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Low-carbon steel fatigue behavior after pack carburizing with buffalo bone charcoal and barium carbonate media

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Abstract

The pack carburizing method is a technique that can be employed to enhance the surface hardness of Low-Carbon Steel (LCS). This method can potentially improve the hardness of the material while maintaining its strength. This study aims to investigate how different carburizing media, specifically varying percentages of Buffalo Bone Charcoal (BBC) powder as a carbon source, impact the mechanical properties of LCS. The temperature in the carburizing process ranges from 850°C and 950°C while maintaining a holding time of 2 hours. The carbon derived from buffalo bone charcoal is finely ground and mixed with barium carbonate (BaCO_3) as the energizer during this process. This study used different ratios of BBC powder and BaCO_3 as carburizing mediums. The ratios tested were 60% BBC + 40% BaCO_3 , 70% BBC + 30% BaCO_3 , and 80% BBC + 20% BaCO_3 , based on the weight of the BBC powder used in the carburizing process. The steel will be combined with BaCO_3 and powdered BBC for this research. Next, the fatigue test was examined. BBC in the pack carburizing process increases LCS carbon content by 0.735% from 0.268%. This change alters the steel's microstructure, possibly increasing its hardness and wear resistance. The direct link between BBC concentration and LCS carbon enrichment shows the process's efficiency. Pack carburizing also improves LCS fatigue strength. This improvement is due to higher BBC concentration, smaller carburizing medium particles, and higher processing temperatures. After carburizing, the LCS can resist 36,625 to 61,435 cycles.

Keywords:

Low carbon steel, buffalo bone charcoal, mechanical properties, high temperature.

1 Introduction

Steel is the most widely used metal in engineering and manufacturing, demonstrating its versatility and strength. Steel, mainly iron, has unique qualities due to its 0.2% to 2.1% carbon content. Sulfur, phosphorus, silicon, and manganese (Mn) are contained in small amounts and carbon in steel [1]. These additional constituents shape the steel's ultimate properties, improving its performance in specific applications.

Steel is divided by carbon concentration into low, medium, and high carbon steel [2]. Softer than hard steel, low-carbon steel (mild steel or tool steel) contains less than 0.3% carbon. Soft and workable, it's famous for many purposes. Medium carbon steel (0.3%–0.6%) balances strength and ductility. Heat treatments can partially harden it, expanding its uses. High-carbon steel, produced by hot grinding, has 0.6%–1.5% carbon [3]. Its high

carbon content makes it strong and hard, making it appropriate for resilient applications. Because of its hardness, high-carbon steel requires specific handling and processing.

Carbon steel is used in many industrial applications due to its good mechanical qualities, although its hardness and wear resistance are low. The reduced hardness of low-carbon steel makes it wear down quickly, resulting in a shorter lifespan under repeated or dynamic loads [4]. Material engineering can improve low-carbon steel performance in harsher environments. The pack carburizing process is particularly successful. This heat treatment involves enveloping the steel workpiece with charcoal or carbon-bearing chemicals and heating it to a temperature where carbon atoms can permeate its surface. Carbon atoms from the surrounding material diffuse into the steel during pack carburizing, enriching its outer layers. A gradient in carbon content emerges, with the largest concentration at the surface and decreasing towards the core. This carbon enrichment increases the surface hardness of low-carbon steel, improving its wear and mechanical stress resistance [5].

Tensile strength, toughness, ductility, hardness, elasticity, and plasticity affect its performance under diverse conditions. Manufacturers and engineers may easily use steel because of its vast availability in plates, sheets, pipes, rods, and profiles and low cost. Hardness and toughness are essential in machine construction and part design, especially for sliding or rubbing. These parts must endure wear, friction, and heavy loads, whether continuous or fluctuating. This dual criterion requires a material with a hard, wear-resistant surface and a robust, ductile core to ensure resilience under stress, especially in repeated or dynamic loading [6]. These components regularly experience static, dynamic, and shock loads, which can cause cracks or fractures.

Interestingly, most fatigue fractures are caused by stress, even at stress levels less than one-third of the material's static tensile strength, especially in structural materials lacking stress concentrations. Misalignment or centering difficulties can cause material failure at lower stress levels. Thus, understanding and controlling these aspects is essential to minimizing early material breakdown and maintaining structural or component longevity and reliability [6].

Fatigue failure is a significant issue in materials science and engineering since it refers to the tendency of materials to fracture and break when subjected to repeated, cyclic stress. Surprisingly, these pressures are far less than what the material would typically experience before reaching its elastic strength limit. Fatigue is a common cause of damage and failures in components of buildings or machinery. These failures frequently occur without any preceding indications, presenting significant hazards to user well-being and resulting in enormous financial burdens. Indeed, it is approximated that fatigue failure is responsible for a minimum of 90% of all failures linked to mechanics [7].

Dynamic loading, where forces continually change and are cyclical, makes machine components prone to fatigue failure. The material can often fail at stress values far lower than those needed to fracture in a single static load application [8]. This discrepancy shows the insidious nature of fatigue failure and the necessity for proactive fatigue resistance improvements in such materials. Carburizing or pack carburizing can improve metal mechanical characteristics and fatigue resistance. Carbon is added to the metal's surface layers to harden it while keeping the core flexible and resilient. This makes the material more resistant to fatigue failure under repetitive, cyclic pressures. Fatigue cracks often start with stress concentrators like notches or sharp edges, whereas the carburized layer equally distributes stress over the material. Doing so increases the material's fatigue strength, extending its service life and improving reliability in demanding applications.

The process of carburizing is a crucial heat treatment method in metallurgy. Its main objective is to modify metals' physical and mechanical properties to meet specific application requirements

better and improve overall performance. Throughout this process, the metal undergoes a sequence of heating and cooling cycles within the solid phase, allowing for the alteration of its internal structure. This precise thermal treatment method can reduce internal stresses, alter grain size, enhance toughness, and form a hardened surface layer surrounding a flexible core. The cooling rate heavily influences the final structure of the metal. If the material is cooled rapidly beyond a critical rate, it will have a harder structure. On the other hand, slower cooling will result in a softer material [9].

Pack carburizing is a form of carbon monoxide from solid compound disintegration interacting with the metal surface to make new carbon and carbon dioxide [10]. This procedure uses a heat-resistant iron box and activated carbon to harden the material's surface. The pack carburizing method requires a carbonate (CO_3) is preferred since it accelerates the reaction as an activator. At the start of pack carburizing, the steel surface's maximum saturation limit of carbon can reach 1.2 %C, creating a large carbon gradient from surface to core. The pack carburizing process works better under these operational conditions' exact control and optimization [11]. Material scientists and engineers can modify metal characteristics to satisfy rigorous industrial applications by knowing and mastering heat treatment procedures. Enhanced surface hardness from carburizing and pack carburizing increases wear resistance, strength, and durability. This balance between surface hardness and core ductility allows the material to withstand cyclic and dynamic stress, reducing fatigue failure risk.

In his groundbreaking material science research, Bahtiar [2] investigated pack carburizing on medium carbon steel using cow bone as an energizer. This study was driven by a comprehensive experimental setup that tested 40%:60%, 30%:70%, and 25%:75% beef bone charcoal and CaCO_3 at 850°C, 900°C, and 950°C for 8 hours. This study sheds light on cow bone charcoal's carburizing properties. The study showed that steel characteristics changed at 40% cow bone charcoal. Cow bone charcoal improved surface hardness up to 0.2 mm, with a hardness value of 780 HV. At 4 mm depth, the hardness was 294 HV, suggesting a progressive reduction but still quite high hardness compared to untreated steel. A 30% concentration of cow bone charcoal gave the steel's surface a hardness of 750 HV at 0.2 mm and 283 HV at 4 mm. In addition, at 25% cow bone charcoal, the surface hardness was 700 HV and decreased to 216 HV at a depth of 4 mm.

The research [4] focused on optimizing nickel electroplating on low-carbon steel to enhance corrosion resistance, evaluated through immersion corrosion tests with a 3.5% NaCl solution. Various electroplating parameters, including plating time and coating thickness, were investigated to determine their impact on the corrosion resistance of low-carbon steel. Results indicated significant effects of specific parameters, such as plating time and coating thickness, on the corrosion resistance of low-carbon steel. By optimizing these parameters, a nickel coating with improved corrosion resistance was achieved, as evidenced by immersion corrosion tests with the 3.5% NaCl solution. This research contributes valuable insights into developing nickel electroplating techniques to enhance corrosion resistance in low-carbon steel materials.

The study [6] examines how buffalo bone charcoal pack carburizing affects the mechanical properties of carbon steel. This detailed study examines how pack carburizing with buffalo bone charcoal affects the mechanical characteristics of carbon steel. This study shows that pack carburizing with buffalo bone charcoal changes carbon steel's mechanical properties, particularly surface hardness and toughness. Temperature and processing length affect pack carburizing results, which are intriguing. This meticulous research illuminates the complex effects of pack carburizing with buffalo bone charcoal on carbon steel's mechanical properties. It highlights its crucial role in improving heat treatment methods for carbon steel performance and resilience.

The importance of mechanical qualities, including hardness, toughness, and tensile strength, influence steel's performance under diverse environments. In machine construction, where hardness and toughness are crucial for withstanding wear, friction, and severe loads, it highlights the importance of steel in production due to its widespread availability and cost-effectiveness. Carburizing and pack carburizing are proactive procedures that might increase fatigue resistance. The paragraph highlights the significance of fatigue failure and how common it is in materials science and engineering. It explains how carburizing works and how it can change metal properties to fit a certain purpose while improving performance in general. It also notes Bahtiar's work on pack carburizing with cow bone as an energizer, drawing attention to the conclusion of the research on how higher concentrations of bone charcoal affected steel properties and how surface hardness was improved.

2 Research Methods

In this comprehensive study, the researchers used solid low-carbon steel, a material known for its exceptional ductility, malleability, and affordable price. Fig. 1 presents a comprehensive illustration of the as-received material, providing valuable information about its original structure and properties. Low carbon steel was selected for its exceptional blend of characteristics that render it well-suited for various uses, such as construction materials, automotive components, and various types of machinery. This particular steel variant has a carbon content ranging from 0.05% to 0.25%, enhancing softness and workability. Despite its lower strength than higher carbon, low carbon steel can still provide sufficient mechanical properties for numerous applications, making it a versatile and widely used option in engineering.

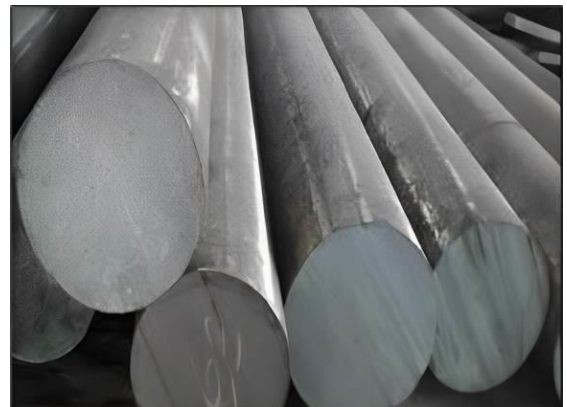


Fig. 1. Low carbon steel.

After deciding on low-carbon steel, the next critical stage were: processing the raw material into fatigue test specimens with the utmost precision and accuracy. Because the results of the fatigue tests would be significantly affected by even small variations from the prescribed dimensions, the manufacture of these specimens was carried out with extreme precision. Fig. 2 was based on literature review that provides an in-depth breakdown of the required dimensions and specifications for the test specimens. The researchers used this diagram as a guide to ensure that all test samples were the same size and shape. Because of the direct relationship between meeting these requirements and the accuracy and credibility of the test results, they must be strictly enforced.

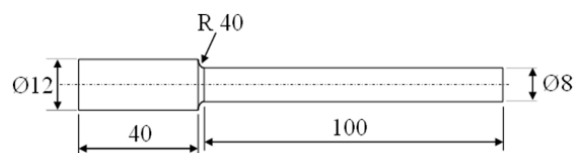


Fig. 2. Dimension specimen of fatigue testing.

Fig. 3 in the study documentation presents a comprehensive visual depiction of the final fatigue test specimen, precisely capturing its geometry and dimensions. This visual aid is essential for verifying that the specimens align with the predetermined standards. The geometry of the fatigue test specimens plays a crucial role in ensuring the precise execution of fatigue tests. The shape and dimensions of the samples have a crucial impact on how the material reacts to cyclic loading. These factors influence stress concentration and the onset of fatigue cracks. A solid foundation for obtaining accurate and consistent data from the fatigue tests through meticulous attention to detail in ensuring the specimens adhere to the specified geometry was implemented.



Fig. 3. Spesimen fatigue testing.

In the carburizing pack process, buffalo bone was chosen as the carburizing agent. The utilization of buffalo bone showcases a forward-thinking approach, as it offers a sustainable and economically viable substitute for conventional carburizing materials. The buffalo bone underwent a meticulous preparation process to guarantee its efficiency in the carburizing pack. Fig. 4(a) in the study documentation presents a visual depiction of the buffalo bone before undergoing any processing. This initial portrayal provides a comprehensive grasp of the material's inherent condition, acting as a reference point for any subsequent alterations or adjustments that may arise during the preparation procedure.

Afterward, the buffalo bone went through a carbonization process to convert it into charcoal, an essential step in preparing the carburizing agent. The process was carried out in a highly controlled environment to guarantee the complete conversion of the buffalo bone into charcoal. The final product is depicted in Fig. 4(b) of the study documentation. Using the charcoal form of the buffalo bone is crucial for achieving a consistent and efficient distribution of carbon during the carburizing pack process. Alongside the buffalo bone charcoal, the activator chosen for the carburizing pack process was barium carbonate (BaCO_3). The activator plays a crucial role in facilitating the release of carbon from the buffalo bone charcoal, ensuring that the carbon is easily accessible to penetrate the surface of the low-carbon steel specimens. Fig. 4(c) in the study documentation presents a visual representation of the barium carbonate used, effectively illustrating this important component's physical characteristics.

After meticulously fabricating fatigue test specimens from low-carbon steel, the study focused on pack carburizing to improve their surface qualities. This phase was significant since it increased the material's surface hardness and wear resistance to improve cyclic loading performance. Pack carburizing begins with meticulous specimen placement in a sturdy steel box. This stage required precision to expose each specimen to the carburizing chemical uniformly. Following the experimental design, Buffalo Bone Charcoal (BBC) grains were evenly scattered over the

specimens. This mixture was the carburizing medium, and barium carbonate activated carbon release and penetration into steel. The study investigated several mixing ratios to find the best composition for surface attributes. Buffalo bone charcoal to barium carbonate ratios of 80%:20%, 70%:30%, and 60%:40% were examined to determine how varying proportions affect carburizing.

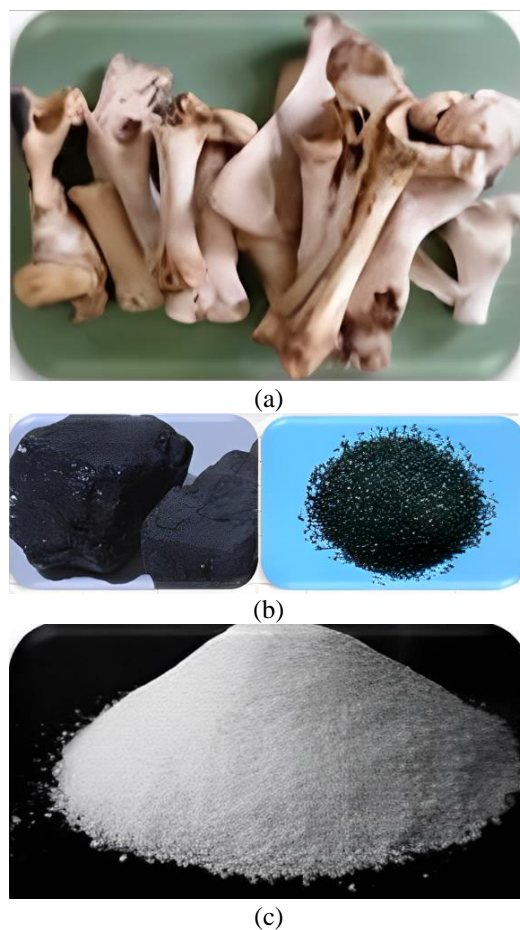
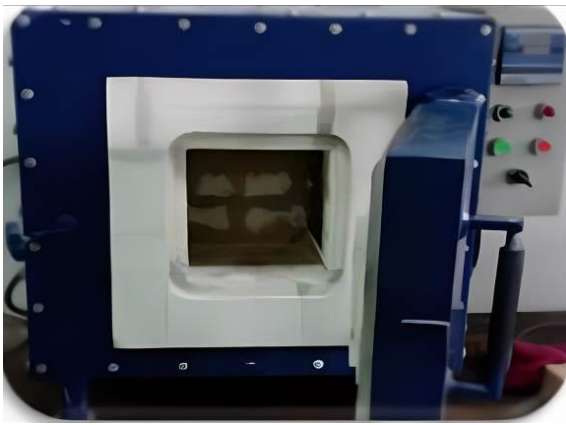


Fig. 4. (a) Low carbon steel, (b) buffalo bone charcoal and (c) BaCO_3 .

Buffalo bone charcoal grain size was considered because it may affect carburizing. Mesh 20 and 40 were utilized in the trials to show how grain size impacts carbon distribution and penetration. The specimens and carburizing medium were carefully placed in the steel box, and any holes were filled with clay to produce a vacuum. This step was essential to keep external air and impurities out and manage the carburizing process. Fig. 5(a) in the study paperwork shows the furnace setup and steel box contents. The carburizing procedure was done at 850°C and 950°C for 2 hours to allow the carbon to enter the steel surface. Normalization cooling was used after carburizing to reduce internal tensions and stabilize the microstructure.

After completing the composition test on all the specimens, the researchers proceeded to the next crucial phase of the study: the fatigue failure test. This test is vital for assessing the material's resistance to fatigue and gaining insights into how the pack carburizing process may have improved the steel's endurance under cyclic loading. The fatigue failure test was performed using specialized equipment, as shown in Fig. 5(b) of the study documentation. This image is intended to offer readers a visual representation of the testing setup, promoting transparency and facilitating the reproducibility of the results. The equipment has been meticulously engineered to expose the specimens to precise cyclic loading, faithfully replicating the conditions in which the material is anticipated to function in practical scenarios.



(a)



(b)

Fig. 5. (a) Electric furnace and (b) fatigue failure test equipment.

3 Results and Discussion

The samples underwent thorough examination after exposure to varying heating temperatures of 850°C and 950°C during the pack carburizing process. The selected range of temperatures was intended to offer a thorough insight into the impact of different thermal conditions on the carbon integration in the low-carbon steel samples. The findings and data collected from the XRD analysis have been compiled and presented in Fig. 6. The visual representation is essential because it enables a quick, transparent, and intuitive understanding of the carbon composition in different samples and conditions. The graphical representation helps to emphasize important trends and variations, providing a clear way to evaluate and compare the results of the carburizing process under various thermal conditions.

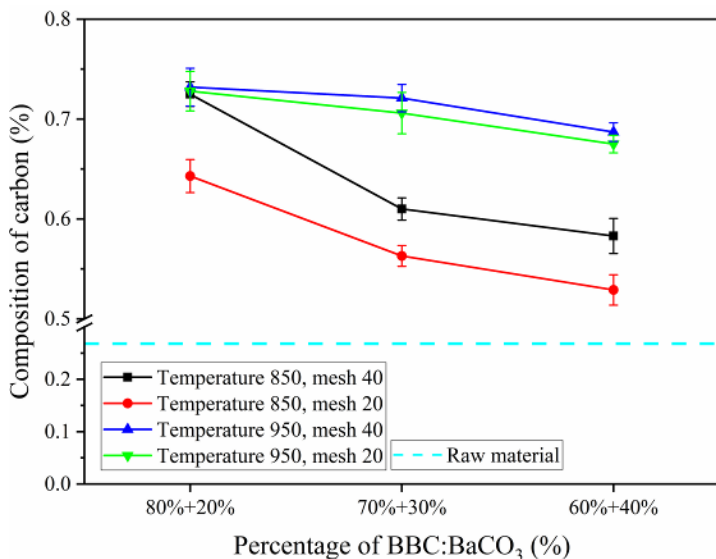


Fig. 6. Carbon (C) composition at temperatures of 850°C and 950°C.

Fig. 6 provides valuable insights into the impact of pack carburizing on Low-Carbon Steel (LCS), specifically when using Buffalo Bone Charcoal (BBC) as the carbon medium. This particular carburizing medium has proven effective in increasing the carbon content in LCS. At first, the LCS had a carbon content of 0.268%. After analyzing the pack carburizing process and considering Fig. 6, it is evident that there is a noticeable correlation: an increase in the percentage of BBC leads to a higher carbon content in the steel. This pattern remains consistent at different temperatures, specifically 850°C and 950°C.

Even when the % of BBC remains constant, and the mesh size is consistent at 20 or 40, we still observe temperature-dependent fluctuations. Carbon content increases to 0.643% for mesh 20 and 0.725% for mesh 40 at 850°C and 80% BBC, respectively. These numbers increase to 0.728% for mesh 20 and 0.732% for mesh 40 at 950°C. This information demonstrates how the heating temperature during the pack carburizing process is critical in establishing the ultimate carbon content of the steel. Research [12] suggests that heating steel close to its critical temperature increases its affinity for carbon, allowing for greater absorption and producing a solid solution, consistent with these findings. Carbon medium oxidation after absorption yields carbon dioxide (CO₂) and carbon monoxide (CO). Carbon monoxide gas combines with the surface of the steel, producing carbon atoms (C), which then permeate the steel. Similar findings are supported by the literature [13], which adds the caveat that post-carburizing carbon content changes due to variations in BBC composition, even under constant mesh and temperature circumstances. Even at constant heating temperatures, the carbon medium plays a vital role in the carburizing process, as evidenced by a drop in BBC composition correlated with a decrease in carbon content.

Similar findings were seen in another study using buffalo bones and coconut shells as carburizing agents [14]. Therefore, the two studies have a lot in common. According to [14], there was a linear relationship between the carburizing temperature and the carbon content of the material. This finding is noteworthy because it provides further evidence that the pack carburizing conditions substantially affect the end-product's characteristics. Interestingly, the buffalo bones used in the study [14] were not the only carburizing agents. Bamboo charcoal and BaCO₃ were also used. This variety of substrates allows for a more comprehensive understanding of the behavior of various carburizing agents across various situations. When combined with BaCO₃, bamboo charcoal showed a tremendous increase in carbon content, with an upswing of up to 100.8% with the rise in carburizing temperature. This is crucial data, as it shows how combining various carburizing chemicals may be more effective than using them singly.

After finishing the composition tests, the study moved on to the next critical phase: fatigue testing. This was done to thoroughly evaluate the impact of the modified material properties, resulting from pack carburizing, on the material's capacity to endure cyclic stress. The fatigue tests were performed at two different carburizing temperatures, 850°C and 950°C, to understand the impact of temperature variations on the material's fatigue resistance. The results of these thorough tests were carefully recorded and are visually displayed in Fig. 7 and Fig. 8 for the carburizing temperatures of 850°C and 950°C, respectively. The data presented in Fig. 7 and Fig. 8 provide valuable insights into the practical implications of the theoretical and empirical changes in material properties. Fig. 8 demonstrates the material's response to cyclic loading, offering a comprehensive view of its endurance and identifying any possible areas of weakness or failure. Through thoroughly examining the results obtained from carburizing at two different temperatures, this study established connections between the carburizing conditions, the resulting material properties, and the material's performance when subjected to repetitive stress.

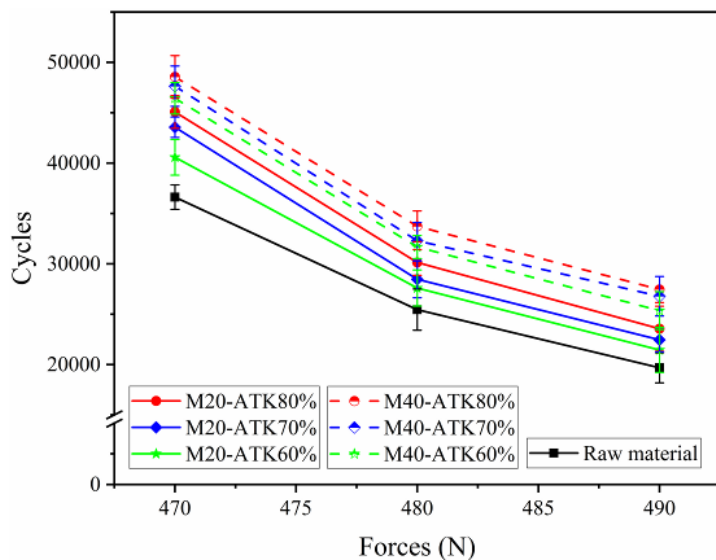


Fig. 7. The correlation between the forces and the cycles at a temperature of 850°C.

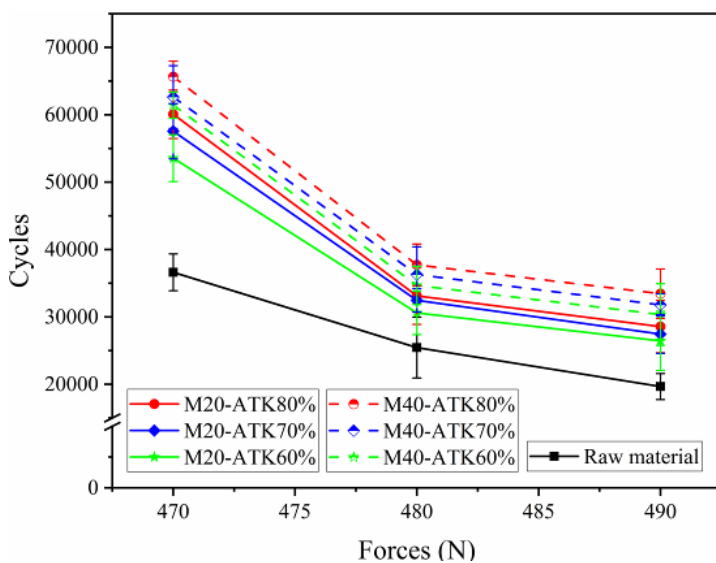


Fig. 8. The correlation between the forces and the cycles at a temperature of 950°C.

The fatigue test produced noteworthy results, providing insight into the correlation between the origin of BBC carbon, the composition ratio, the mesh's quality, and the material's endurance during cycles or rotations under stress. When exposed to identical temperature conditions, it was noted that specimens with a higher BBC ratio and finer mesh had a longer life cycle compared to those with a lower BBC ratio and coarser mesh. For example, when the temperature was set at 850°C, and a mesh size of 40 was used, applying a load of 490 N resulted in 25,356 cycles or rotations. Interestingly, with a slightly lower load of 470 N under the same conditions, an impressive 46,435 cycles were achieved. A higher load harms the cycle endurance, resulting in a faster failure of the test specimen. Understanding these results requires thoroughly examining factors related to the pack carburizing process, such as the heating temperature, the ratio of BBC to BaCO₃, and the resulting carbon content. The fatigue behavior of the material is influenced by these factors, revealing how changes at the microstructural level can significantly impact the material's overall performance when subjected to cyclic stress.

The fatigue test results of this study confirm the significant improvement in fatigue strength observed in carburized specimens compared to uncarburized ones, as previously demonstrated by Supriyono and Jamasri[15]. The consistency observed in our study highlights the strength of their conclusions, further emphasizing the importance of the carburizing process in enhancing the fatigue resistance of materials. The corroboration of this information

further solidifies the understanding in this area of study and highlights the practical importance of carburization in improving the mechanical properties of low-carbon steel.

Na Xiao et al. [16] comprehensive analysis shows that carburizing treatment increases fatigue strength in many materials. These noteworthy academic discoveries confirm that carburizing improves low-carbon steel's mechanical qualities. The procedure enhances surface hardness, wear resistance, and fatigue strength, essential for good performance under cyclic loading and sustained service in challenging operational conditions. Carburizing creates a hardened, wear-resistant shell and a resilient, ductile core in steel. This inherent characteristic gradient balances strength and toughness, protecting the material from mechanical stresses during service. This study emphasizes elongation, which must be acknowledged. Despite carburizing's many benefits, material elongation is still essential. This is a crucial topic of discussion, demanding a more sophisticated assessment of carburizing's mechanical behavior and trade-offs.

Despite the improvement in other mechanical qualities, carburizing does not affect elongation, a key metric of ductility [17]. Carburization increases surface hardness and fatigue strength but creates a more rigid and brittle surface layer that reduces plastic deformation before breakage. In applications that require ductility, this trade-off is most noticeable. Aerospace, automotive, and structural engineering require materials that sustain dynamic stress and deformation without catastrophic collapse. The delicate balance between improved mechanical characteristics and maintained ductility is crucial.

This trade-off requires a complex carburizing process selection and customisation approach to meet application needs. Engineers can improve mechanical performance and minimize downsides by carefully modifying carburizing temperature, time, and quenching procedures. Advanced surface engineering procedures, including post-carburization treatments or alloying elements, may help fine-tune the material's microstructure and reduce surface hardening-related brittleness. Understanding the application's mechanical requirements and integrating carburization into the materials engineering framework is crucial. By combining improved mechanical qualities with ductility, engineers may traverse carburization's trade-offs to create materials that suit modern engineering requirements.

4 Conclusion

The investigation has provided valuable conclusions that offer a deeper understanding of the impact of the pack carburizing process on Low-Carbon Steel (LCS) when Buffalo Bone Charcoal (BBC) is used as the carburizing medium. The conclusions from this research include:

1. The pack carburizing process with BBC greatly increases the carbon content in LCS. There has been a significant increase of 0.735% in the carbon percentage compared to the original state of LCS, which initially had a carbon content of 0.268%.
2. There is a significant change in the steel's microstructure, which could result in enhanced hardness and wear resistance. There is a clear correlation between the amount of BBC used in the process and the resulting carbon content in LCS. As the percentage of BBC increases, the carbon composition of LCS becomes more pronounced.
3. The fatigue strength of LCS is significantly improved by the pack carburizing process with BBC. Factors contributing to this improvement include a greater concentration of BBC, a smaller particle size of the carburizing medium, and elevated temperatures during the heating process. After undergoing carburizing treatment, the material significantly improves its capacity to endure cyclic stress. Under typical circumstances, LCS exhibited a life cycle of 36,625 cycles. Nevertheless, this value skyrocketed to 61,435 cycles following the pack carburizing process. Further research can focus on refining the

pack carburizing process to suit specific applications, studying the prolonged impact of increased carbon content on material performance, and exploring alternative carburizing mediums to broaden the scope of attainable material properties.

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