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## Effect of Holding Time on Hardness and Microstructure of AISI 1045 Steel after Carburizing-Quenching Process

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### A B S T R A C T

This study investigates the effect of carburising holding time on the hardness and microstructure of AISI 1045 medium-carbon steel after quenching. The carburising process was conducted at 900°C using 100% coconut shell charcoal as the carburising medium, with holding times of 15, 30, 60, and 120 minutes. After carburising, the specimens were directly quenched in lubricating oil without reheating. Five specimens were prepared for each treatment condition, and hardness testing was performed according to ASTM E18 using the Rockwell B hardness scale (HRB). Five hardness measurements were conducted on each specimen to ensure repeatability. The results indicate that increasing holding time improved hardness and promoted martensitic transformation due to deeper carbon diffusion. The average hardness increased from 81.46 HRB for untreated specimens to 94.45 HRB for specimens carburized for 120 minutes. ANOVA analysis confirmed that holding time significantly affected hardness values, and regression analysis yielded an  $R^2$  of 0.962. Microstructural observations revealed increasing martensite formation with longer holding times. The findings demonstrate that carburizing holding time plays an important role in improving the surface characteristics of AISI 1045 steel.

#### Contribution to Sustainable Development Goals (SDGs):

**SDG 9:** Industry, Innovation and Infrastructure

**SDG 12:** Responsible Consumption and Production

## 1. INTRODUCTION

### 1.1. Research Background

Medium-carbon steel is widely used in manufacturing industries because it offers a balanced combination of strength, toughness, and machinability [1]. AISI 1045 steel, which contains approximately 0.45% carbon, is commonly used for shafts, gears, couplings, and automotive components that require moderate mechanical strength and wear resistance [2]. However, many engineering applications require higher surface hardness to improve wear resistance while maintaining adequate toughness in the core material.

Surface hardening by heat treatment is one of the most effective methods for improving the mechanical performance of

medium-carbon steel. Among various heat-treatment techniques, carburising combined with quenching is widely used because it increases surface hardness through carbon diffusion and martensitic transformation [3]. During carburizing, carbon atoms diffuse into the steel surface at elevated temperatures in a carbon-rich environment. Subsequent rapid cooling during quenching transforms carbon-enriched austenite into martensite, thereby improving hardness and wear resistance.

Several parameters influence the effectiveness of the carburizing process, including temperature, carbon potential, holding time, and cooling medium [4]. Among these parameters, holding time is particularly important because it determines the depth of carbon diffusion into the steel surface. Longer holding times generally increase carbon penetration and promote martensitic transformation after quenching [5]. However,



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excessive holding time may result in distortion, residual stress, and inefficient energy consumption [6]. Therefore, optimization of carburizing holding time is necessary to obtain improved hardness without introducing undesirable effects.

Previous studies have investigated the influence of carburizing parameters on steel properties. Lee et al. [6] reported that increasing the carburising temperature and holding time increased the hardness of medium-carbon steel but also increased the risk of dimensional distortion. Tian et al. [5] demonstrated that holding time strongly affects carbon diffusion depth and martensitic transformation. Masoumi et al. [7] concluded that carburized steel with sufficient case depth exhibited improved wear resistance and fatigue performance. More recent studies published between 2020 and 2025 also emphasized the importance of quenching media and environmentally friendly carburizing materials in improving the mechanical properties of steel. Nurhadi and Suryana [8] reported that holding time significantly affected the microstructure and hardness characteristics of AISI 1045 steel during heat treatment. Sulistiyawan et al. [9] demonstrated that increasing the holding time during oil quenching improved martensitic formation and hardness distribution in AISI 1045 steel. In addition, recent eco-carburising investigations have shown that biomass-based carburising media, such as coconut shell charcoal and crab-shell biocarbonate, can effectively improve surface hardness while reducing environmental impact [10], [11].

Although previous studies have discussed carburising and quenching processes, few have quantitatively evaluated the optimal carburising holding time for AISI 1045 steel under constant carburising conditions using combined statistical and microstructural analysis. In addition, the utilization of 100% coconut shell charcoal as an environmentally friendly carburizing medium has received limited attention. Therefore, this study aims to investigate the effect of carburising holding time on the hardness and microstructure of AISI 1045 steel and to determine the relationship between holding time and the martensitic transformation through hardness testing, ANOVA, regression analysis, and microstructural observation.

## 1.2. Literature Review

Carburising is a thermochemical heat treatment process used to improve the surface hardness and wear resistance of steel by diffusing carbon into the surface [3]. The effectiveness of

carburizing depends on several process parameters, including carburizing temperature, holding time, and cooling conditions [4]. Longer holding times generally increase carbon diffusion depth and improve the formation of martensite during quenching.

Lee et al. [6] investigated the effects of carburising temperature and holding time on medium-carbon steel and reported that increasing holding time significantly improved hardness due to deeper carbon penetration. However, excessively long holding times also increased the possibility of distortion and thermal stress formation.

Tian et al. [5] studied the relationship between carburizing parameters and microstructural evolution in alloy steel. Their study revealed that increasing holding time increased the depth of carbon diffusion and promoted martensitic transformation during quenching. The study also demonstrated that holding time has a direct relationship with hardened case depth.

Masoumi et al. [7] evaluated the wear and fatigue behavior of carburized steel subjected to quenching treatment. The results showed that carburized steel with sufficient carbon diffusion depth exhibited superior wear resistance and fatigue performance compared to untreated steel.

Most previous studies mainly focused on carburizing temperature variation, quenching media variation, or simulation-based diffusion analysis. In contrast, the present study specifically emphasises the effect of holding time at a constant carburising temperature using experimental hardness testing, ANOVA, regression modelling, and microstructural characterisation. Unlike Sulistiyawan et al. [9], who mainly evaluated oil quenching during hardening, this study investigates the carburising-quenching process using direct oil quenching after carburising. Furthermore, while several recent studies used mixed carburising agents and additional catalysts [10], [11], the present work uses 100% coconut shell charcoal as a simple, environmentally friendly, and low-cost carburising medium for AISI 1045 steel surface-hardening applications. Previous work by Tafrant et al. [12] also demonstrated that quenching media significantly influence hardness and microstructural evolution in medium-carbon steel, thereby underscoring the importance of cooling conditions in optimising carburising-quenching treatments. To clarify the position and contribution of the present study compared to previous investigations, a concise comparison of related studies is presented in Table 1.

**Table 1.** Comparison of Previous Studies and Present Work

Study	Main Focus	Limitation	Contribution of Present Study
Lee et al. [6]	Effect of carburizing temperature and holding time	Limited statistical analysis	Focus on holding time optimization using ANOVA and regression
Tian et al. [5]	Carbon diffusion and microstructural evolution	Simulation-oriented analysis	Experimental evaluation of hardness and martensitic transformation
Sulistiyawan et al. [9]	Hardening with oil quenching	No carburizing treatment	Direct carburizing-quenching process using lubricating oil
Tuny et al. [10]	Eco-carburizing with mixed biocarbonate media	Complex carburizing composition	Use of 100% coconut shell charcoal as a simple eco-friendly medium
Present study	Holding time effect during carburizing-quenching	Limited to one carburizing temperature	Quantitative evaluation of hardness, microstructure, and statistical relationship

### 1.3. Research Objective

This study aims to investigate the effect of carburising holding time on the hardness and microstructure of AISI 1045 steel and to determine the optimal holding time for achieving maximum hardness and a dominant martensitic transformation.

## 2. MATERIALS AND METHODS

### 2.1. Material Preparation

The material used in this study was AISI 1045 medium carbon steel. The specimens were prepared in cylindrical form with a diameter of 50 mm and a thickness of 10 mm. Prior to heat treatment, the specimen surfaces were cleaned to remove contaminants.

### 2.2. Carburizing Process

The carburizing process was conducted at 900°C using 100% coconut shell charcoal as the carburizing medium. The holding times applied during carburizing were 15, 30, 60, and 120 minutes. For each holding-time variation, five specimens were prepared to ensure experimental repeatability and consistency of the experimental results.

### 2.3. Quenching Process

After the carburizing process was completed, the specimens were directly quenched using lubricating oil as the cooling medium without any reheating process.

### 2.4. Hardness Testing

Hardness testing was performed according to ASTM E18 using the Rockwell B hardness scale (HRB) with a 100 kgf load and a 1/16-inch steel ball indenter. Five hardness measurements were conducted on each specimen at different surface points, resulting in a total of 25 measurements for each treatment condition. The average hardness value was then calculated and used for statistical analysis. The repeated measurements were intended to improve data reliability and ensure experimental repeatability.

### 2.5. Microstructural Analysis

Microstructural observations were conducted using an optical metallurgical microscope at 500× magnification. The specimens were polished and etched using 2% nital solution before observation.

### 2.6. Data Analysis

The experimental data were analysed using descriptive statistics and analysis of variance (ANOVA) to determine the significance of holding time on hardness values. Regression analysis was also performed to evaluate the relationship between carburizing holding time and hardness.

## 3. RESULT AND DISCUSSION

### 3.1. Hardness Test Results

The hardness test results revealed a significant increase in hardness after the carburizing-quenching treatment. Table 2 presents the average hardness values for each holding time.

**Table 2.** Average Hardness of AISI 1045 Steel after Carburizing-Quenching Treatment

Treatment Condition	Average Hardness (HRB)
Untreated specimen	81.46
Holding time 15 minutes	93.54
Holding time 30 minutes	93.83
Holding time 60 minutes	94.08
Holding time 120 minutes	94.45

The hardness values presented in this study were measured using the Rockwell B hardness scale (HRB) according to ASTM E18. The untreated specimen exhibited the lowest hardness value because its microstructure was dominated by ferrite and pearlite phases, which possess relatively low hardness compared to martensite. After carburizing and quenching, hardness increased significantly due to carbon diffusion and martensitic transformation occurring near the steel surface.

During the carburising process, carbon atoms diffused into the steel surface at elevated temperatures, forming a carbon-enriched layer known as the carburised case. Increasing holding time promoted deeper carbon diffusion, leading to greater carbon supersaturation in the austenitic phase before quenching. During rapid cooling using lubricating oil, the carbon-rich austenite transformed into martensite through diffusionless transformation kinetics, thereby increasing surface hardness.

The gradual increase in hardness with longer holding time indicates that carbon diffusion became more effective as the carburizing duration increased. However, the hardness increase after 60 minutes became less significant. This condition suggests that carbon diffusion gradually approached equilibrium concentration near the steel surface, reducing the effectiveness of additional holding time. In carburizing treatment, once the near-surface region approaches carbon saturation, the diffusion rate decreases because the concentration gradient becomes smaller. Similar findings were reported by Tian et al. [5], who observed that prolonged carburising time eventually led to diminishing hardness improvement due to diffusion equilibrium.

The relationship between carburized case depth and hardness can also explain the observed results. Longer holding times generally increased case depth and promoted the formation of a thicker martensitic layer after quenching. Nevertheless, after a certain holding time, the increase in case depth became less substantial, resulting in only marginal hardness improvement.

ANOVA analysis showed that holding time significantly affected hardness ( $p < 0.05$ ), indicating that carburising duration had a statistically significant effect on the hardness of AISI 1045 steel. The statistical analysis also showed that the average hardness values for each treatment condition were within the 95% confidence interval, indicating good consistency and reliability of the experimental data.

The linear regression equation obtained from the analysis is:

$$\text{Hardness} = (8,2 \times 10^{-3})t + 93,52 \quad (1)$$

The polynomial regression equation is expressed as:

$$\text{Hardness} = (1,64 \times 10^{-5})t - (5,9 \times 10^{-5})t^2 + 93,34 \quad (2)$$

The regression model produced an  $R^2$  value of 0.962, indicating a strong relationship between holding time ( $t$ ) and

Rocwell B hardness. Regression significance analysis also showed that the regression model was statistically significant, with a p-value below 0.05.

Residual analysis indicated that the residuals were randomly distributed around the regression line, with no systematic deviations. This condition indicates that the regression model was appropriate for representing the relationship between carburizing holding time and hardness.

The relationship between hardness and holding time is shown in Figure 1.

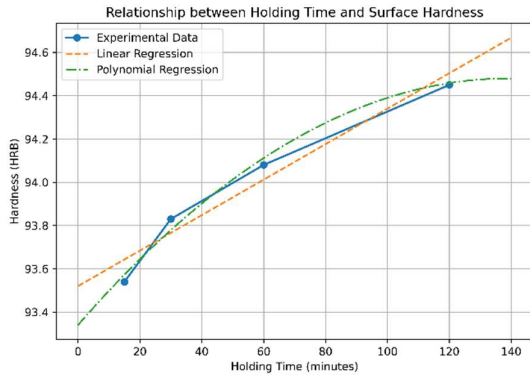


Fig. 1 The relationship of Surface hardness and holding time

Based on figure 1, the polynomial model indicates that the optimum holding time for maximum hardness is approximately 138.98 minutes.

### 3.2. Microstructural Analysis

The untreated AISI 1045 steel specimen (Figure 2) exhibited a microstructure dominated by ferrite and pearlite phases. Ferrite appeared as bright regions, whereas pearlite appeared as darker, uniformly distributed lamellar structures.

After the carburizing-quenching process, a significant microstructural transformation occurred. The carburized specimens exhibited increasing martensitic formation with longer holding times. At a holding time of 15 minutes, ferrite and martensite were present in nearly equal proportions. At 30 minutes, martensite became more dominant than ferrite. Specimens treated for 60 and 120 minutes showed a microstructure predominantly composed of martensite.

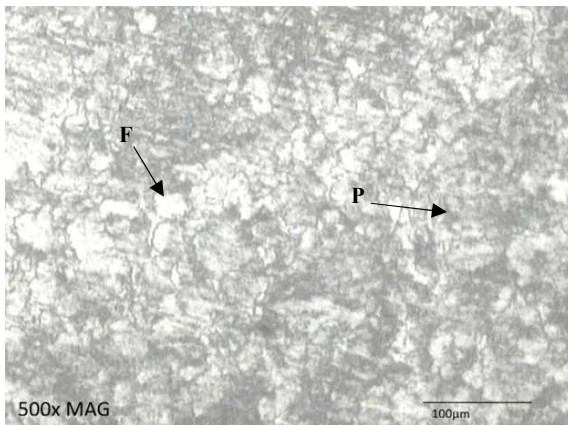


Fig. 2. Microstructure of untreated AISI 1045 steel dominated by ferrite and pearlite phases (500×).

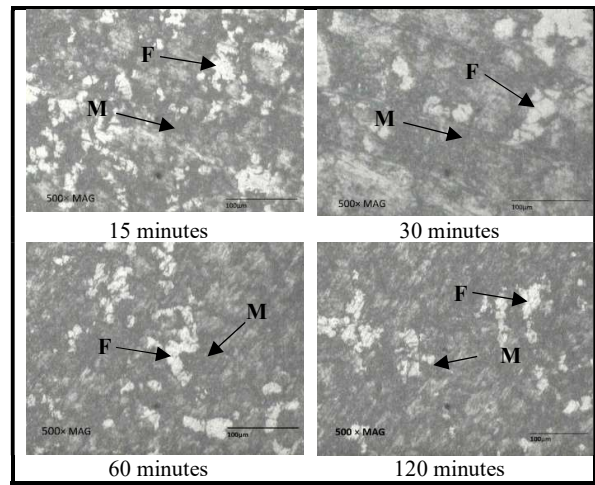


Fig. 3 Comparison of the microstructure of AISI 1045 steel with different holding time treatments

Figure 3 shows the relationship between holding time during carburising and the dominant microstructure observed in AISI 1045 steel after quenching. The results show that increasing the holding time gradually increased the formation of martensite within the steel structure. At a holding time of 15 minutes, the microstructure consisted of ferrite and martensite in nearly equal proportions, indicating limited carbon diffusion into the material surface. At 30 minutes, martensite became more dominant due to increased carbon absorption during carburizing. Meanwhile, specimens treated for 60 and 120 minutes exhibited predominantly martensitic structures, demonstrating that longer holding times promoted deeper carbon diffusion and more complete martensitic transformation during quenching. This transformation is directly related to the increase in hardness observed in Table 1, since martensite has a harder, stronger crystal structure than ferrite and pearlite. In summary, the conditions are depicted in Table 3.

Table 3. Relationship between Holding Time and Dominant Microstructure

Holding Time	Dominant Microstructure
Untreated	Ferrite and Pearlite in similar proportions
15 minutes	Ferrite and martensite in a similar proportion
30 minutes	Martensite is more dominant than ferrite
60 minutes	Martensite dominant
120 minutes	Martensite highly dominant

The increasing dominance of martensite with longer holding times explains the corresponding increase in hardness values. During carburising, carbon atoms diffuse into the surface layer, stabilising the austenitic phase at elevated temperatures. During rapid cooling, carbon-rich austenite transforms into martensite, increasing hardness. The increase in hardness is strongly associated with carbon diffusion depth and martensitic transformation.

Longer holding times enhanced carbon diffusion into the steel surface, producing a thicker carburized layer. Consequently, more martensite formed during quenching, leading to higher hardness values. However, the rate of hardness increase gradually decreased after 60 minutes, indicating that carbon diffusion approached saturation.

The optimum holding time predicted by polynomial regression analysis was approximately 138.98 minutes. Beyond this duration, the increase in hardness is expected to become insignificant or even decrease due to excessive carbon concentration and possible microstructural instability.

These findings are consistent with previous studies conducted by Lee et al., Tian et al., and Masoumi et al., which reported that holding time strongly influences carbon diffusion depth, martensitic transformation, and surface hardness. Therefore, optimizing holding time is essential for achieving the desired balance between hardness, wear resistance, and structural integrity.

#### 4. CONCLUSION

The carburizing-quenching process significantly affected the hardness and microstructure of AISI 1045 steel. Increasing carburizing holding time increased hardness and promoted martensitic transformation due to deeper carbon diffusion into the steel surface. The highest average hardness obtained in this study was 94.45 HRB at a holding time of 120 minutes. Statistical analysis confirmed that holding time significantly influenced hardness values, and regression analysis indicated a strong relationship between holding time and hardness ( $R^2 = 0.962$ ).

The results indicate that optimization of carburizing holding time can improve the surface performance of AISI 1045 steel for industrial applications requiring enhanced wear resistance, surface durability, and longer component service life, particularly for machine elements such as shafts, gears, and couplings.

However, this study was limited to a single carburizing temperature and a lubricating-oil quenching medium. In addition, direct measurement of carburized case depth and wear resistance testing were not conducted in the present investigation.

Future studies should investigate the effects of different carburising media, quenching rates, and case-depth characteristics on the wear resistance and fatigue behaviour of carburised AISI 1045 steel.

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