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Effect of Holding Time in Pack Carburizing Using Bamboo Charcoal on the Mechanical Properties of ST 41 Steel

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ABSTRACT

This study investigates the effect of holding time in the pack carburizing process using bamboo charcoal on the mechanical properties of ST 41 steel. The carburizing treatment was conducted at a temperature of 850 °C using a solid carburizing medium consisting of bamboo charcoal and barium carbonate in an 80:20 ratio. Holding time variations of 45, 65, and 85 minutes were applied. After carburizing, the specimens were quenched in SAE 20W-50 oil and subsequently tempered at 350 °C for 20 minutes. Mechanical characterization included Vickers hardness testing, wear testing, and impact testing. The results indicate that holding time has a significant influence on the mechanical properties of ST 41 steel. The average hardness increased with longer holding time, from 162.0 VHN for untreated material to 175.2 VHN at 45 minutes, 185.5 VHN at 65 minutes, and 196.5 VHN at 85 minutes. Wear test results showed a reduction in wear rate with increasing holding time, reaching the lowest value of 0.000029 $mm^3/kg \cdot m$ at 85 minutes. In contrast, impact strength decreased as holding time increased, from 3.302 J/mm^2 for untreated steel to 2.934 J/mm^2 at 85 minutes. These results demonstrate that longer holding time in pack carburizing enhances surface hardness and wear resistance of ST 41 steel but reduces its impact toughness. An 85-minute holding time provides the best hardness and wear resistance, although accompanied by a decrease in impact strength. This study provides a reference for optimizing heat treatment parameters to improve the performance of mechanical components, particularly gears.

1. Introduction

Gears are critical mechanical components widely used in industrial and automotive applications to transmit power and rotational motion between shafts. During operation, gears are subjected to high dynamic loads, repeated contact stresses, and continuous friction, which demand high surface hardness, good wear resistance, and adequate core toughness to ensure reliable performance and long service life [1,2]. Consequently, material selection and heat treatment processes play a decisive role in

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determining the durability and efficiency of gear components.

Low-carbon steels, such as ST 41 steel, are commonly used in mechanical and structural applications due to their good formability, weldability, and cost effectiveness [3,4]. However, in the as-received condition, ST 41 steel exhibits relatively low surface hardness and poor wear resistance, which limit its direct application in components exposed to severe friction and contact loading [5]. To overcome these limitations, surface hardening treatments are often applied to improve surface properties while maintaining a tough and ductile core [6].

Carburizing is one of the most widely used thermochemical heat treatment processes for enhancing the surface hardness of low-carbon steels. This process involves diffusing carbon atoms into the steel surface at elevated temperatures, followed by rapid cooling to form a hard martensitic layer. Among various carburizing methods, pack carburizing is favored for its simplicity, low cost, and suitability for small- to medium-scale applications. In pack carburizing, the steel is heated in a sealed container filled with a solid carbonaceous medium, allowing carbon diffusion to occur effectively during the holding period [2].

Bamboo charcoal has gained increasing attention as an alternative solid carburizing medium due to its high carbon content, porous structure, low cost, and environmental sustainability. Its large surface area promotes the generation of carbon monoxide during heating, which facilitates carbon diffusion into the steel surface. Previous studies have shown that bamboo charcoal is effective in improving surface hardness and wear resistance of low-carbon steels when used in pack carburizing processes [7].

One of the key parameters influencing the effectiveness of pack carburizing is holding time. Holding time determines the duration available for carbon diffusion, directly affecting case depth, surface hardness, and resulting mechanical properties. While longer holding times generally increase carbon diffusion and surface hardness, they may also reduce impact toughness due to the formation of a thicker and harder surface layer. Therefore, an optimal holding time is required to balance hardness, wear resistance, and toughness according to the intended application [8].

Based on these considerations, this study aims to investigate the effect of holding time in pack carburizing using bamboo charcoal on the mechanical properties of ST 41 steel. The mechanical behavior is evaluated through hardness, wear, and impact testing to provide a comprehensive understanding of the trade-off between surface hardness and impact toughness. The results of this study are expected to contribute to the optimization of heat treatment parameters for improving the performance of ST 41 steel components, particularly gears subjected to high wear conditions.

2. Methodology

This research employed an experimental method to investigate the effect of holding time in the pack carburizing process using bamboo charcoal on the mechanical properties of ST 41 steel. The methodology was designed to ensure controlled processing conditions, repeatability, and reliable evaluation of mechanical performance.

2.1. Materials

The material used in this study was low-carbon steel ST 41 in the as-received condition. The steel specimens were prepared according to the requirements of each mechanical test. Bamboo charcoal was used as the solid carbon source in the pack carburizing process, while barium carbonate ($BaCO_3$) served as an energizer to promote carbon diffusion. The carburizing medium consisted of a mixture of bamboo charcoal and barium carbonate in an 80:20 weight ratio. SAE 20W-50 oil was used as the quenching medium.

2.2. Specimen Preparation

ST 41 steel was cut into specimens with dimensions suitable for hardness, wear, and impact testing. The surfaces of all specimens were ground and polished to remove surface oxides and machining marks, ensuring uniform exposure during carburizing. Prior to heat treatment, all specimens were cleaned with alcohol to eliminate contaminants such as oil and dust.

2.3. Pack Carburizing Process

The pack carburizing process was carried out using a sealed steel container. The specimens were placed inside the container and fully surrounded by the carburizing medium to ensure uniform carbon diffusion. The container was then closed tightly to prevent the entry of air and placed inside an electric furnace.

Carburizing was performed at a constant temperature of 850 °C. Three holding time variations were applied: 45 minutes, 65 minutes, and 85 minutes. These holding times were selected to evaluate the effect of carbon diffusion duration on the mechanical properties of ST 41 steel. After the holding time elapsed, the container was removed from the furnace, and the specimens were immediately extracted for further treatment.

2.4. Quenching and Tempering

After carburizing, all specimens were rapidly quenched in SAE 20W-50 oil at room temperature to transform the austenitic structure into martensite, thereby increasing surface hardness. Following quenching, the specimens were tempered at 350 °C for 20 minutes to reduce brittleness and residual stresses induced during quenching. After tempering, the specimens were allowed to cool in still air.

2.5. Mechanical Testing

Mechanical characterization was conducted through hardness, wear, and impact testing.
Vickers hardness testing was performed in accordance with ASTM E92/E384 standards using a diamond pyramid indenter. Multiple indentations were made on each specimen to obtain representative hardness values, and the average hardness was reported in Vickers Hardness Number (VHN).

Wear testing was carried out using a universal wear testing machine following ASTM G133. The test was conducted under constant load and sliding distance conditions. Wear rate was calculated based on the volume loss of material per unit load and sliding distance and expressed in $mm^3/kg \cdot m$.

Impact testing was conducted using the Charpy V-notch method in accordance with ASTM E23. Standard impact specimens with a V-shaped notch were tested at room temperature. The absorbed impact energy was recorded and converted into impact strength values expressed in J/mm^2.

2.6. Data Analysis

The experimental data obtained from hardness, wear, and impact tests were analyzed by comparing the results of untreated specimens with those subjected to different holding times. The relationship between holding time and mechanical properties was evaluated to identify trends and trade-offs between surface hardness, wear resistance, and impact toughness. The results were presented in the form of tables and graphs to facilitate interpretation and discussion.

3. Results

3.1. Hardness Test Results

The Vickers hardness test results show a clear increase in surface hardness of ST 41 steel after the pack carburizing process. The untreated (raw) material exhibited an average hardness of 162.0 VHN. After carburizing, the hardness increased progressively with increasing holding time. Specimens carburized for 45 minutes showed an average hardness of 175.2 VHN, while those treated for 65 minutes reached 185.5 VHN. The highest hardness value of 196.5 VHN was obtained at a holding time of 85 minutes.

These results indicate that holding time plays a significant role in determining the hardness of carburized ST 41 steel. Longer holding times provide greater opportunity for carbon atoms to diffuse into the steel surface, resulting in a harder case layer [9].

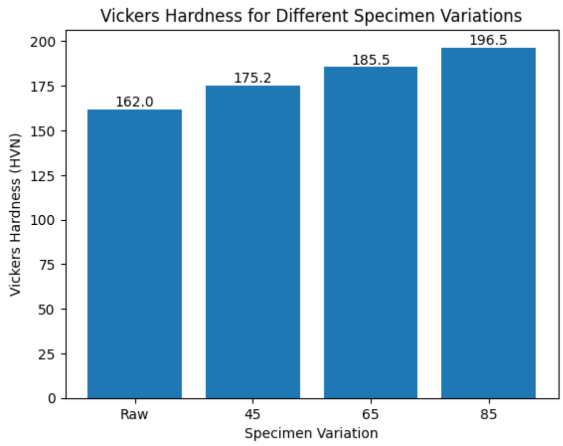

Fig.1. Vickers hardness for different specimen variations

3.2. *Wear Test Results*

The wear test results demonstrate a substantial reduction in wear rate following the carburizing treatment. The untreated ST 41 steel showed an average wear rate of 0.000107 $mm^3/kg \cdot m$. After carburizing, the wear rate decreased significantly with increasing holding time. At a holding time of 45 minutes, the wear rate decreased to 0.000041 $mm^3/kg \cdot m$. Further reductions were observed at 65 minutes (0.000035 $mm^3/kg \cdot m$), with the lowest wear rate recorded at 85 minutes (0.000029 $mm^3/kg \cdot m$). These results confirm that the carburizing process effectively enhances the wear resistance of ST 41 steel, particularly when longer holding times are applied [10, 11].

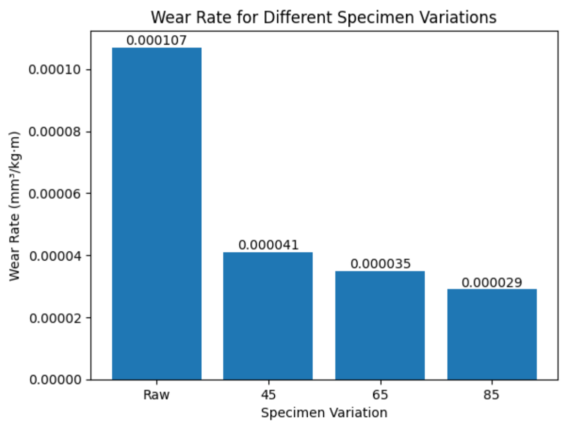

Fig.2. Wear rate for different specimen variations

3.3. *Impact Test Results*

The impact test results reveal an opposite trend compared to hardness and wear resistance. The untreated ST 41 steel exhibited the highest impact strength, with an average value of 3.302 J/mm^2. After carburizing, impact strength decreased as holding time increased. At 45 minutes, the impact strength reduced to 3.248 J/mm^2, followed by 3.215 J/mm^2 at 65 minutes. The lowest impact strength, 2.934 J/mm^2, was observed at a holding time of 85 minutes. This decrease indicates that increasing holding time in pack carburizing leads to reduced toughness of ST 41 steel [12].

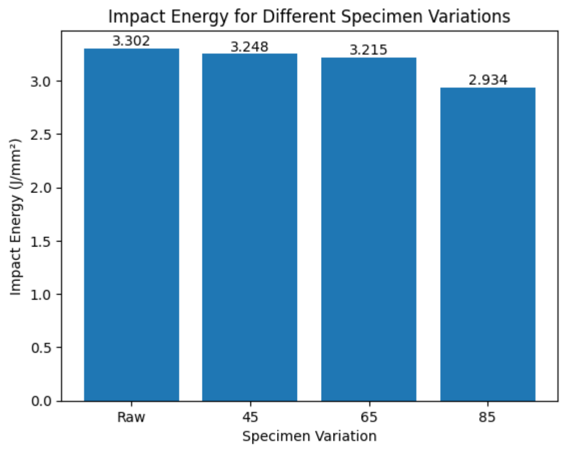

Fig.3. Impact energy for different specimen variations

4. Discussion

4.1. *Effect of Holding Time on Hardness*

The increase in hardness with longer holding time can be attributed to enhanced carbon diffusion during the pack carburizing process. At 850 °C, carbon atoms from the bamboo charcoal medium diffuse into the austenitic surface layer of ST 41 steel. Longer holding times allow a greater amount of carbon to penetrate the surface, increasing the local carbon concentration and promoting the formation of a harder martensitic structure after quenching [13].

Additionally, the presence of barium carbonate as an energizer facilitates the generation of carbon monoxide gas, which accelerates carbon transfer to the steel surface.

The gradual increase in hardness from 45 to 85 minutes suggests that carbon diffusion had not reached saturation within the examined time range. These findings are consistent with diffusion-controlled carburizing theory and previous studies reporting a direct relationship between holding time and surface hardness in low-carbon steels.

4.2. Relationship Between Hardness and Wear Resistance

The observed reduction in wear rate with increasing holding time is closely related to the increase in surface hardness. A harder surface layer reduces plastic deformation and micro-cutting during sliding contact, which are primary mechanisms of wear in low-carbon steels. As the case hardness increases, the material becomes more resistant to adhesive and abrasive wear mechanisms [14].

At the longest holding time of 85 minutes, the formation of a thicker and harder carburized layer provides superior resistance to material removal, resulting in the lowest wear rate. This strong inverse relationship between hardness and wear rate confirms that pack carburizing using bamboo charcoal is effective in improving tribological performance. The results align with established tribology principles, where increased hardness generally leads to improved wear resistance under dry sliding conditions.

4.3. Effect of Holding Time on Impact Toughness

In contrast to hardness and wear resistance, impact strength decreased with increasing holding time. This behavior is primarily due to the formation of a hardened surface layer with reduced ductility. As holding time increases, the carburized layer becomes thicker and richer in carbon, which promotes martensite formation during quenching. While martensite significantly increases hardness, it also introduces brittleness [15].

Although tempering was applied to reduce internal stresses, the high carbon content in the surface layer still limits the ability of the material to absorb impact energy. Under impact loading, cracks are more likely to initiate and propagate through the brittle carburized layer, resulting in lower absorbed energy. This trade-off between hardness and toughness is a well-known consequence of surface hardening treatments and must be carefully considered in component design.

4.4. Optimization of Holding Time for Engineering Applications

From an application perspective, the results suggest that an 85-minute holding time provides the highest hardness and wear resistance, making it suitable for components subjected to severe surface contact and friction, such as gears and shafts. However, the accompanying reduction in impact toughness indicates that this condition may not be ideal for applications involving high shock or impact loads [16].

Therefore, the selection of holding time should be based on the specific service requirements of the component. For applications requiring a balance between wear resistance and toughness, intermediate holding times such as 65 minutes may offer a more favorable compromise. These findings highlight the importance of optimizing carburizing parameters to achieve desired mechanical performance.

4.5. Microstructural Interpretation: Carbon Diffusion, Martensite Formation, and Cementite (Fe_3C)

The changes in mechanical properties observed in this study are closely associated with microstructural transformations occurring during the pack carburizing, quenching, and tempering processes. At the carburizing temperature of 850 °C, ST 41 steel exists in the austenitic phase, which has a high solubility for carbon. Carbon atoms generated from the bamboo charcoal medium diffuse into the steel surface through interstitial mechanisms, resulting in a carbon concentration gradient from the surface toward the core [17].

As holding time increases, the diffusion depth of carbon also increases, leading to the formation of a thicker carburized case layer.

This behavior follows Fick's second law of diffusion, where diffusion depth is proportional to the square root of time. Therefore, specimens treated for 85 minutes are expected to exhibit a deeper and more carbon-rich case layer compared to those treated for 45 and 65 minutes. During quenching in oil, the carbon-enriched austenite near the surface transforms into martensite, a supersaturated body-centered tetragonal (BCT) phase characterized by high hardness and strength. The increased carbon content in the surface layer enhances lattice distortion in martensite, which explains the progressive increase in hardness with longer holding times. In contrast, the core region, with lower carbon content, predominantly transforms into ferrite and pearlite, maintaining sufficient ductility and toughness [18].

In addition to martensite formation, the presence of cementite (Fe_3C) is expected in the carburized layer, particularly at higher holding times. Increased carbon concentration promotes carbide precipitation along prior austenite grain boundaries and within martensitic laths during cooling and subsequent tempering. The formation of Fe_3C contributes to increased hardness and wear resistance by acting as a hard reinforcing phase that resists plastic deformation and abrasive wear [19].

The improved wear resistance observed at longer holding times can therefore be attributed to the combined effects of a harder martensitic matrix and dispersed cementite particles. This microstructural combination effectively reduces adhesive wear and limits micro-ploughing during sliding contact. The thicker diffusion layer formed at longer holding times also ensures that the hardened surface remains effective throughout the wear test, preventing rapid exposure of the softer core material [20].

However, the same microstructural features that enhance hardness and wear resistance also lead to a reduction in impact toughness. The high carbon martensite and cementite-rich surface layer exhibit limited plastic deformation capability, making the material more susceptible to crack initiation under impact loading. Cracks tend to initiate at the brittle carburized layer and propagate rapidly, resulting in lower absorbed impact energy. Although tempering at 350 °C reduces internal stresses and partially relieves brittleness, it does not fully compensate for the increased carbon content associated with longer holding times.

5. Conclusions

This study investigated the effect of holding time in the pack carburizing process using bamboo charcoal on the mechanical properties of ST 41 steel. Based on the results of hardness, wear, and impact testing, as well as the microstructural interpretation, the following conclusions can be drawn:

1. Pack carburizing significantly increased the surface hardness of ST 41 steel, and the hardness improvement was strongly influenced by holding time. The average hardness increased from 162.0 VHN for untreated material to 175.2 VHN, 185.5 VHN, and 196.5 VHN at holding times of 45, 65, and 85 minutes, respectively. This increase is attributed to enhanced carbon diffusion and the formation of a martensitic and carbide-rich surface layer.
2. The wear resistance of ST 41 steel improved markedly after carburizing. The wear rate decreased continuously with increasing holding time, reaching the lowest value of 0.000029 $mm^3/kg \cdot m$ at 85 minutes. The improvement in wear resistance is closely related to the increased surface hardness, the formation of martensite, and the presence of cementite (Fe_3C), which collectively reduce plastic deformation and material removal during sliding contact.
3. In contrast to hardness and wear resistance, the impact toughness of ST 41 steel decreased with increasing holding time. The impact strength dropped from 3.302 J/mm^2 for untreated steel to 2.934 J/mm^2 at a holding time of 85 minutes. This reduction is caused by the increased brittleness of the carburized surface layer resulting from high carbon martensite and carbide precipitation, despite the application of tempering.
4. The mechanical behavior of carburized ST 41 steel is governed by a gradient microstructure consisting of a hard, martensitic and cementite-rich surface layer

and a tougher ferrite–pearlite core. Longer holding times produce a deeper diffusion layer and higher carbon concentration, which enhances surface-related properties but reduces toughness. Among the conditions studied, a holding time of 85 minutes provides the highest hardness and wear resistance, making it suitable for applications dominated by surface wear, such as gear components. However, for applications requiring a balance between wear resistance and impact toughness, intermediate holding times may be more appropriate.

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