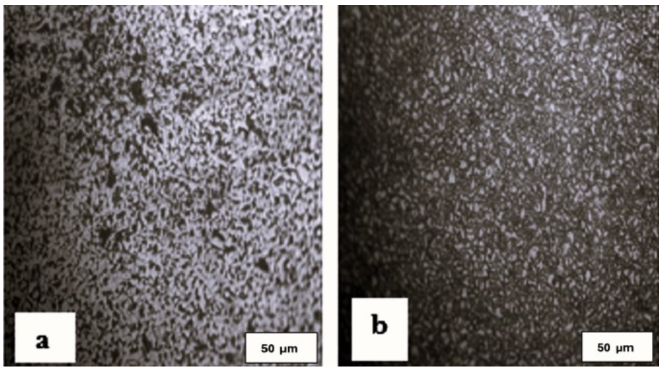


Figure 7. Microstructures of LCS Samples: (a) Un-carburized; (b) Carburized.

The observed case hardening depth varies, likely owing to temperature gradients, indicating a lack of uniformity in the carburized layer. This inconsistency is attributed to the formation of martensite in some regions and a mixture of pearlite and martensite in others. In contrast, the core microstructure remained relatively unchanged, retaining its original ferrite and pearlite composition with minimal variation, which agrees with the findings of Aramide et al. [18] and [23]

In addition, the figures present that the un-carburized low-carbon steel sample (Figure 7a) exhibits a distinct distribution of pearlite (light regions) and ferrite (dark regions). In contrast, the carburized low-carbon steel sample (Figure 7b) displays a core with a higher concentration of pearlite and ferrite than its un-carburized counterpart. Carburized low-carbon steel demonstrates a heightened concentration of pearlite, indicative of carbon diffusion into steel. Microstructural analysis revealed that carburized low-carbon steels experience lower mass loss than their un-carburized counterparts, which is attributed to increased pearlite formation in the surface layers. This finding corroborates the literature results [17], [18], which suggest that phase dispersion and grain refinement are more pronounced at the surface edges compared to regions closer to the core, characterized by a coarser grain structure [19], [20].

4. Conclusion

This study investigated the mechanical properties of SNSA and ES as organic carbon additives for carburizing LCS. This research focused on hardness distribution, tensile properties, impact energy, and microstructural analysis to understand the effects of carburization on LCS. The results showed a significant increase in hardness in the carburized LCS of 513 HB compared to un-carburized LCS with 398 HB, which was attributed to surface carbon enrichment. However, tensile testing revealed that carburization did not improve the strength of 221.3 N/mm^2 LCS, with un-carburized samples exhibiting a higher yield strength (YS) and ultimate tensile strength (UTS) of 241.1 N/mm^2.

Impact testing indicated that carburized LCS has an increased resistance to fracture, requiring more energy for failure, which suggests potential improvements in toughness and durability. SEM-EDS analysis showed metallurgical bonding and graphite layering on the carburized sample surface, indicating an improved morphology due to carbon diffusion. The increased carbon content after carburization, as confirmed by EDS analysis, aligns with the existing literature. XRD analysis revealed both the crystalline and amorphous characteristics of organic carbon, offering insights into the structural properties of carburized LCS. A higher concentration of pearlite in the carburized LCS was observed, suggesting enhanced carbon diffusion and reduced mass loss, leading to improved material integrity. The study concluded that the SNS and ES ash mixture effectively enhanced LCS, making it suitable for agricultural tools, automotive components, marine fasteners, and other applications requiring high strength within the range of 400HB- 500HB hardness value and UTS within the range of 200-280 N/mm^2 and exposure to saline conditions. Future research could explore the application of carburized LCS with organic carbon additives in various industries, optimize the obtained results, and employ more sophisticated analytical methods to gain deeper insights into the microstructural changes and phase transformations that occur during carburization.

Declaration of competing interests

The authors have no competing interests relevant to this article to declare.

Data Availability Statement

All data generated or analyzed during this study are included in this article.

Authors' contribution statement

MOA: Conceptualization, material preparation, data collection, and writing (draft, review, and editing); TJ: Supervision, Validation, writing, review, and editing; TAA and LWB: Data analysis, draft writing, review, and editing.

Acknowledgments

The authors acknowledge the contributions of Engr Abdullahi Mohammed of Federal Polytechnic Bida, Nigeria, and financial support from Tshwane University of Technology (TUT), Pretoria, South Africa, without which this work would not have been published.

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