The object of this research is the pack carburizing of ST 37 low-carbon steel using activated carbon derived from catfish bone waste as a sustainable carburizing medium. ST 37 has low surface hardness, and it is not established how carburizing temperature and holding time govern the resulting hardness and microstructure when a fish-bone-derived carbon is used. Specimens were carburized at 800°C and 875°C for 45, 90, and 115 minutes, followed by water quenching; surface hardness was measured on the Rockwell B scale and the case region was examined by optical microscopy. At 800°C the surface hardness increased from 53.33 to 87.00 HRB as the holding time rose from 45 to 115 minutes, with the case microstructure progressing from ferrite with coarse pearlite to fine pearlite and then to a finer ferrite-carbide constituent. At 875°C the hardness reached 98.33 HRB at every holding time, with the case transforming to a fine, dark-etching ferrite-carbide constituent; this value lies at the upper limit of the Rockwell B scale, so it represents the maximum measurable, not the true, case hardness, and temperature exerted a stronger influence than time. No fully martensitic case formed, which is consistent with the low hardenability of ST 37 and is favorable because hardness is raised without a brittle case. Unlike conventional carburizing that relies on commercial charcoal, the present medium uses fish-bone waste and reaches maximum hardness at 875°C in 45 minutes. These findings apply to small-scale surface hardening of low-carbon steel where fish-bone waste is locally available and a tough, wear-resistant surface is required. The results confirm that catfish bone waste can serve as a low-cost, sustainable carburizing medium for low-carbon steel

Keywords: pack carburizing, ST37, catfish bone, full factorial design, thermochemical treatment, sustainable

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IMPROVING THE SURFACE HARDNESS OF ST 37 LOW-CARBON STEEL BY PACK CARBURIZING WITH CATFISH BONE-DERIVED ACTIVATED CARBON: EFFECT OF TEMPERATURE AND HOLDING TIME

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1. Introduction

Low-carbon steel such as ST 37 is widely used in engineering applications owing to its good ductility, formability, and low cost. However, its relatively low surface hardness limits its use in components subjected to wear, friction, and surface fatigue, such as gears, shafts, and sprockets [1, 2]. Surface-hardening techniques are therefore commonly employed to improve wear resistance while preserving core toughness.

Carburizing is one of the most effective surface-hardening methods for low-carbon steels. Through carbon diffusion at elevated temperatures it raises the surface carbon content and enables harder microstructures to form

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after quenching [3, 4]. Carbon diffusion is the spontaneous movement of atoms within a material toward a uniform composition; according to Fick's first law, the diffusion flux depends on the diffusion coefficient and the concentration gradient, and the rate of carbon diffusion is governed mainly by temperature, composition, and time [5]. Among the available techniques, pack carburizing remains attractive because of its simplicity, low cost, and suitability for small-scale industries [1].

Recent research has focused on environmentally friendly and low-cost carbon sources derived from agricultural or biological waste, such as coconut shell, cow bone, and other agro-wastes [5–7]. Catfish bone waste is abundant in the food-processing industry and contains substantial carbon and calcium compounds, which makes it a potential alternative carburizing medium after activation [8, 9]. Nevertheless, catfish bone-derived activated carbon has not been characterized for pack carburizing of ST 37 steel, and the combined influence of carburizing temperature and holding time on the resulting hardness and microstructure has not been established.

Therefore, research devoted to the development of a sustainable pack-carburizing process for ST 37 low-carbon steel using activated carbon derived from catfish bone waste is relevant, because it can replace commercial charcoal with a low-cost biological residue while still raising the surface hardness of the steel.

2. Literature review and problem statement

The paper [1] presents the results of research on pack carburizing of ST 37 low-carbon steel. Shown, that embedding the steel in a solid carbon medium raises the surface carbon content and the hardness after quenching, and that pack carburizing remains the simplest and lowest-cost route for low-carbon steel [3]. But there were unresolved issues related to the carbon source, since conventional pack carburizing relies on commercial charcoal, which adds cost and is not always locally available.

Although [1] reported the surface hardness, it was not linked to the evolving case microstructure, leaving the phase transformations responsible for the hardening unexplained – a gap the present study sets out to close.

The paper [5] presents the results of research on AISI 1020 steel pack-carburized with coconut-shell charcoal. Shown, that carburizing temperature and holding time strongly affect the resulting surface hardness and microstructure. This approach was used in [7] for ASTM A36 steel with coconut shell and goat bone and in [6] with natural shell powders, while in [2] buffalo bone charcoal improved the wear and fatigue behavior of low-carbon steel [10]. A way to reduce the dependence on commercial charcoal can be the use of shell- and bone-derived carbon together with a carbonate energizer [6, 7, 11–13]. Each of these sources, however, has a specific constraint: [6] used natural shell powders on SCM 420 alloy steel rather than plain low-carbon steel. The source [7] combined coconut shell with goat bone but did not isolate the contribution of the bone-derived apatite. The source [11] focused on the electrochemical response of the carburized layer rather than its case hardness. In the source [12] varied only the carbonate energizer while keeping the carbon source fixed. The source [13] relied on Pomacea shell powder, which carbonate chemistry differs from that of fish bone. None of them evaluated catfish bone-derived carbon as the primary carbon source for ST 37 steel. However, these studies used coconut shell, cattle or buffalo bone, shell powders, or other agro-wastes, and none has characterized catfish bone activated carbon for ST 37 steel.

However, [5] relied on a coconut-shell energizer and never benchmarked it against a bone-derived, apatite-rich carbon, so the carbon-supplying capacity of biological-apatite sources for low-carbon steel remained untested.

The carburizing literature also shows that carburizing temperature and holding time are the parameters that most strongly affect case formation and hardness [5, 14–16].

These studies differ in scope. The source [14] confirmed the dominant role of temperature for SCM 420 steel but used a shell-powder energizer. The source [15] observed the same trend in AISI 1020 with corn-cob carbon without quantifying how much each factor contributed. In the source [16] extended the holding time only to find the hardness saturating, much like the 875°C plateau seen here. None of them used a full factorial design to rank the two parameters quantitatively.

The phases that form on cooling, namely pearlite, bainite, or martensite, depend on the surface carbon level, the cooling rate, and the hardenability of the steel [17, 18]. For plain low-carbon grades such as ST 37, the limited hardenability tends to favor pearlitic and bainitic transformation over martensite. Catfish bone carbon has probably been overlooked because earlier work concentrated on the more abundant coconut shell and cattle bone. What remains untested is whether catfish bone activated carbon can effectively harden ST 37, and how carburizing temperature and holding time govern its hardness and microstructure.

Beyond the choice of steel and process route, the carbon source itself has become a focus of recent work. Activated carbons derived from biological waste retain substantial fixed carbon and, once chemically activated, develop additional porosity that raises their carbon-donating activity during carburizing. Fish-processing residues are a particularly attractive precursor: catfish (Pangasius sp.) bone has been converted into activated carbon-hydroxyapatite composites by H_3PO_4 activation, confirming that the bone matrix supplies both carbon and a calcium-bearing phase [8]. Chemically activated fish bone, whether raw or calcined, likewise develops a reactive, high-surface-area structure [9]. These results indicate that catfish bone, after K_2CO_3 activation, can in principle serve as a carbon donor for solid-state carburizing; its use as a pack-carburizing medium for structural steel, however, has not yet been reported.

It is worth noting, though, that [8, 9] studied fish-bone-derived carbon mainly as an adsorbent rather than as a carburizing energizer; its ability to harden a steel case had therefore never been demonstrated before this study.

The carburizing parameters and the energizer also govern the outcome. In pack carburizing of AISI 1020 steel, the carburizing temperature controls the carbon diffusion coefficient and, in turn, the surface hardness and case development [15], consistent with the temperature-dominated behavior reported for coconut-shell and bone media [5]. A carbonate energizer is normally added to sustain the CO-CO_2 atmosphere that transfers carbon to the surface; $CaCO_3$ and shell-derived carbonates have been shown to raise the carbon potential and the resulting hardness of mild steel [11, 12].

All this suggests that it is advisable to conduct a study devoted to the effect of carburizing temperature and holding time on the surface hardness and microstructure of ST 37 steel using catfish bone-derived activated carbon as a sustainable carburizing medium.

3. The aim and objectives of the study

The aim of the study is to determine the effect of carburizing temperature and holding time on the surface hardness and microstructure of ST 37 low-carbon steel using catfish bone-derived activated carbon as a sustainable carburizing medium. This will allow a low-cost surface-hardening route for low-carbon steel based on a locally available fish-processing waste.

To achieve this aim, the following objectives were accomplished:

– to evaluate the surface hardness of ST 37 steel pack-carburized at 800°C and 875°C for holding times of 45, 90, and 115 minutes;

– to identify the microstructural phases formed in the case region under each condition and to relate them to the measured hardness;

– to rank the relative influence of carburizing temperature and holding time on the surface hardness by a full factorial factor-effect analysis, and on that basis to establish the most efficient carburizing schedule for the catfish bone medium.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of this research is the pack carburizing of ST 37 low-carbon steel using activated carbon derived from catfish bone waste as a sustainable carburizing medium. The hypothesis is that activated carbon derived from catfish bone waste can raise the surface hardness of ST 37, to a degree governed mainly by carburizing temperature and, to a lesser extent, by holding time.

Assumptions:

a) the five hardness readings per specimen represent the carburized surface;

b) the case thickness measured optically on a polished cross-section indicates the extent of carbon enrichment.

Simplification: all specimens were water-quenched directly from the carburizing temperature without an intermediate reheat.

4. 2. Materials

The material used in this study was commercial low-carbon steel ST 37 with an approximate composition of 0.17 wt.% C, 0.5 wt.% Mn, and balance Fe. Specimens were machined into cylindrical samples 20 mm in diameter and 10 mm in thickness, as shown in Fig. 1. Prior to carburizing, the samples were ground and cleaned with acetone to remove surface contaminants such as dirt, oil, rust, and scale, which would otherwise hinder uniform carbon absorption into the ST 37 surface. The carburizing medium was activated carbon prepared from catfish bone waste, mixed with 10 wt.% $CaCO_3$ as an energizer.

This cylindrical geometry offers a flat end face for stable Rockwell-B indentation and a representative diametral section for case measurement, so that the reported hardness and case-depth values reflect only the carburized surface layer.

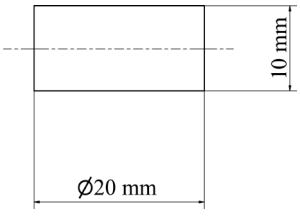


Fig. 1. Geometry of the cylindrical ST 37 specimen used for pack carburizing

4. 3. Methods

4. 3. 1. Preparation of catfish bone activated carbon

Catfish bones were cleaned, dried, and carbonized at 500°C for 2 hours. The carbonized bones were crushed and sieved to a fine powder. Chemical activation was performed using a potassium carbonate (K_2CO_3) solution, followed by drying and heat treatment at 800°C to enhance porosity and carbon activity. Potassium carbonate is a water-soluble inorganic salt that is alkaline and hygroscopic, which promotes pore development in the bone-derived char during activation. After activation, the carbon was repeatedly washed with hot distilled water until the filtrate reached a neutral pH (about 7) to remove residual potassium salts, and was then dried at 110°C before use.

4. 3. 2. Pack carburizing procedure

Pack carburizing was conducted by embedding the steel specimens in a sealed steel box filled with the activated catfish bone carbon and the $CaCO_3$ energizer. The process was carried out at two temperatures, 800°C and 875°C, each with holding times of 45, 90, and 115 minutes. After carburizing, all specimens were immediately quenched in water at room temperature. The carburizing was carried out in a Nabertherm electric muffle furnace (Nabertherm GmbH, Germany) at the Laboratory of the Department of Mechanical Engineering, Universitas Merdeka Malang (Indonesia), with PID thermocouple temperature control (maximum operating temperature about 1100°C and control accuracy about ±5°C).

4. 3. 3. Hardness testing

Surface hardness was measured on the Rockwell B (HRB) scale using a 1.588 mm (1/16 in) hardened steel ball indenter, with a minor load of 10 kgf and a major load of 100 kgf, in accordance with ASTM E18. Each specimen was tested at five locations on the carburized surface, and the average value was reported. The test was performed on an HR-150A bench-type Rockwell hardness tester. The Rockwell B scale was chosen because the as-carburized ST 37 surface remained within its measurable range; however, in accordance with ASTM E18 the HRB scale approaches its upper limit for hard cases, so readings near this limit (about 100 HRB) are reported here as screening-level indicators of the maximum measurable hardness rather than as absolute case hardness. For a fully hardened case the Rockwell C (HRC) or Vickers (HV) scale is more appropriate and is recommended for future work.

4. 3. 4. Microstructure observation and case measurement

Metallographic specimens were prepared by standard grinding and polishing, followed by etching with 2% nital.

Cross-sections were examined with an optical microscope at 200× magnification to identify the phases and to measure the carburized case. For each condition, the case thickness was determined from three measurements (DL1–DL3) across the case and is reported as the mean with its standard deviation. The optical microscope used was a Nikon optical microscope (model 59520). Each micrograph carries a 50 μm scale bar derived from the calibrated length measurements recorded by the microscope software on the same field. Cross-sectional microhardness (depth-profile) measurements were not carried out; the case is therefore characterized from surface hardness and optical case-boundary measurements only, which is acknowledged as a limitation in Section 6.

4. 3. 5. Full factorial design and factor-effect analysis

The two factors, carburizing temperature (two levels: 800 and 875°C) and holding time (three levels: 45, 90, and 115 min), were arranged as a full 2 × 3 factorial design, so that all six factor combinations were tested once. The carbonate energizer content was held at 10 wt.% in every run, so that only temperature and holding time varied and the carburizing ability of the catfish bone carbon itself could be isolated. Because a full factorial evaluates every combination directly, the factor effects were ranked from the mean surface-hardness response (the delta between factor-level means), and an analysis of variance (ANOVA) was used only to give an indicative decomposition of the observed variation. As each combination was run without replication ($n = 1$) and the hardness at 875°C saturated the Rockwell B scale, the ANOVA is treated as descriptive rather than as a formal test of significance: it provides no pure-error term, so its residual reflects the temperature × time interaction together with the scale-saturation artefact. The signal-to-noise (S/N) transform used in an earlier draft was removed, because it is redundant for a fully evaluated factorial design and adds no information beyond the mean response.

5. Results of the pack carburizing experiments

5. 1. Surface hardness and case characteristics

The case thickness, microstructure, and surface hardness for all conditions are summarized in Table 1, and the dependence of surface hardness on holding time is shown in Fig. 2.

At 800°C the surface hardness rose from 53.33 HRB at 45 min to 77.67 HRB at 90 min and 87.00 HRB at 115 min. At 875°C it reached 98.33 HRB at all three holding times. The case thickness did not vary monotonically with holding time, and the within-condition scatter was large at 875°C (up to ± 11.4 μm).

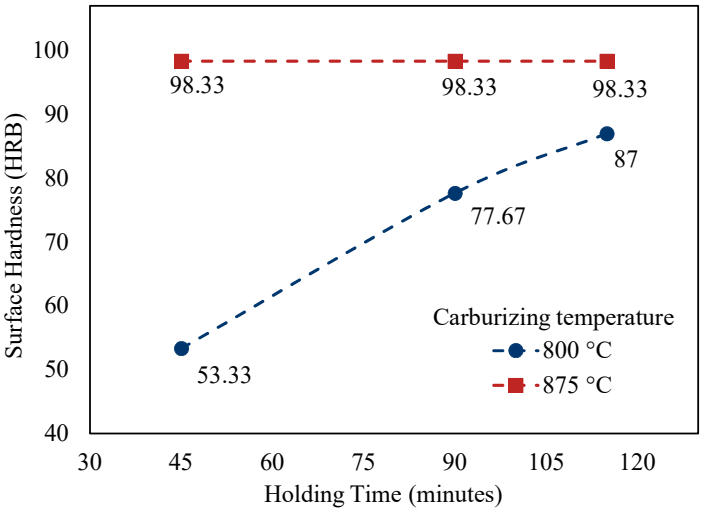


Fig. 2. Surface hardness of ST 37 steel as a function of holding time at 800°C and 875°C. The dashed lines join the experimental points and serve only as a visual guide; they are not an approximating function

5. 2. Microstructure

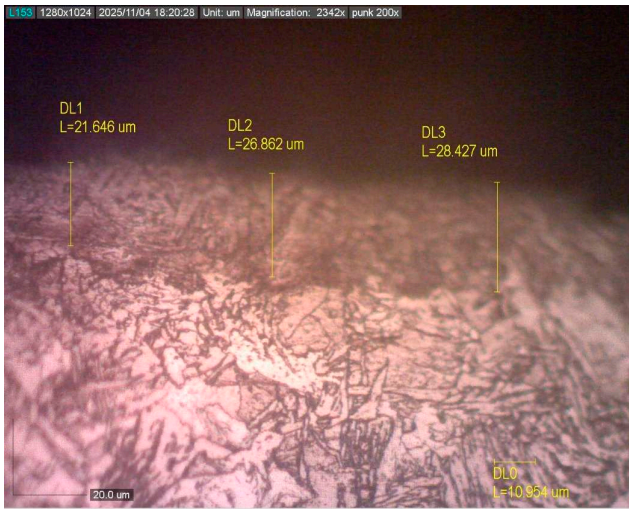
Representative cross-sectional micrographs of the carburized case are shown in Fig. 3 (800°C) and Fig. 4 (875°C). At 800°C the case microstructure evolved with holding time from ferrite with coarse pearlite (45 min) to ferrite with fine pearlite (90 min) and, at 115 min, to a darker, finer ferrite-carbide constituent. At 875°C the case consisted of ferrite with a fine, dark-etching ferrite-carbide constituent at all three holding times. Because these constituents were identified only by optical microscopy at 200×, they could not be assigned unambiguously as bainite, very fine pearlite, or auto-tempered low-carbon martensite; scanning electron microscopy or EBSD would be required for a definitive phase identification. Given the low hardenability of ST 37 and the measured hardness, any martensite formed on water quenching was limited in amount and largely auto-tempered, so a fully martensitic case did not develop.

Comparing Fig. 3 with Fig. 4 shows that raising the carburizing temperature from 800 to 875°C refines the case constituent from a ferrite-pearlite mixture to a finer, darker ferrite-carbide structure. This shift accompanies the higher surface hardness listed in Table 1 and is examined in more detail in the discussion that follows.

Table 1

Case thickness, microstructure, and surface hardness of pack-carburized ST 37 steel

Carburizing temperature	Holding time (min)	Case thickness (μm), mean ± SD	Microstructure	Surface hardness (HRB)
800°C	45	25.6 ± 3.5	Ferrite + coarse pearlite	53.33
800°C	90	47.7 ± 4.4	Ferrite + fine pearlite	77.67
800°C	115	36.8 ± 2.5	Ferrite + dark ferrite-carbide constituent	87.00
875°C	45	40.0 ± 11.4	Ferrite + fine ferrite-carbide constituent	98.33
875°C	90	32.5 ± 3.2	Ferrite + fine ferrite-carbide constituent	98.33
875°C	115	22.3 ± 8.4	Ferrite + fine ferrite-carbide constituent	98.33



a



b



c

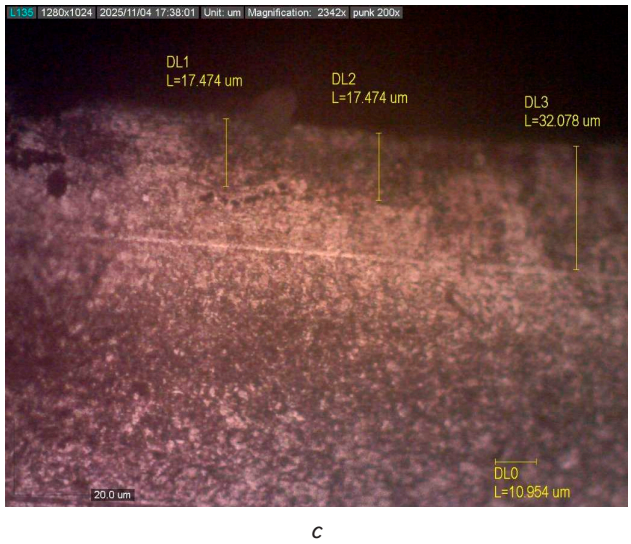
Fig. 3. Cross-sectional microstructure of ST 37 carburized at 800°C (200×, 2% nital):
a – 45 min; *b* – 90 min;
c – 115 min; water quenched; scale bar 50 μm



a



b



c

Fig. 4. Cross-sectional microstructure of ST 37 carburized at 875°C (200×, 2% nital):
a – 45 min; *b* – 90 min;
c – 115 min; water quenched; scale bar 50 μm

5. 3. Factor-effect analysis of surface hardness

The mean surface-hardness response for each factor level is summarized in Table 2, and the corresponding factor main-effect plots are shown in Fig. 5 (temperature) and Fig. 6 (holding time). The mean hardness rises with both temperature and holding time, and the temperature levels are more widely separated than the holding-time levels, indicating a stronger temperature effect.

Table 2

Response table of the mean surface hardness for ST 37 steel

Factor	Level	Mean surface hardness (HRB)
Carburizing temperature	800°C	72.67
Carburizing temperature	875°C	98.33
Holding time	45 min	75.83
Holding time	90 min	88.00
Holding time	115 min	92.67

The delta (maximum − minimum) of the mean hardness is 25.66 HRB for temperature and 16.84 HRB for holding time, so temperature ranks first and holding time second. The analysis of variance in Table 3 gives an indicative decomposition that attributes about 62% of the observed variation to temperature and about 19% to holding time, with the remaining 19% associated with the residual and the temperature×time interaction; because each condition was run once ($n = 1$), these percentages are descriptive rather than a formal test of significance.

Table 3

Analysis of variance for surface hardness

Source	DOF	Sum of squares	Contribution (%)
Carburizing temperature	1	987.66	62.0
Holding time	2	302.34	19.0
Residual	2	302.30	19.0
Total	5	1592.30	100

Because the surface hardness at 875°C is identical (98.33 HRB) at all three holding times, the variance of that temperature level is artificially zero owing to saturation of the Rockwell B scale. The residual term in Table 3 therefore partly reflects this scale ceiling rather than pure experimental error, and the ANOVA percentages should be read as indicative rather than exact.

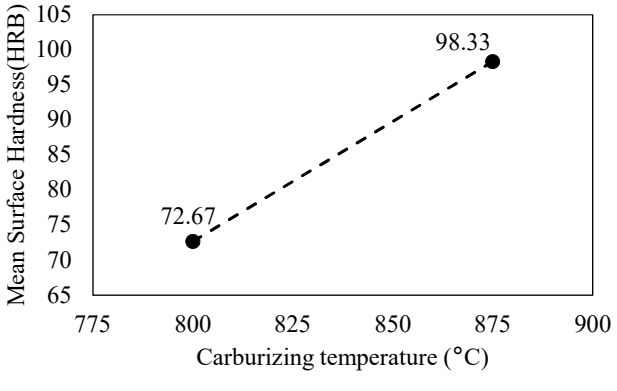


Fig. 5. Main-effect plot of the mean surface hardness as a function of carburizing temperature. The dashed line joins the two-level means and is a visual guide only

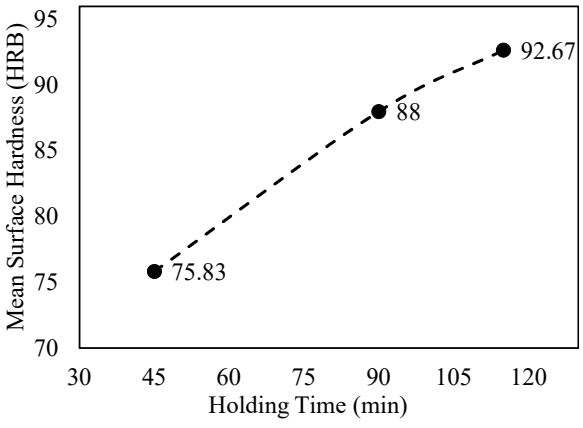


Fig. 6. Main-effect plot of the mean surface hardness as a function of holding time. The dashed line joins the three-level means and is a visual guide only

The mean hardness rises far more steeply with carburizing temperature than with holding time, which echoes the ANOVA result (Table 3): temperature is the dominant factor, accounting for about three times as much of the hardness variation as holding time.

6. Discussion of the carburizing results

Surface hardness tracks the case microstructure. At 800°C the increase from 53.33 to 87.00 HRB accompanies the progression from ferrite with coarse pearlite to fine pearlite and then to a finer, darker ferrite-carbide constituent (Fig. 3, Table 1). Pearlite refinement reflects greater surface carbon enrichment and more uniform carbon transfer with longer holding time, while the darker constituent at 115 min indicates that the enriched surface transformed during water quenching into a harder, fine ferrite-carbide structure [5, 6]. This monotonic hardness trend at 800°C is the most reliable quantitative result of the study (Fig. 2).

At 875°C the three holding times returned an identical value of 98.33 HRB, and the case transformed to a fine, dark-etching ferrite-carbide constituent (Table 1, Fig. 4). This value lies close to the practical ceiling of the Rockwell B scale, so the identical readings indicate saturation of the scale rather than exactly equal surface hardness. For surfaces approaching this range, the Rockwell C scale or a Vickers microhardness traverse resolves differences more reliably and is recommended for future work [17]. The result nonetheless shows that the maximum measurable hardness was reached even at the shortest holding time, so temperature exerts a stronger influence than holding time [5, 14].

The absence of a fully martensitic case under all conditions is consistent with the low hardenability of plain low-carbon ST 37 steel. On water quenching, its limited hardenability together with the measured hardness indicates that any martensite formed was small in fraction and largely auto-tempered, so the case is dominated by fine ferrite-carbide constituents rather than by fresh martensite (Fig. 3, 4) [17–19]. This is advantageous rather than a shortcoming, because it raises surface hardness above the as-received condition while avoiding the brittleness of a fully martensitic case, which suits components requiring improved wear resistance without loss of toughness [2, 17, 20, 21].

The case thickness did not increase monotonically with holding time; at 875°C the measured value fell from 40.0 μm at 45 min to 22.3 μm at 115 min (Table 1). Each value is the mean of three-point measurements on a single etched cross-section, and the standard deviations are large, reaching ± 11.4 μm at 875°C and 45 min. These values therefore carry appreciable measurement uncertainty and should be treated as indicative rather than as a quantitative measure of carbon-penetration kinetics. At 875°C the almost complete transformation of the case to a fine ferrite-carbide constituent also lowered the etch contrast between case and core, making the boundary harder to delineate. Carbon penetration is therefore discussed only descriptively, and the surface hardness is used as the primary indicator of carburizing effectiveness.

The hardness levels obtained here are consistent with those reported for low-carbon steels carburized in biomass-derived media. Studies using coconut-shell charcoal and animal-bone powders report surface hardness rising with temperature and holding time as the case is enriched and refined [2, 5, 7], and pack carburizing of AISI 1020 shows the carbon diffusion coefficient, and hence the hardness, increasing strongly with temperature [15]. The progression observed at 800°C, from ferrite with coarse pearlite to fine pearlite and finally a finer ferrite-carbide constituent, follows the same enrichment-driven sequence and indicates that catfish bone carbon supplies a carbon flux comparable to that of established media.

Mechanistically, the stronger effect of temperature than of time follows from Fick's first law: raising the temperature from 800 to 875°C increases the diffusion coefficient exponentially, whereas a longer holding time extends the diffusion distance only in proportion to the square root of time. At 875°C the surface carbon therefore reaches the level needed to saturate the Rockwell B scale within the shortest holding time, and further time yields no measurable gain. The $CaCO_3$ energizer sustains this carbon transfer by maintaining a CO-rich atmosphere around the specimens [11, 12], so that the activated catfish bone carbon, despite originating from waste, delivers a carbon potential sufficient for full case transformation.

From a materials-economy standpoint, replacing commercial charcoal with activated catfish bone carbon valorizes a fish-processing residue that would otherwise be discarded, in line with the broader effort to convert biological waste into functional carbons [8, 9]. Combined with the modest 875°C / 45 min schedule, this makes the route attractive for small-scale surface hardening where energy and material costs are constrained.

The factor-effect analysis reinforces the ranking obtained from the raw data: temperature contributes about three times as much as holding time to the variation in surface hardness (Table 2, 3), in agreement with the diffusion-controlled nature of carburizing, in which temperature raises the carbon diffusion coefficient exponentially [15]. The two main-effect plots differ in shape as well as in size. The temperature effect is a single large step (Fig. 5), whereas the holding-time effect decelerates, the mean hardness gaining 12.17 HRB between 45 and 90 min but only 4.67 HRB between 90 and 115 min (Fig. 6). That deceleration is what a diffusion distance growing with the square root of time would produce. The optimum combination indicated by the mean response, namely 875°C with the longest holding time, lies within the saturated hardness region; in practice the same maximum is already reached at 875°C and 45 min, so the shortest holding time at the higher temperature is the most efficient setting.

This temperature-dominated contribution is consistent with reports on pack carburizing of other low-carbon steels. For AISI 1020 carburized with corn cob charcoal, the carbon diffusion coefficient, and hence the case hardness, was governed primarily by temperature [15], and the temperature-and-time study reported for the same grade likewise identified temperature as the stronger factor [5]. The present factor-effect ranking therefore agrees with the established kinetics of solid-state carburizing and confirms that the catfish bone medium follows the same diffusion-controlled behavior as conventional carbon sources [8, 16].

Taken together, the findings confirm that catfish bone-derived activated carbon provides sufficient carbon activity for effective pack carburizing of ST 37 steel. The practical significance of the results can be stated explicitly. Scope of application: the route suits small-scale, low-cost surface hardening of plain low-carbon steel components such as shafts, pins, and sprockets, using a fish-processing waste as the carbon source. Conditions of application: it applies where the required surface performance is moderate wear resistance with retained core toughness rather than a fully hardened martensitic case, and where the 800–875°C range is adopted deliberately as an energy-saving, low-distortion regime; for a higher case hardness a higher carburizing temperature, typically 900–950°C, would be required and is identified as future work. Expected effects: replacing commercial charcoal with activated catfish bone carbon is expected to lower material cost and valorise a waste stream while still raising the surface hardness of ST 37, and because carburizing at 875°C for 45 min already attains the maximum measurable hardness, extending the holding time gives no additional hardness benefit and only increases energy use.

This study has several limitations. The case thickness was estimated optically from three points on a single section, the HRB scale saturated at 875°C, and no microhardness depth profile or carbon-content measurement was obtained, so the extent of carbon enrichment is inferred indirectly. The study also did not measure wear resistance or core toughness, and a single specimen was used per condition.

Distinct from these limitations is a methodological disadvantage of the design itself: a single replicate per condition ($n = 1$). With no repeats, the measurement scatter cannot be estimated statistically, and the apparent residual term in the ANOVA is inflated. Future work can remove this disadvantage by running at least three replicates per factor combination and by switching to the Vickers scale, which avoids the HRB saturation observed at 875°C.

Future work should add a Vickers microhardness depth profile to quantify the effective case depth and to resolve hardness differences beyond the HRB ceiling, replicate each condition to provide error bars, and measure wear resistance to confirm the practical benefit of the fish-bone carburizing medium.

7. Conclusions

1. Carburizing temperature and holding time both influence the surface hardness of ST 37 steel pack-carburized with catfish bone activated carbon, but temperature exerts the stronger effect. At 800°C the hardness increased from 53.33 to 87.00 HRB between 45 and 115 minutes, whereas at 875°C

the maximum measurable value of 98.33 HRB was reached at every holding time.

2. The hardness response is governed by the case microstructure. At 800°C the structure progressed from ferrite with coarse pearlite to fine pearlite and then to a finer ferrite-carbide constituent, while at 875°C it consisted of a fine, dark-etching ferrite-carbide constituent. No fully martensitic case formed under any condition, which is attributed to the low hardenability of ST 37 and allows surface hardening without a brittle case; a definitive phase assignment would require SEM or EBSD.

3. The factor-effect analysis ranks carburizing temperature ahead of holding time. The delta of the mean surface hardness is 25.66 HRB for temperature and 16.84 HRB for holding time, and the analysis of variance attributes about 62% of the observed variation to temperature against about 19% to time. Since the maximum measurable hardness is already reached at 875°C after 45 minutes, that combination is the most efficient schedule for pack carburizing ST 37 in the catfish bone medium, and a longer hold adds energy cost without adding hardness.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data supporting the findings of this study are available within the manuscript.

Use of artificial intelligence

The following artificial intelligence tool was used during the preparation of this manuscript:

Model: Gemini 3.5.

Where used: manuscript structuring, language editing

Specific task performed by AI: reorganizing the manuscript into the journal format, editing English grammar and style.

How the authors checked AI outputs: all text and figures were reviewed by the authors against the original experimental data; no AI-generated text was adopted without review.

Influence on conclusions: the AI tool did not influence the scientific conclusions; all experimental data, analysis, interpretation, and conclusions are the work of the authors.

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Authors' contributions

Pungky Eka Setyawan: Conceptualization, Investigation, Data curation, Visualization, Writing – original draft; **Agus Suprapto**: Supervision, Methodology, Writing – review & editing; **Djoko Andrijono**: Validation, Writing – review & editing; **Ignasius Sandrianus Jono Suarao**: Investigation, Resources; **Ike Widyastuti**: Formal analysis; **Jumiadi**: Validation, Resources; **Mesti Nadya**: Investigation, Visualization.

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