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Effect of Pack Carburizing Temperature on the Surface Hardness of ST37 Low-Carbon Steel Using Coconut Shell Charcoal

Pengaruh Temperatur Pack Carburizing terhadap Kekerasan Permukaan Baja Karbon Rendah ST37 Menggunakan Arang Tempurung Kelapa

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Abstract. Steel is widely used in engineering applications due to its favorable mechanical properties, availability, and cost-effectiveness. However, ST37 low-carbon steel exhibits relatively low surface hardness and wear resistance, limiting its application in components subjected to friction and mechanical loading. This study investigates the effect of pack carburizing temperature on the surface hardness of ST37 steel using coconut shell charcoal as a carburizing medium. The carburizing process was performed at temperatures of 900°C, 1000°C, and 1100°C with a constant holding time of 30 minutes, quenched in water at room temperature (25 ± 2°C). Surface hardness was evaluated using the Rockwell B (HRB) scale. The collected data were analyzed using descriptive statistics and one-way analysis of variance (ANOVA) at a significance level of 0.05. The results showed a gradual increase in average hardness from 48.3 HRB for the untreated specimens to 48.6 HRB, 48.9 HRB, and 49.1 HRB for specimens carburized at 900°C, 1000°C, and 1100°C, respectively, corresponding to a maximum increase of 1.65%. Although the hardness values exhibited an increasing trend with temperature, ANOVA results indicated that the differences among treatment groups were not statistically significant ($F = 1.37$, $p = 0.269$). The modest improvement is attributed to enhanced carbon diffusion at elevated temperatures, while the short holding time may have limited the development of a thicker carburized layer. These findings demonstrate that carburizing temperature influences the surface hardening behavior of ST37 steel; however, longer holding times and microstructural characterization are recommended to achieve more significant hardness enhancement and a better understanding of the carburizing mechanism.

Keywords : Pack carburizing; Carburizing temperature; ST37 low-carbon steel; Surface hardness; Carbon diffusion

1. INTRODUCTION

Steel is one of the most widely utilized engineering materials due to its mechanical strength, versatility, and cost-effectiveness. It is extensively applied in construction, automotive, machinery, and manufacturing industries. Among the various types of steel, low carbon steel—particularly ST37—is commonly used because of its good ductility, weldability, and machinability. However, despite these advantages, ST37 steel exhibits relatively low surface hardness and limited wear resistance, which restrict its application in components subjected to continuous friction and mechanical loading, such as gears, shafts, and rotating parts. To overcome this limitation, surface hardening treatments are commonly employed. One of the most economical and practical methods is carburizing, a thermochemical process that enriches the surface layer of steel with carbon atoms at elevated temperatures. This process increases surface carbon content while maintaining the toughness of the core material. Among the various carburizing techniques, pack carburizing is widely used due to its simplicity and low operational cost. In this method, steel specimens are heated in a carbon-rich solid medium—typically charcoal combined with an energizer such as calcium carbonate ($CaCO_3$). After the carburizing stage, rapid quenching in water or oil promotes the transformation of austenite into martensite, resulting in a harder and more wear-resistant surface layer.

The effectiveness of pack carburizing is strongly influenced by processing parameters, particularly temperature and holding time. Increasing temperature enhances atomic mobility and accelerates carbon diffusion into the steel surface, potentially improving surface hardness and case depth. Recent studies have confirmed that elevated carburizing temperatures and appropriate holding times significantly affect microstructural evolution, carbon diffusion, case depth, and mechanical properties of carburized steels [1]–[3]. Although numerous studies have reported the beneficial effects of carburizing on low-carbon steels, specific investigations focusing on temperature variation in pack carburizing of ST37 steel remain limited. Most previous research emphasizes variations in carburizing media composition or different steel grades.

For example, Baali et al. [4] demonstrated that carburizing holding time influences the structure and hardness of steel, while Santoso et al. [5] reported that both temperature and holding time affect the hardness and microstructural characteristics of pack-carburized AISI 1020 steel. Adedipe et al. [6], [7] highlighted the effectiveness of organic and biomass-derived carburizing additives, including coconut-shell-based media, for improving the surface properties of low-carbon steel. A recent review by Madu et al. [8] further emphasized that carburizing temperature, soaking time, carbon source, and cooling conditions jointly determine carbon diffusion and mechanical performance. High-temperature, time-dependent, and quenching-dependent effects on carburized-layer microstructure, case depth, and hardness have also been reported for low-carbon, automotive, and low-alloy steels [9]–[12]. Studies using locally available carburizing media and alternative energizers have likewise demonstrated their potential to improve hardness and wear resistance [13]–[15]. However, systematic evaluation of temperature variation in pack carburizing treatment specifically for ST37 steel using coconut shell charcoal, while maintaining a fixed short holding time, has not been extensively reported.

Despite numerous studies on pack carburizing, the combined influence of multiple process variables often makes it difficult to isolate the specific contribution of temperature to hardness development. Therefore, this study focuses on quantifying the isolated effect of carburizing temperature variation (900°C–1100°C) on ST37 low-carbon steel while maintaining a fixed holding time of 30 minutes and constant processing conditions. This approach enables a clearer evaluation of the role of temperature in carbon diffusion and surface hardening behavior. The results contribute to the understanding of low-cost carburizing treatments using coconut shell charcoal as a sustainable and locally available carbon source for industrial applications.

2. METHODS

2.1 Research Design

This study employed a laboratory-based experimental research design to investigate the effect of pack carburizing temperature on the surface hardness of ST37 low-carbon steel. The experiment involved heat treatment at three different temperature levels: 900°C, 1000°C, and 1100°C, followed by rapid quenching in mineral water. The untreated specimens were used as the control group. Surface hardness measurements were conducted after the heat treatment process using the Rockwell Hardness Test on the B scale (HRB).

2.2 Materials and Specimen Preparation

The material used in this study was ST37 low-carbon steel, selected due to its widespread industrial application, good machinability, and relatively low surface hardness. The specimens were machined into rectangular dimensions of 150 mm × 80 mm × 10 mm to ensure geometric uniformity and consistency throughout the carburizing, quenching, and hardness testing processes. Maintaining identical specimen dimensions minimized variations in heat transfer, carbon diffusion, and cooling rates, thereby improving the reliability and repeatability of the experimental results. The prepared specimens were divided into four groups, each consisting of ten specimens to improve the reliability and repeatability of the results.

Table 1. Specimen Grouping

Group	Treatment Condition
A	Untreated raw material (Control)
B	Pack carburized at 900°C
C	Pack carburized at 1000°C

Group	Treatment Condition
D	Pack carburized at 1100°C

2.3 Pack Carburizing Procedure

The pack carburizing process was conducted using coconut shell charcoal as the primary carbon source, mixed with calcium carbonate ($CaCO_3$) as an energizer to enhance carbon diffusion. The specimens were embedded in the carburizing medium inside a sealed container.

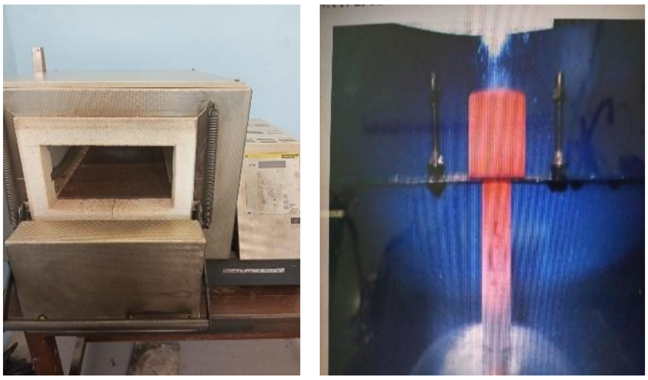

Figure 1. Laboratory furnace used for the pack carburizing heat treatment of ST37 steel specimens.

The container was heated in a laboratory furnace to the designated temperatures of 900°C, 1000°C, and 1100°C, with a constant holding time of 30 minutes for each treatment group (Figure 1). Upon completion of the soaking period, the specimens were immediately removed and quenched in tap water at room temperature (25 ± 2°C) to facilitate martensitic transformation. The overall experimental procedure is summarized in Figure 2.

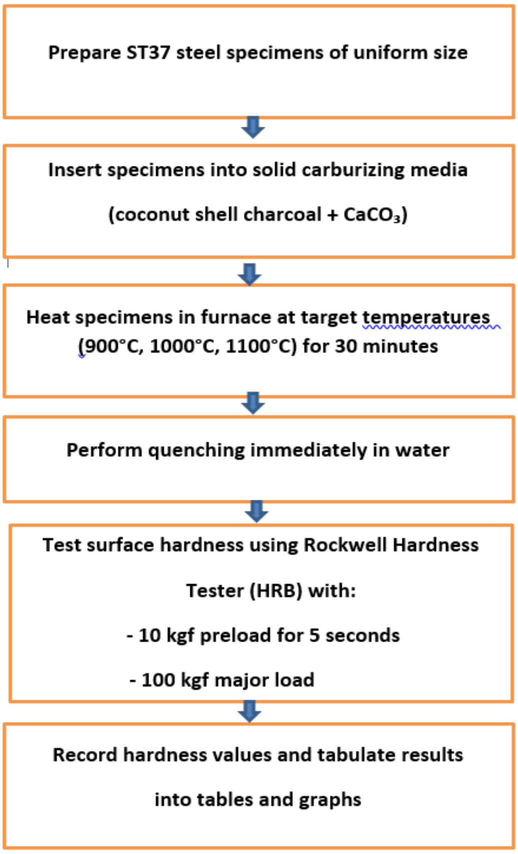

Figure 2. Flowchart of the experimental procedure and data collection process.

The control specimens were tested in the as-received condition without undergoing any heat treatment or carburizing process.

2.4 Hardness Testing

Surface hardness testing was performed using a Rockwell Hardness Tester on the B scale (HRB). For each specimen, multiple indentation measurements were taken at different surface points to minimize measurement error and improve accuracy. Nine indentations were made at different locations on each specimen. The mean of the three measurements was used as the representative hardness value for each specimen. Thus, ten specimen-level mean values were obtained for each treatment group.

2.5 Research Variables

Independent Variable:
Carburizing temperature (900°C, 1000°C, 1100°C)
Dependent Variable:
Surface hardness (HRB)
Controlled Variables:

- Material: ST37 low-carbon steel
- Carburizing medium: Coconut shell charcoal + $CaCO_3$
- Holding time: 30 minutes
- Quenching medium: Mineral water
- Specimen dimensions

2.6 Data Analysis

The collected hardness data were analyzed using descriptive and inferential statistical methods. The mean hardness and standard deviation (SD) were calculated for each treatment group to evaluate the central tendency and data dispersion. The percentage increase in hardness relative to the untreated specimens was also determined to assess the effectiveness of the pack carburizing process. To evaluate whether the differences in hardness among treatment groups were statistically significant, a one-way analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$. The ANOVA results were used to determine the influence of carburizing temperature on the surface hardness of ST37 low-carbon steel.

Graphical representations were prepared to illustrate trends and differences among treatment groups and to facilitate comparison of the experimental results. Statistical calculations were performed using Microsoft Excel to ensure consistency and accuracy of the data analysis.

2.7 Instrument Calibration and Measurement Reliability

To ensure measurement accuracy, before testing, the Rockwell hardness tester was verified using a certified HRB reference block in accordance with the applicable standard laboratory procedure. Repeated measurements were performed on selected specimens to verify consistency and reduce random error. This approach ensured the reliability and reproducibility of the hardness data.

3. RESULTS AND DISCUSSION

3.1 Surface Hardness (HRB) Test

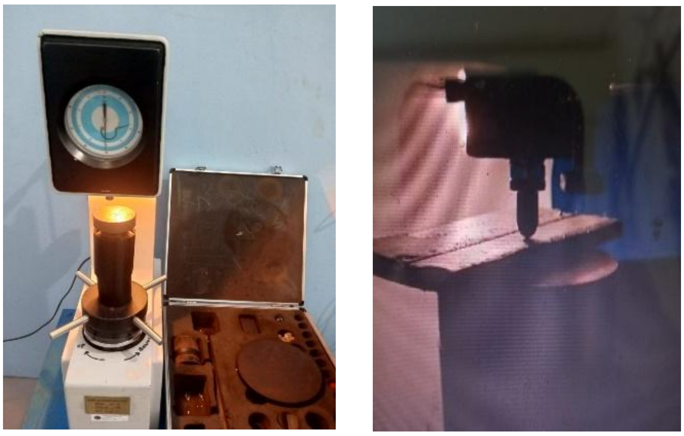

Figure 3. Rockwell Hardness Tester used for measuring the surface hardness of ST37 steel specimens.

The hardness test results of ST37 low-carbon steel specimens after pack carburizing treatment at different temperatures are presented in Table 2.

Table 2. Surface Hardness (HRB) of ST37 Steel under Different Carburizing Temperatures

Treatment	1	2	3	4	5	6	7	8	9	10	Mean (HRB)
Raw Material	51	48	48	47	47	47	49	49	49	48	48.3
900°C	48	48	48	49	49	49	48	48	50	49	48.6
1000°C	49	48	48	48	50	50	49	50	49	48	48.9
1100°C	48	48	49	49	48	49	50	50	50	50	49.1

A graphical comparison of the average hardness values is illustrated in Figure 4.

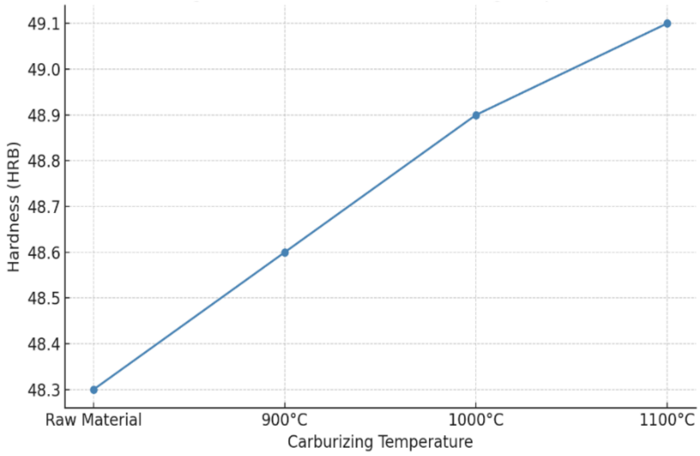

Figure 4. Average Surface Hardness versus Carburizing Temperature

The results indicate a gradual and consistent increase in surface hardness with increasing carburizing temperature. The untreated specimens exhibited an average hardness of 48.3 HRB. After pack carburizing, the average hardness increased to 48.6 HRB at 900°C, 48.9 HRB at 1000°C, and 49.1 HRB at 1100°C.
The percentage increase in hardness from the untreated material to the highest treatment temperature (1100°C) is calculated as:

$$\frac{49.1-48.3}{48.3} x\ 100\% = 1.65\% \quad (1)$$

Although the absolute increase in hardness is relatively small, the consistent upward trend across all treatment levels suggests a positive relationship between carburizing temperature and surface hardness.

3.2 Statistical Analysis

To evaluate whether the differences in hardness values among treatment groups were statistically significant, a one-way analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$. The calculated F-value ($F = 1.37$) was lower than the critical F-value ($F(3,36) = 1.37$, $\alpha = 0.05$), indicating that the differences among the treatment groups were not statistically significant ($p = 0.269$).

Table 3. Mean Hardness and Standard Deviation

Treatment	Mean (HRB)	SD
Raw Material	48.3	1.25

Treatment	Mean (HRB)	SD
900°C	48.6	0.70
1000°C	48.9	0.88
1100°C	49.1	0.88

The calculated standard deviation values indicate relatively low data dispersion, suggesting good repeatability and consistency of the hardness measurements. The lower standard deviation values observed in the carburized specimens compared to the untreated specimens indicate more uniform hardness distribution after heat treatment.

Although a gradual increasing trend in hardness was observed with increasing carburizing temperature, the statistical analysis suggests that the variation in temperature within the tested range (900°C–1100°C) did not produce a significant change in surface hardness under the present experimental conditions.

This result implies that the holding time of 30 minutes may have limited the effective carbon diffusion depth, reducing the statistical impact of temperature variation. Further studies with extended soaking time or microhardness profiling are recommended to better capture the effect of carburizing temperature.

3.3 DISCUSSION

The increase in hardness observed in this study can be explained by enhanced carbon diffusion at elevated temperatures. According to diffusion principles and Fick's second law, the diffusion coefficient increases with temperature according to an Arrhenius-type relationship due to greater atomic mobility. As the carburizing temperature rises, carbon atoms diffuse more effectively into the steel surface, increasing carbon concentration within the austenitic phase. Upon rapid quenching, the carbon-enriched austenite is expected to transform into martensite, which may contribute to increased surface hardness. However, the relatively modest hardness increment (1.65%) indicates that temperature alone may not be sufficient to generate substantial surface hardening under the present experimental conditions. The holding time of 30 minutes likely limited the diffusion depth, resulting in a relatively thin carburized layer. Since diffusion depth is proportional to the square root of time, longer soaking durations could potentially produce more pronounced hardness improvements.

These findings are consistent with previous studies. Baali et al. [4] and Santoso et al. [5] reported that carburizing temperature and holding time influence hardness and microstructural development. Adedipe et al. [6], [7] demonstrated that organic carburizing additives can facilitate carbon transfer and improve surface properties, while Madu et al. [8] summarized the strong dependence of carburizing performance on temperature, soaking time, carbon source, and cooling conditions. Furthermore, Zhang et al. [1], Ballem et al. [2], Viliš et al. [3], Teixeira et al. [9], Boumediri et al. [10], Abdenour et al. [11], and Kolawole et al. [12] confirmed that treatment parameters significantly affect carbon diffusion, microstructure, case depth, hardness, and other mechanical properties in different steel grades. Although several of these studies focused on alloy steels rather than ST37 low-carbon steel, they provide useful insight into the role of carburizing temperature, duration, and cooling conditions in hardness development.

Compared to studies reporting higher hardness increments, the relatively moderate improvement in this research may be attributed to several factors, including shorter holding time, differences in carbon potential of the carburizing medium, and the use of Rockwell B scale testing.

The HRB method may be less sensitive to thin hardened layers compared with microhardness testing methods such as Vickers hardness (HV), which are commonly used to evaluate case-depth profiles. Despite the modest increase, the results demonstrate that coconut shell charcoal combined with $CaCO_3$ can facilitate carbon transfer to the steel surface. This finding is supported by previous studies showing that locally available carbonaceous materials and alternative quenching media can provide economical and more sustainable options for pack carburizing and surface-property enhancement [7], [13]–[15].

Overall, the results indicate an increasing trend in surface hardness with increasing carburizing temperature, although the differences were not statistically significant under the investigated conditions. Nevertheless, further optimization of soaking time and detailed microstructural analysis are recommended to achieve more significant surface strengthening and to fully characterize the carburized layer.

3.4 Research Limitations

This study has several limitations that should be considered when interpreting the results. First, the carburizing holding time was limited to 30 minutes, which may not have been sufficient to produce significant carbon diffusion depth. Since diffusion depth is strongly dependent on both temperature and time, longer soaking durations could potentially yield more pronounced hardness enhancement.

Second, the hardness evaluation was conducted using the Rockwell B (HRB) scale. While suitable for general hardness assessment, this method may be less sensitive in detecting thin carburized layers compared to microhardness testing methods such as Vickers hardness (HV), which provide better resolution for surface case depth profiling.

Third, this study did not include microstructural analysis or metallographic examination. The absence of microstructural observations limits the ability to directly confirm martensitic transformation and determine the carburized case depth. Future research should incorporate optical microscopy or scanning electron microscopy (SEM) analysis to better characterize the carburized layer.

Finally, statistical analysis indicated that the differences among treatment groups were not statistically significant at $\alpha = 0.05$. This suggests that further optimization of process parameters, including soaking time and carbon potential control, is required to achieve more substantial and statistically significant surface hardening effects.

4. CONCLUSION

This study investigated the effect of pack carburizing temperature (900°C, 1000°C, and 1100°C) on the surface hardness of ST37 low-carbon steel using coconut shell charcoal combined with $CaCO_3$ as the carburizing medium. The experimental results demonstrated a gradual increase in surface hardness with increasing carburizing temperature. The highest hardness value (49.1 HRB) was obtained at 1100°C, representing a 1.65% increase compared to the untreated material (48.3 HRB).

However, one-way ANOVA revealed that the differences in hardness among treatment groups were not statistically significant at the 95% confidence level. This finding suggests that, under the current experimental conditions, temperature variation alone—without extended holding time—may not produce substantial surface hardening in ST37 steel.

Despite the modest increase, the results suggest that higher carburizing temperatures may promote carbon diffusion and surface strengthening; however, the observed differences were not statistically significant. The use of coconut shell charcoal as a locally available carburizing medium also demonstrates potential for cost-effective and sustainable surface treatment applications in small- and medium-scale industries.

Future research is recommended to investigate longer soaking times, microstructural characterization, case depth measurement, and alternative quenching media in order to optimize the carburizing process and achieve more significant hardness improvement.

5. ACKNOWLEDGEMENT

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