

## Comparative Analysis of Carburizing Media on Surface Hardness, Mechanical, and Thermal Properties of ST 40 Steel

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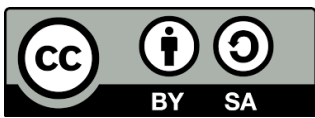
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### Keywords:

ST 40 steel; Pack carburizing; Carburizing media; Surface hardness; Tensile properties.

### ABSTRACT

Selecting an appropriate carburizing medium requires balancing surface hardness, mechanical strength, ductility, and thermal behavior. This study compared the mechanical and thermal properties of ST 40 steel carburized using coconut shells, durian peels, and bovine bones with those of untreated steel. The specimens were evaluated through tensile testing, Rockwell hardness testing, and thermal analysis. Coconut shells produced the highest tensile strength and surface hardness, increasing tensile strength from 312.47 to 378.62 MPa and hardness from 35.0 to 42.8 HRC, while reducing elongation from 11.83% to 8.64%. Bovine bones provided intermediate improvements in mechanical strength, whereas durian peels preserved the highest elongation among the carburized specimens. All specimens retained approximately 99.75–99.83% of their initial mass at 1000 °C. Thermal analysis revealed that the principal calorimetric peak shifted from approximately 805 °C in untreated steel to 794–798 °C following carburizing. These findings demonstrated that different carburizing media produced distinct mechanical and thermal responses, highlighting the importance of selecting a medium according to specific engineering requirements. Coconut shells were the most effective medium for improving tensile strength and surface hardness, although these improvements were accompanied by reduced ductility. Furthermore, high mass retention during thermal analysis did not independently establish the thermal stability or durability of the carburized surface during subsequent heating.



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## INTRODUCTION

Carburizing is a thermochemical surface treatment process used to increase the surface hardness of steel while preserving the mechanical properties of its core. Carbon enrichment and subsequent heat treatment produce differences in microstructure and mechanical properties between the surface layer and the core, influencing the material's overall response to applied loads (Adedipe et al., 2023; Ooi et al., 2023). Therefore, evaluating the effectiveness of carburizing requires examining not only surface hardness but also tensile strength and ductility to obtain a comprehensive understanding of the material's mechanical behavior (Mahmood, 2024; Ooi et al., 2023).

For ST 40 steel, the characteristics of the carbonaceous carburizing medium are important factors influencing surface hardening performance. Ngafwan et al. (2021) demonstrated that carburizing ST 40 steel using different carbon particle sizes produced variations in hardness, with smaller particles resulting in higher hardness values under the investigated conditions. These findings highlighted the importance of carburizing medium

characteristics and provided a basis for comparing coconut shell charcoal, durian peel, and bovine bone as carburizing media in terms of their effects on the mechanical properties and thermal behavior of ST 40 steel (Ojahan et al., 2021).

Previous studies have demonstrated the potential of biomass-derived and other waste-based materials as carburizing media, with treatment effectiveness depending on the medium composition and processing conditions (Adedipe et al., 2023; Afolalu et al., 2021; Kolawole et al., 2021; Pradana et al., 2025; Rafi et al., 2024; Robittah et al., 2025; Titok et al., 2025; Tuny et al., 2025). Edun et al. (2023) investigated the use of palm kernel shells, coconut shells, and wood powder for surface hardening medium-carbon steel under different carburizing temperatures and holding times. Similarly, coconut shell charcoal has been shown to act as an effective carbon source in the pack carburizing of low-carbon steel (Ojahan et al., 2021; Rahmadi et al., 2026). These findings emphasized the importance of considering the source, particle size, and processing conditions of carburizing media when evaluating surface hardening performance.

Although previous studies have established the influence of carburizing media on surface hardness, integrated comparisons of mechanical strength, retained ductility, and thermal behavior remain limited, particularly for ST 40 steel treated with coconut shell charcoal, durian peel, and bovine bone. Research on carburized steel has indicated that tensile behavior cannot be adequately explained by surface hardness alone because the mechanical response depends on the combined characteristics of the hardened surface layer and the underlying core (Ooi et al., 2023). Furthermore, Liu et al. (2021) demonstrated that thermal exposure could influence carbon distribution, surface hardness, and residual stress in carburized AISI 316L austenitic stainless steel. However, differences in chemical composition, microstructure, and carburizing mechanisms between stainless steel and low-carbon steel necessitate a separate evaluation of the thermal response of ST 40 steel.

The theoretical foundation of this study was based on carbon diffusion and the formation of microstructural and mechanical property gradients during carburizing and subsequent heat treatment. Ojahan et al. (2021) demonstrated that carbon supplied by coconut shell charcoal and bovine bone could increase the carbon content of low-carbon steel under appropriate processing conditions. Ooi et al. (2023) further indicated that the mechanical behavior of case-hardened steel was influenced by the mechanical contributions of both the carbon-enriched surface layer and the core. These findings supported the combined evaluation of tensile strength, elongation, and surface hardness to characterize the relationship between surface strengthening and the material's capacity for plastic deformation.

The novelty of this study lay in its integrated evaluation of the mechanical and thermal properties of ST 40 steel carburized using coconut shell charcoal, durian peel, and bovine bone, with untreated steel serving as the reference condition. The experimental approach combined tensile testing and Rockwell hardness measurements with thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and differential scanning calorimetry (DSC). This integrated approach was supported by Edun et al. (2023), who incorporated material characterization, hardness testing, and thermogravimetric analysis to evaluate carburized steel. Accordingly, the contribution of the present study was its comparative assessment of three carburizing media using complementary mechanical and thermal characterization methods.

The significance of this study was associated with the need to select carburizing media according to the mechanical and thermal performance requirements of engineering components. Improvements in surface hardness must be evaluated alongside other mechanical properties because surface hardening may be accompanied by changes in tensile behavior and ductility (Bontong et al., 2024; Edun et al., 2023; Kolawole et al., 2021). Thermal behavior also requires consideration because exposure to elevated temperatures can modify the characteristics of carburized surface layers under certain conditions (Liu et al., 2021). Consequently, mass retention during heating was evaluated as a separate thermal parameter rather than as direct evidence of retained surface hardness, mechanical strength, or microstructural stability.

Based on these considerations, this study aimed to compare the effects of coconut shell charcoal, durian peel, and bovine bone as carburizing media on the tensile strength, elongation, surface hardness, and thermal behavior of ST 40 steel relative to untreated specimens. The selected parameters reflected the importance of evaluating the combined mechanical responses of the hardened surface layer and core, as well as potential changes associated with thermal exposure (Liu et al., 2021; Ooi et al., 2023). The findings were expected to contribute to a better understanding of the relationships between carburizing medium selection and the mechanical and thermal properties of ST 40 steel. From a practical perspective, the study sought to provide a basis for selecting suitable carburizing media according to component requirements for surface hardness, mechanical strength, ductility, and thermal performance.

## METHOD

### Material preparation and carburizing

The experimental protocol comprised four conditions: untreated ST 40 steel and ST 40 steel carburized using coconut shell charcoal, durian peel, or bovine bone as the carburizing medium. The media were prepared following a procedure adapted from Kolawole et al. (2023), which involved washing, oven-drying at 110 °C for 8 h, grinding, and sieving to obtain particle sizes of 200 µm or smaller. Each medium was mixed with calcium carbonate (CaCO<sub>3</sub>) as a carburizing energizer at a medium-to-energizer mass ratio of 100:20, following Okoye et al. (2022). The steel specimens were embedded in the prepared mixtures inside sealed steel containers. The carburizing process involved heating at a rate of 5 °C/min to 950 °C, maintaining this temperature for 3 h, and subsequently quenching the specimens in SAE 40 oil. The specimens were then tempered at 300 °C for 1 h, followed by air cooling. The heat treatment parameters were adapted from Kolawole et al. (2023). The experimental conditions and carburizing medium formulations are summarized in Table 1.

**Table 1.** Sample Compositions

| Sample   | carburizing media   |
|----------|---------------------|
| Sample 1 | without carburizing |
| Sample 2 | coconut shell       |
| Sample 3 | durian skin         |
| Sample 4 | beef bones          |

### Mechanical testing

Tensile configuration uses a BISS UT-D4-0100 universal testing machine at room temperature and a crosshead speed of 2 mm min<sup>-1</sup>, adapted from a published steel-testing

protocol. Round specimens use a 6 mm gauge diameter and 30 mm initial gauge length, consistent with the metric ASTM E8M geometry. Ultimate tensile strength is calculated from maximum force divided by initial cross-sectional area; elongation is determined from the change in gauge length after fracture. Surface hardness is measured on clean, flat surfaces using a Rockwell tester, such as the FIE RAB-250-D, with a 120° diamond indenter, 10 kgf preliminary force and 150 kgf total force. A 5 s total-force dwell is selected within the standard Rockwell dwell range.

### Thermal analysis

Thermal configuration uses a NETZSCH STA 449 F3 with approximately 10 mg specimens in alumina crucibles. Heating proceeds from 50 to 1000 °C at 20 °C min<sup>-1</sup> under argon flowing at 50 mL min<sup>-1</sup>. These settings combine published steel-analysis procedures and instrument guidance. Temperature and heat-flow calibration use certified metal standards, with an empty-crucible baseline recorded under identical conditions. Mass is normalized to its initial value, DTG is calculated against temperature, and DSC heat flow is normalized by specimen mass.

## RESULTS AND DISCUSSION

### Effect of carburizing media on tensile behaviour and surface hardness

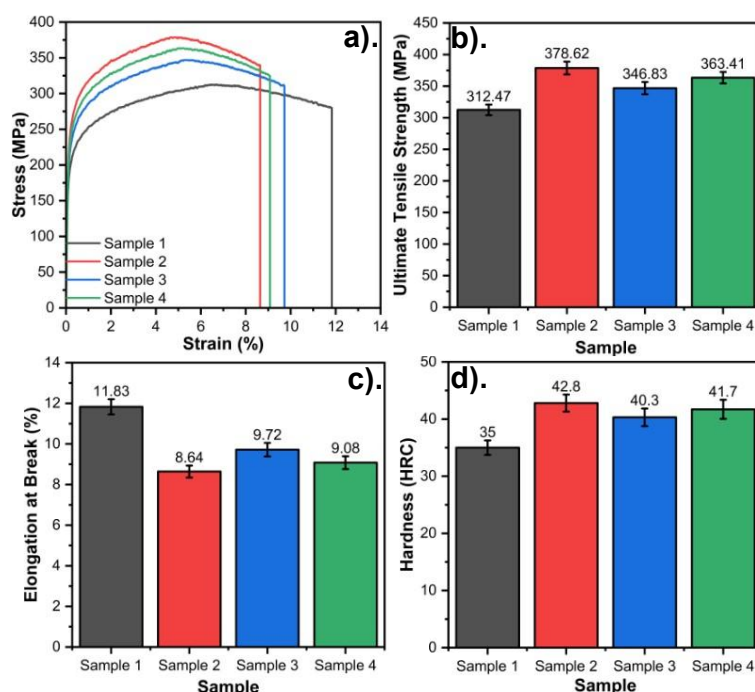


**Figure 1.** Tensile behaviour and surface hardness of ST 40 steel processed using different carburizing media. a, Tensile stress–strain curves. b, Ultimate tensile strength. c, Elongation at break. d, Rockwell C surface hardness

The carburized ST 40 steel specimens exhibited higher tensile strength but lower elongation than the non-carburized specimen (Fig. 1a–c). The ultimate tensile strength increased from 312.47 MPa for Sample 1 to 378.62, 346.83 and 363.41 MPa for the coconut-shell, durian-peel and bovine-bone conditions, respectively. These values correspond to increases of 21.2%, 11.0% and 16.3%. The consistent ordering of peak stresses identifies

coconut shell as the condition producing the greatest tensile strengthening within the investigated dataset, followed by bovine bone and durian peel.

The strength increase was accompanied by reduced tensile deformability. Elongation decreased from 11.83% in the non-carburized specimen to 8.64% with coconut shell, 9.72% with durian peel and 9.08% with bovine bone. The coconut-shell condition therefore combined the highest tensile strength with the largest elongation reduction, approximately 27.0% relative to Sample 1. Durian peel retained the highest elongation among the carburized specimens, whereas bovine bone provided an intermediate response. This inverse relationship establishes a strength–ductility trade-off; the measured elongation alone, however, does not identify the fracture mechanism or quantify impact toughness.

Surface hardness followed the same ranking as tensile strength (Fig. 1d). Relative to the baseline of 35.0 HRC, hardness increased to 42.8 HRC with coconut shell, 40.3 HRC with durian peel and 41.7 HRC with bovine bone, giving increments of 7.8, 5.3 and 6.7 HRC, respectively. The agreement between these rankings suggests that the conditions producing greater surface resistance to indentation also produced stronger tensile specimens. Nevertheless, surface hardness and tensile strength characterize different material responses. Ooi et al. (2023) demonstrated substantial variation in plastic behaviour with depth in carburized steel, illustrating why a single surface hardness measurement cannot establish case depth or describe the mechanical response throughout the specimen.

Differences in carbon-transfer conditions offer a plausible explanation for the observed media dependence. The use of coconut shell and other agricultural residues for steel case hardening has been investigated by Edun et al. (2023). Moreover, Ngafwan et al. (2021) reported that smaller carbon particles produced greater surface hardness in ST 40 steel, indicating that carburizing effectiveness also depends on the physical characteristics of the carbon source. Accordingly, the present ranking should be interpreted as the outcome of the tested processing conditions. Greater carbon enrichment or a larger fraction of hard transformation products could explain the coconut-shell response, but neither mechanism is established by these mechanical measurements. Carbon concentration profiles, cross-sectional hardness measurements and phase identification would clarify their respective contributions.

The results support selecting a carburizing medium according to the required combination of strength, hardness and deformation capacity. Coconut shell favours maximum strengthening and surface hardness, durian peel favours greater retained tensile ductility, and bovine bone provides an intermediate combination. This distinction is more informative for material selection than identifying one medium as universally superior.

### **Thermogravimetric and calorimetric response**

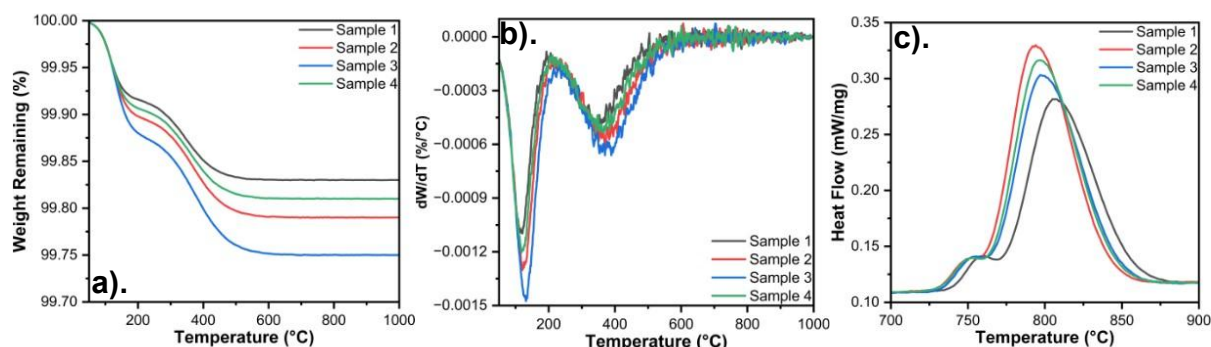


**Figure 2.** Thermogravimetric and calorimetric profiles of ST 40 steel processed using different carburizing media. a, TGA curves showing remaining mass during heating to 1000 °C. b, DTG curves expressed as  $dW/dT$ . c, DSC heat-flow profiles over 700–900 °C

The TGA profiles show small net mass changes across all ST 40 steel samples up to 1000 °C (Fig. 2a). The remaining mass is approximately 99.83% for non-carburized steel, 99.79% for coconut-shell carburization, 99.75% for durian-peel carburization and 99.81% for bovine-bone carburization. These values correspond to losses of approximately 0.17%, 0.21%, 0.25% and 0.19%, respectively. Durian peel therefore produces the largest mass decrease, whereas bovine bone gives the highest mass retention among the carburized conditions. Most of the decrease occurs below approximately 550–600 °C, followed by an almost constant mass at higher temperatures.

The DTG curves resolve this decrease into two temperature intervals: a sharp minimum around 110–140 °C and a broader minimum around 350–390 °C (Fig. 2b). Sample 3 exhibits the most negative derivative in both regions, consistent with its greater cumulative mass loss. Its first minimum approaches  $-0.0015\% \text{ } ^\circ\text{C}^{-1}$ , indicating the steepest mass decrease per degree of heating. The low-temperature event may involve desorption of minor surface species, while the broader event could include volatilization or reactions involving residual surface material. These assignments remain provisional because the atmosphere and evolved gases are unspecified. Zurek et al. (2023) demonstrated in S304HCu steel that oxide formation and carbon removal can compete during heating, illustrating why net mass change alone cannot identify the underlying reaction.

The DSC profiles reveal a principal calorimetric peak near 805 °C for the non-carburized sample, shifting to approximately 794–798 °C after carburization (Fig. 2c). Peak heat flow increases from approximately  $0.28 \text{ mW mg}^{-1}$  for Sample 1 to  $0.30\text{--}0.33 \text{ mW mg}^{-1}$  for the carburized samples, with coconut shell producing the highest response. A weaker shoulder is also visible near 750 °C. These features are compatible with solid-state transformation behaviour, potentially including overlapping magnetic and austenitization contributions. Sentsho et al. (2026) distinguished magnetic and structural transitions in ferritic steels using calorimetry, dilatometry and neutron diffraction, demonstrating the value of complementary measurements for assigning thermal events. Accordingly, the present peak positions should be treated as characteristic calorimetric temperatures rather than definitive transformation boundaries. Greater peak height also does not establish greater transformation enthalpy without baseline-corrected integration.

Combined with the mechanical results, coconut-shell carburization provides the highest tensile strength and surface hardness together with intermediate mass retention. Its mechanical advantage therefore addresses a different performance criterion from the smaller mass changes observed with bovine bone. Moreover, Liu et al. (2021) showed that thermal exposure can redistribute carbon and alter surface hardness in carburized 316L steel. The present profiles consequently characterize mass and calorimetric responses, while retention of the strengthened surface after thermal exposure remains a separate property to establish.

## CONCLUSION

This study demonstrated that the selection of carburizing media influenced the tensile strength, surface hardness, ductility, and thermal behavior of ST 40 steel. Coconut shell charcoal produced the highest tensile strength (378.62 MPa) and surface hardness (42.8 HRC), compared with 312.47 MPa and 35.0 HRC, respectively, for untreated steel. However, these improvements were accompanied by a reduction in elongation from 11.83% to 8.64%. Durian peel preserved the highest elongation among the carburized specimens, whereas bovine bone produced intermediate mechanical properties and the highest mass retention among the three carburizing treatments. All specimens retained approximately 99.75–99.83% of their initial mass at temperatures up to 1000 °C, while the principal calorimetric peak shifted from approximately 805 °C in untreated steel to 794–798 °C following carburizing. These findings provided an integrated basis for selecting carburizing media according to specific mechanical and thermal performance requirements. Coconut shell charcoal was the most suitable medium when increased tensile strength and surface hardness were prioritized, whereas durian peel offered advantages when greater ductility was required. Nevertheless, high mass retention during thermal analysis did not establish whether the mechanical properties or microstructural integrity of the carburized surface layer were preserved during heating. Further research should investigate carbon concentration profiles, cross-sectional hardness distributions, effective case depth, and phase composition. Additional mechanical testing following thermal exposure is also recommended to clarify the mechanisms of surface hardening and evaluate the thermal stability and mechanical durability of the carburized layer under service conditions.

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## CONFLICT OF INTEREST

The author states that there is no conflict of interest in the preparation of this article.

## AUTHOR CONTRIBUTIONS

All authors contributed to conceptualization, search and synthesis of literature, interpretation of results, manuscript preparation, and critical review of manuscripts. All authors have read and approved the final version of the manuscript.

## GENERATIVE AI STATEMENT

The authors declare that Generative Artificial Intelligence (Generative AI) was used solely to assist with language refinement, grammatical correction, and improvement of manuscript readability. All scientific concepts, interpretations, literature synthesis, analyses, and conclusions were developed by the authors. All AI-assisted content was carefully

reviewed, verified, and revised by the authors, who take full responsibility for the accuracy, integrity, and final content of the manuscript.

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