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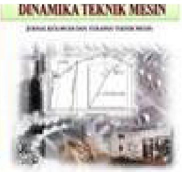

Effect of solid carburizing process using natural catalysts on the wear resistance ofAISI 1018 steel

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ABSTRACT

Low carbon steel AISI 1018 is extensively used in agricultural and mechanical components owing to its good formability and weld ability; however, its low surface hardness restricts its wear performance. Solid carburizing is a well-established surface hardening technique to address this limitation, while the utilization of natural catalysts derived from local biomass presents a sustainable and cost-effective alternative to conventional chemical activators. This study examines the effect of solid carburizing using natural catalysts broiler chicken bone powder, laying hen bone powder, and duck bone powder on the wear resistance of AISI 1018 steel. Carburizing treatments were performed using teak charcoal as the carbon source, mixed with the natural catalysts, at 900 °C for 1, 1.5, 2, and 3 h, *followed by rapid cooling to induce surface hardening. The treated specimens were evaluated through hardness measurements and dry sliding wear tests, complemented by microstructural analyses to assess surface morphology and effective case depth. The results reveal a pronounced increase in surface hardness and a significant improvement in wear resistance compared with untreated steel. These improvements are associated with enhanced carbon diffusion and the formation of a martensitic carburized layer after quenching. Overall, the findings demonstrate that solid carburizing assisted by natural catalysts is an effective approach to improving the wear resistance of AISI 1018 steel, offering a sustainable and economically viable surface modification route for low carbon steel employed in agricultural and engineering applications.*

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1. INTRODUCTION

The material low carbon steels such as AISI 1018 are extensively used in agricultural and mechanical components due to their good formability, weld ability, and low production cost, Callisterand and Rethwisch

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(2020). These advantages make AISI 1018 suitable for structural frames, shafts, and soil engaging components in agricultural machinery. However, the low carbon content of this steel inherently limits its surface hardness and wear resistance, resulting in accelerated surface degradation and reduced service life under abrasive and sliding contact conditions, Wong and Tung (2016). Improving surface wear performance while maintaining a tough and ductile core therefore remains a key requirement for low-carbon steel applications.

Various surface engineering techniques have been applied to enhance the wear resistance of low-carbon steels, including carburizing, nitriding, boriding, and hardfacing, Bolton and Higgins (2020). Among these methods, solid carburizing (pack carburizing) remains attractive due to its simplicity, low equipment cost, and suitability for small and medium scale manufacturing, Zhang et al. (2018). Previous studies have demonstrated that solid carburizing using conventional chemical activators, such as barium carbonate ($BaCO_3$) and sodium carbonate (Na_2CO_3), effectively increases surface hardness and wear resistance through enhanced carbon diffusion and martensitic transformation after quenching, Masoumi et al. (2019). Nevertheless, these chemical activators pose environmental and health concerns, motivating the search for safer and more sustainable alternatives.

Recent developments in surface engineering have emphasized the use of biomass-derived materials as carbon sources and activators in solid carburizing processes. Charcoal from coconut shells, palm shells, and wood has been reported to provide effective carbon enrichment while reducing environmental impact (Pratama et al., 2019; Siregar et al., 2021). In parallel, calcium rich waste materials, particularly animal bone powders, have attracted attention as natural catalysts due to their ability to promote CO generation during carburizing reactions (Hidayat et al., 2022; Rahman et al. ,2020). This approach represents the current state of the art in eco-friendly carburizing technology.

Despite these advancements, systematic and comparative studies on the influence of different poultry bone powders as natural catalysts on the wear resistance and carburized layer characteristics of AISI 1018 steel remain limited. In particular, the effects of broiler chicken, laying hen, and duck bone powders under identical carburizing conditions have not been comprehensively reported. This study addresses this research gap by evaluating the wear behavior, hardness, and microstructural evolution of AISI 1018 steel subjected to solid carburizing using various poultry bone-derived catalysts, contributing to the development of sustainable surface hardening strategies for agricultural and engineering applications.

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2. RESEARCH METHODS

The base material used in this study was low carbon steel AISI 1018. Specimens were machined to the required dimensions for hardness, wear, and microstructural characterization. Prior to carburizing, all specimens were ground using silicon carbide papers (grit 240–1200) and ultrasonically cleaned in ethanol. Teak wood charcoal was used as the carbon source. Natural catalysts were prepared from broiler chicken bones, laying hen bones, and duck bones. The bones were washed, dried at 110 °C for 24 h, calcined at 800 °C for 2 h, and milled and sieved to obtain powder with particle sizes below 100 µm.

Table 1. The chemical composition and mechanical properties of specimen

Content	Specification
Carbon (C)	0.15 – 0.20 %
Iron, (Fe)	98.0 %
Manganese,, (Mn)	0.60 – 0.90 %
Phosphorous, (P)	≤ 0.040 %
Sulfur, (S)	≤ 0.050 %
Tensile Strength, Ultimate	370 – 440 MPa
Tensile Strength, Yield	205 – 250MPa
Elongation at Break (in 50 mm)	5 – 25 %
Modulus of Elasticity	200 GPa
Bulk Modulus (typical for steel)	140 GPa
Poissons Ratio	0.29
Shear Modulus	79.3 GPa

The research steps and equipment used, as shawn in Figure 1. Solid carburizing was carried out using the pack carburizing method. The carburizing mixture consisted of teak charcoal mixed with natural catalysts at a fixed weight ratio. The specimens were embedded in the mixture and sealed in a low carbon steel container (carburizing box) to minimize oxidation. Carburizing was performed in an electric furnace at 900 °C, soaking time variations for 1, 1.5, 2, and 3 h, with temperature controlled using a calibrated thermocouple. After carburizing, the specimens were immediately quenched in water at room temperature to induce martensitic transformation in the carburized layer.

Surface hardness was measured using a Vickers hardness tester in accordance with ASTM E92 with a load of 500 g and a dwell time of 10 s, while wear resistance was evaluated using a dry sliding pin-on-disk test following ASTM G99, with wear rate determined from mass loss measurements using a precision balance. Microstructural observations were conducted using optical microscopy to examine surface morphology and effective case depth after etching with 2% nital, complemented by scanning electron microscopy (SEM) and all experimental results were averaged and comparatively analyzed to assess the effect of different natural catalysts on the wear resistance and surface characteristics of AISI 1018 steel.

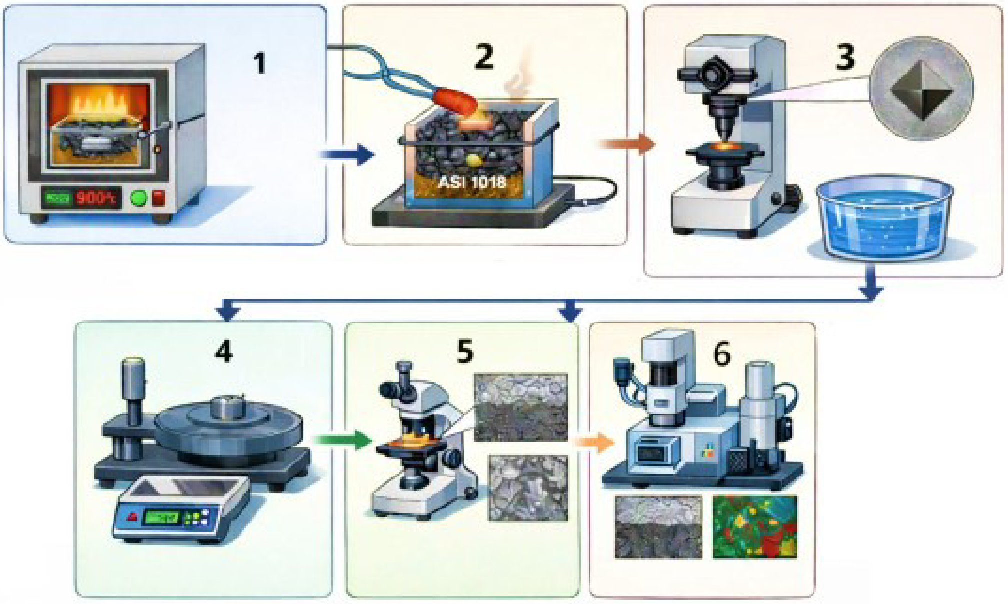

Figure 1.The research steps and equipment used. 1. Pack carburizing, 2. quenching, 3. surface hardness testing, 4. wear testing, 5. microstructure analysis, 6. SEM-EDS analysis

The solid carburizing treatment using natural catalysts resulted in a noticeable modification of the surface hardness, wear resistance, microstructural characteristics of AISI 1018 steel. The results Figure 2 presents the surface hardness values of untreated and carburized AISI 1018 steel treated using different natural catalysts. The untreated specimen exhibited the lowest hardness, reflecting the ferritic–pearlitic microstructure typical of low-carbon steel. All carburized specimens showed a pronounced increase in surface hardness, confirming the effectiveness of the solid carburizing process. Specimens treated with poultry bone-derived catalysts demonstrated higher hardness compared to the untreated steel, indicating improved carbon diffusion during carburizing. Differences in hardness among broiler chicken, laying hen, and duck bone catalysts suggest variations in catalytic activity, which may be associated with differences in calcium-based compound content. The increased hardness is primarily attributed to carbon enrichment at the surface and subsequent martensitic transformation induced by quenching, consistent with previous reports on pack carburized low-carbon steels.

The Figure 2 shows that an increase in soaking time consistently increases surface hardness under all treatment conditions. In specimens without catalysts, the increase in hardness was relatively slow because carbon diffusion was limited by the low carbon activity in the carburizing medium. In contrast, specimens with natural catalysts showed a more significant increase in hardness as the soaking time increased, indicating the role of catalysts in accelerating the formation of active carbon gas and increasing the rate of carbon diffusion to the steel surface. Among all variations, laying hen bone catalyst produced the highest hardness values at every soaking time, particularly at 2–3 hours, indicating more stable catalytic effectiveness over longer heating times. Broiler chicken bone and duck bone catalysts also significantly increased hardness compared to no catalyst, but at a more moderate rate of increase. This trend is consistent with the time-controlled carbon diffusion mechanism, where longer holding times allow for the formation of a thicker and more homogeneous martensite layer after quenching.

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The results indicate that surface hardness increases consistently with increasing soaking time for all treatment conditions. In the specimen without catalyst, the hardness increase is relatively limited, rising from approximately 240 HV at 1 h to 350 HV at 3 h. This behavior suggests restricted carbon diffusion due to the low rate of active carbon gas formation during the pack carburizing process in the absence of a catalyst.

In contrast, the addition of animal bone based catalysts (naturalcatalysts) significantly enhances surface hardness. The laying hen bone catalyst produces the highest hardness values at all soaking times, reaching approximately 530 HV at 3 h, followed by the broiler bone catalyst (500 HV) and the duck bone catalyst (470 HV). This improvement is associated with the presence of CaO and calcium phosphate compounds in animal bones, which act as catalysts in the generation of CO gas, thereby accelerating the transfer of active carbon to the steel surface, in accordance with the results of the study, Callister and Rethwisch (2020).

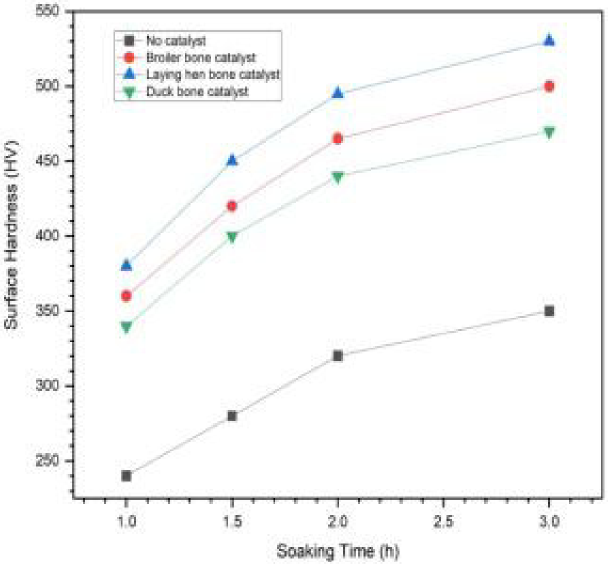


Figure 2. Effect of natural catalysts on surface hardness

The variation in hardness among different natural catalysts indicates that mineral composition, surface area, and porosity play critical roles in determining catalytic effectiveness. Laying hen bones are presumed to possess a more reactive and thermally stable structure under carburizing conditions, enabling a higher and more sustained carbon diffusion rate compared to broiler and duck bone, Alaneme and Bodunrin (2013).

Furthermore, the tendency for hardness improvement to level off beyond 2 h of soaking time suggests that the process approaches carbon saturation at the surface layer. Under this condition, further increases in soaking time contribute only marginally to hardness enhancement due to the reduced carbon concentration gradient between the surface and the core material.

Overall, these findings confirm that animal bone–derived catalysts, originating from organic waste materials, are effective in enhancing the performance of the pack carburizing process. Their utilization not only improves surface mechanical properties but also supports environmentally friendly and sustainable manufacturing practices through the valorization of local bio-waste resources, Odusote et al. (2012).

The wear performance of untreated and carburized specimens is summarized in Figure 3, which show the wear rate obtained from dry sliding pin-on-disk tests. Untreated AISI 1018 steel exhibited the highest wear rate, indicating poor resistance to material removal under sliding contact. In contrast, all carburized specimens demonstrated a substantial reduction in wear rate. The improvement in wear resistance closely correlates with the increased surface hardness, as a harder surface is more resistant to plastic deformation and adhesive wear. Among the carburized specimens, those treated with poultry bone catalysts showed lower wear rates, suggesting that the enhanced carburized layer provided better protection against surface damage. These results confirm that solid carburizing using natural catalysts effectively improves the tribological performance of AISI 1018 steel.

The wear rate results reveal a consistent reduction with increasing soaking time for all treatment conditions, indicating progressive improvement in surface tribological performance as the carburizing duration increases. The specimen without catalyst exhibits the highest wear rate throughout the soaking time range, decreasing from approximately 5.8×10^{-5} $mm^3/N \cdot m$ at 1 h to 3.2×10^{-5} $mm^3/N \cdot m$ at 3 h. This relatively high wear rate is attributed to limited carbon diffusion and insufficient surface hardening when pack carburizing is performed without catalytic assistance, (Davis, 2017; Totten and Howes, 2016).

The incorporation of animal bone based catalysts significantly enhances wear resistance, as evidenced by the markedly lower wear rates compared to the non-catalyzed condition. Among the catalysts, the broiler bone catalyst demonstrates the best tribological performance, followed by the laying hen bone catalyst and the duck bone catalyst. At a soaking time of 3 h, the wear rate decreases to approximately 1.4 $\times 10^{-5}$ mm³/N·m for broiler bone, compared with 1.7 $\times 10^{-5}$ mm³/N·m and 1.9 $\times 10^{-5}$ mm³/N·m for laying hen and duck bone catalysts, respectively. This improvement is mainly associated with the formation of a harder and more uniform carburized layer promoted by catalytic enhancement of carbon transfer reactions, Alaneme et al. (2018).

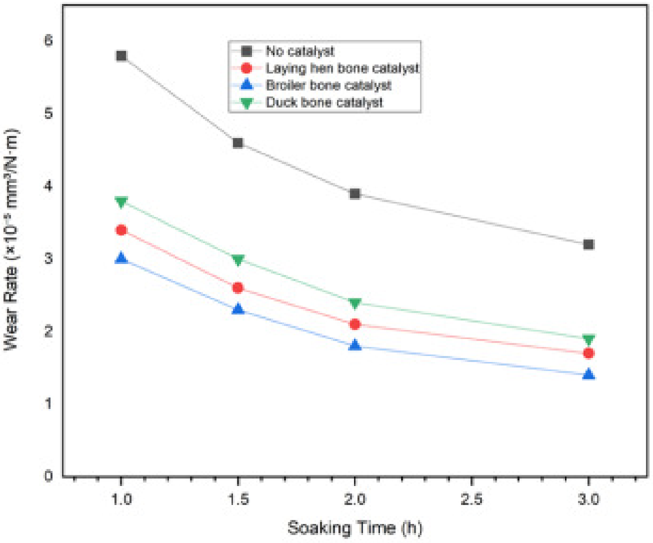


Figure 3. Effect of natural catalysts on wear rate of AISI 1018 steel carburized

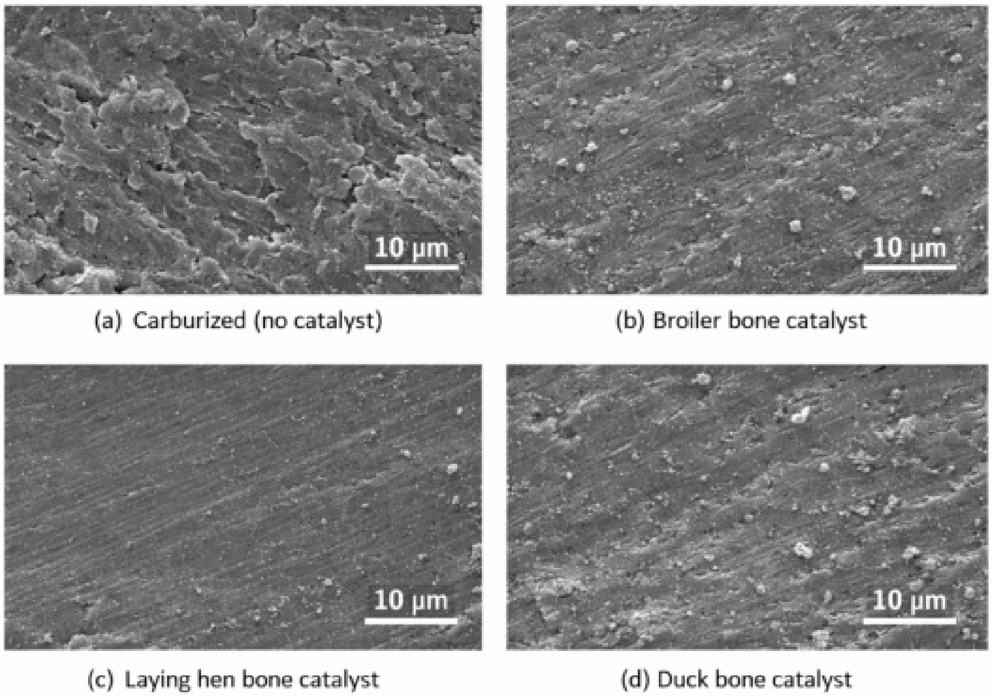
The variation in wear behavior among the different bone catalysts suggests that catalytic efficiency is strongly influenced by mineral composition, CaO content, and pore structure. Bones with higher calcium-based phases and suitable porosity facilitate sustained CO generation during carburizing, leading to higher carbon uptake and improved surface integrity, Odusote et al. (2018). Consequently, surfaces treated with more effective catalysts exhibit lower material removal under sliding conditions.

Moreover, the gradual reduction in wear rate with increasing soaking time indicates enhanced carbon saturation and surface densification, which suppress adhesive and abrasive wear mechanisms. Nevertheless, the diminishing rate of improvement at longer soaking times suggests that the carburized layer approaches a saturation limit, beyond which further soaking yields only marginal tribological benefits, Holmberg et al. (2017).
Overall, the observed wear rate trends are consistent with the corresponding surface hardness results, confirming an inverse relationship between hardness and wear rate. These findings demonstrate that bone-derived catalysts from bio-waste materials are effective in improving the tribological performance of carburized steel while supporting environmentally sustainable surface engineering practices.

Optical micrographs of the carburized specimens, shown in Figure 4, reveal the formation of a distinct hardened surface layer with a gradual transition to the softer core material. The effective case depth varied slightly depending on the type of natural catalyst used, supporting the observed differences in hardness and wear resistance. SEM images (Figure 4) illustrate a refined surface microstructure in carburized specimens, with reduced evidence of plastic deformation compared to untreated steel. EDS analysis qualitatively confirmed increased carbon concentration in the near-surface region, indicating successful carbon diffusion during the carburizing process. Furthermore, XRD patterns (Figure 4) identified martensitic phases in carburized specimens after quenching, while untreated steel showed predominantly ferritic pearlitic phases. The presence of martensite, combined with carbon enrichment, explains the enhanced hardness and wear resistance achieved through solid carburizing assisted by natural catalysts.

The SEM image shows the morphological differences on the surface of AISI 1018 after the solid carburising process with and without natural catalysts. In the carburised specimen without catalyst (a), the surface appears rough and inhomogeneous, characterised by microcracks, peeling layers, and uneven carbon particle agglomeration. This condition indicates ineffective carbon diffusion, resulting in an unevenly formed carburization layer that is susceptible to adhesive and abrasive wear mechanisms. Specimens with broiler chicken bone catalyst (b) show improved surface morphology compared to those without catalyst. The surface is relatively more homogeneous with more regular friction marks, although there are still residual particles and fine debris. This indicates that the broiler bone catalyst is capable of increasing carbon activity, but carbon distribution is not yet fully optimal.

In specimens with laying hen bone catalyst (c), the surface appears the smoothest and most uniform, with minimal cracks and debris. Smooth and continuous friction traces indicate the formation of a more homogeneous and stable martensite layer. This morphology correlates directly with increased surface hardness and the highest wear resistance, as shown by the hardness and wear test results.



(a) Carburized (no catalyst) (b) Broiler bone catalyst

(c) Laying hen bone catalyst (d) Duck bone catalyst

Figure 4. Effect of natural catalysts on microstructural characteristics of AISI 1018 steel carburized

4. CONCLUSION

The results confirm that natural catalysts significantly enhance surface hardness and wear resistance in the pack carburizing of low-carbon steel, AISI 1018. Increasing soaking time improves surface performance for all conditions; however, specimens without catalysts show the lowest hardness and highest wear rate. Among the catalysts, laying hen bone powder catalyst produces the highest hardness, while broiler bone powder catalyst yields the lowest wear rate, demonstrating superior tribological behavior. SEM micrographs reveal smoother and more uniform surfaces for catalyzed specimens, correlating with reduced wear resistance. Overall, natural catalyst derived catalysts effectively promote carbon diffusion and offer a sustainable, eco-friendly alternative for improving carburized steel surfaces.

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