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Bio-Based Surface Engineering of AISI 316L for Durable Electromedical Devices

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Abstract

This study investigates a bio-based pack carburizing treatment for AISI 316L austenitic stainless steel using an environmentally friendly carburizing mixture composed of 70% Alaban wood charcoal and 30% eggshell powder. The treatment was conducted to improve the surface properties of AISI 316L for potential use in non-implant metallic components of electromedical devices. Solid-state pack carburizing was performed at 600 °C, 700 °C, and 800 °C for 3 h. The treated specimens were evaluated in terms of surface carbon content, microstructural changes, diffusion layer thickness, surface hardness, and hardness distribution. The results showed that increasing carburizing temperature enhanced carbon absorption and surface modification. The highest surface carbon content of 0.80% was obtained at 800 °C. At the same temperature, the surface hardness increased to 346 HV, and the maximum diffusion layer thickness reached 16.7 µm. Microstructural observations revealed the gradual formation of a darker and more continuous carbon-enriched modified layer as the carburizing temperature increased. These improvements indicate that the treated surface became more resistant to localized deformation, repeated contact, and light friction, which are important factors for maintaining the durability and functional reliability of metallic parts in electromedical devices. These findings indicate that the Alaban wood charcoal–eggshell powder mixture can act as an effective bio-based carburizing medium for improving the surface durability of AISI 316L stainless steel. Therefore, the proposed treatment not only enhances the surface performance of AISI 316L but also offers a sustainable and low-cost surface engineering approach for non-implant electromedical components exposed to repeated handling, cleaning, and maintenance activities.

Keywords: AISI 316L stainless steel, bio-based carburizing, surface hardness, diffusion layer, sustainable surface engineering.

I. INTRODUCTION

AISI 316L austenitic stainless steel is widely recognized as an important engineering material for biomedical, healthcare, and electromedical applications because of its excellent corrosion resistance, good biocompatibility, and reliable mechanical properties [1] – [4]. In electromedical equipment, this alloy can be used for various non-implant metallic components, such as holders, supports, guides, clamps, casings, brackets, connectors, and structural frames that require mechanical stability, hygienic compatibility, and long-term reliability [5]. These components are commonly exposed to repeated contact, handling, cleaning, assembly, and light mechanical loading during operation and maintenance. However, despite its good corrosion resistance, AISI 316L still has relatively low surface hardness and limited wear resistance [6], [7]. These limitations may accelerate surface wear, localized deformation, and service degradation when the material is used in components subjected to friction, contact stress, and repeated maintenance activities [3], [8], [9]. Therefore, improving the surface durability of AISI 316L is important to support the reliability and service life of metallic components in electromedical equipment.

In durable electromedical systems, surface degradation is not only a metallurgical issue but also an engineering concern. Damage occurring on metal surfaces can reduce dimensional precision, disturb functional performance, and increase maintenance intensity in applications where reliability and durability are essential [8], [10]. Therefore, enhancing the surface properties of AISI 316L while maintaining its beneficial bulk characteristics has become an important field of study. Surface engineering provides an effective approach by modifying only the outer surface layer without significantly affecting the toughness and corrosion resistance of the substrate material [11], [12], [13].

Among various surface modification techniques, carburizing has attracted considerable attention as a thermochemical treatment capable of increasing surface hardness and improving wear resistance [14], [15]. This improvement occurs through the diffusion of carbon atoms into the outer surface layer of the material. When properly controlled, carburizing treatment on stainless steel can form a hardened surface region with better resistance to localized deformation and repeated mechanical contact [16], [17], [18]. However, carburizing AISI 316L remains challenging because the

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chromium-rich passive oxide layer on the surface acts as a barrier that limits carbon diffusion into the material [4], [18]. Consequently, the effectiveness of the process strongly depends on the optimization of processing parameters, particularly temperature, holding time, and carburizing media, to ensure sufficient carbon diffusion without significantly reducing the intrinsic corrosion resistance of the alloy [19], [20], [21].

Recently, researchers have shown increasing interest in more sustainable and environmentally friendly thermochemical treatments [22], [23], [24]. Biomass-derived carbon sources are increasingly investigated as substitutes for conventional carburizing materials because they are renewable, inexpensive, and widely available. Wood charcoal has been identified as an effective carbon source, while eggshell waste, which contains a high amount of calcium carbonate, can influence the carburizing environment through its decomposition products and possible catalytic effects during heating [15], [25]. The utilization of these waste-based materials is attractive not only because they can function technically, but also because they support sustainable manufacturing by converting local biological waste into valuable resources [19].

Previous studies have reported that thermochemical treatment at temperatures between 600 and 800 °C can modify the surface properties of stainless steels [12], [26]. These modifications include increased surface carbon content, diffusion layer formation, and hardness improvement. When the process is carefully controlled, harmful carbide precipitation can also be minimized [18], [27]. However, many earlier studies mainly focused on metallurgical behavior or employed conventional carburizing materials [28], [29]. Only a limited number of investigations have explored hybrid bio-based carburizing systems for AISI 316L [7], [30]. Unlike those studies, the present work not only examines the changes in surface properties of AISI 316L caused by the carburizing process, but also applies a hybrid waste-based bio-carburizing medium consisting of Alaban wood charcoal and eggshell powder as a more sustainable surface engineering approach. In addition, this study specifically discusses the potential improvement in the durability of non-implant metallic components in electromedical devices that experience repeated contact, handling, and maintenance, an aspect that has rarely been addressed in previous studies. Therefore, the novelty of this work lies in the integration of environmentally friendly carburizing media, the evaluation of temperature effects on the surface characteristics of AISI 316L, and its relevance to improving the service life of metallic components in electromedical applications.

Based on this research gap, the present study investigates a bio-based surface engineering approach for AISI 316L stainless steel using a carburizing medium consisting of 70% Alaban wood charcoal and 30% eggshell powder. The treatment was carried out at temperatures of 600, 700, and 800 °C for 3 hours to evaluate how temperature influences surface carbon enrichment, microstructural evolution, diffusion layer thickness, and hardness distribution. The originality of this study lies in the application of a hybrid waste-derived carburizing medium to medical-grade stainless steel and the interpretation of the results in relation to improving the durability of metallic components used in electromedical equipment. Therefore, this study aims to demonstrate that sustainable surface engineering can serve as a practical strategy for producing more durable AISI 316L components for electromedical applications.

II. Materials and Methods

A. Materials

The material used in this study was austenitic stainless steel AISI 316L. This material was selected because it is widely applied in biomedical and healthcare fields, including its use in metallic components of electromedical devices, due to its high corrosion resistance and good biocompatibility. For the experiment, cylindrical samples were prepared with a diameter of 12 mm and a thickness of 20 mm. These samples were used for microstructural observation, hardness measurement, and chemical composition analysis.

Prior to the carburizing process, the specimen surfaces were mechanically prepared to obtain uniform surface conditions. The samples were ground using abrasive papers with grit sizes of 400, 600, 800, 1000, and 1200, cleaned with ethanol, and dried before being placed in the carburizing box. The chemical composition of the untreated AISI 316L stainless steel was identified using Optical Emission Spectroscopy (OES), and the results are presented in Table 1.

B. Carburizing Process

The carburizing process is shown in Figure. 1. During this process, a carburizing mixture consisting of Alaban wood charcoal and eggshell powder was used at a ratio of 70:30. Alaban wood charcoal acted as the main carbon source, while eggshell powder was used as a bio-based activator due to its calcium carbonate content. The austenitic stainless steel AISI 316L specimens were placed inside the carburizing box and completely covered with the carburizing mixture. The specimens were positioned at the center of the carburizing medium to ensure uniform contact between the sample surface and the carbon-rich mixture.

The carburizing box was then placed in the furnace. The furnace temperature was increased to 600 °C, 700 °C, and 800 °C at a controlled heating rate of 10 °C/min. Each specimen was held at the target temperature for 3 hours to allow carbon diffusion into the steel surface. The carburizing process was carried out under solid carburizing conditions inside a sealed carburizing box without external protective gas. Therefore, while the specimens were surrounded and protected by the carburizing medium inside the box. After the holding time was completed, the specimens were removed from

TABLE 1.
TYPICAL CHEMICAL COMPOSITION OF AISI 316L AUSTENITIC STAINLESS STEEL

Element	C	Mn	Si	Cr	Ni
%	0.0210	1.5200	0.4100	16.90	10.08

Figure 1. Carburizing Process.

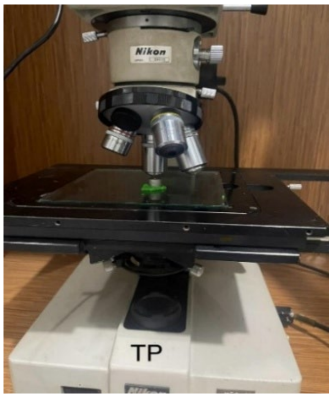

Figure 2. Optical microscope used for microstructural analysis.

the furnace and allowed to cool in air at room temperature. The same carburizing procedure was applied to all samples so that the effect of carburizing temperature could be compared under similar processing conditions.

C. Hardness Testing

The hardness test was performed using the Vickers microhardness method. The surface hardness data and hardness distribution shown in Figure 4 and Figure 6 were obtained using a Vickers microhardness tester. The test was conducted with an indentation load of 100 gf and a dwell time of 10 s. Measurements were carried out at ten points on each specimen, starting from the treated surface toward the inner region of the substrate, namely at 0 µm, 100 µm, 200 µm, 300 µm, 400 µm, 500 µm, 600 µm, 700 µm, 800 µm, and 900 µm from the surface. This measurement pattern was used to observe the hardness distribution of AISI 316L stainless steel after carburizing. The reported hardness values were obtained from three repeated measurements at each measurement position to obtain representative values.

The Vickers hardness was calculated using (1), which follows the standard Vickers hardness relationship used in microhardness testing [31]:

$$HV = 0.1891 \frac{F}{d^2} \quad (1)$$

Where is vickers hardness (HV), indentation load (F), and diagonal length (d).

D. Microstructure Analysis

Microstructural analysis was performed using an optical microscope, as shown in Figure 2, to observe microstructural changes and the thickness of the carbon diffusion layer on the steel after the pack carburizing process. The microstructural images shown in Figure 3 and the diffusion layer images shown in Figure 5 were obtained from cross-sectional observations using an optical microscope at 200× magnification.

Prior to observation, the treated specimens were sectioned, ground, polished, and prepared for metallographic analysis. The samples were etched using glyceregia reagent consisting of 15 mL HCl, 10 mL glycerol, and 5 mL HNO_3 for approximately 15 s at room temperature, following the ASTM E407 standard practice for etching stainless steel to reveal microstructural features and carbon-rich modified layers [30].

Cross-sectional observation was focused on the near-surface region to identify the carbon-rich modified layer formed after carburizing. The diffusion layer thickness was measured from the outer surface toward the substrate based on the visible boundary of the modified layer in the optical micrographs. Measurements were carried out at five different positions on each observed cross-section to obtain representative diffusion layer thickness values. This procedure was used to compare the effect of carburizing temperature on the growth of the carbon diffusion layer.

E. Mathematical Modeling

To theoretically support the carburizing mechanism in this study, several mathematical models were applied to describe the diffusion behavior of carbon, the increase in surface carbon concentration, and its influence on hardness. The equations used in this section were adopted from general diffusion theory, Arrhenius temperature-dependent diffusion behavior, and diffusion-based surface hardening relationships reported in previous carburizing and thermochemical treatment studies [11], [31], [32]. The growth of the carburized layer during heat treatment is represented using a one-dimensional diffusion model based on Fick's law. The diffusion depth, x_d is expressed as [32], [33]:

$$x_d = \sqrt{D(T) \cdot t} \quad (2)$$

Whare x_d is the diffusion depth, $D(T)$ is the temperature-dependent diffusion coefficient, and t is the holding time. Equation (2) shows that the thickness of the diffusion zone depends on both holding time and carburizing temperature. This equation explains that a longer holding time and a higher diffusion coefficient can increase the effective carbon penetration depth.

The temperature dependence of the diffusion coefficient is described using the Arrhenius relationship [32], [33]**:**

$$D(T) = D_0 \exp\left(-\frac{Q}{RT}\right) \quad (3)$$

Equation (3) explains that the rate of carbon diffusion increases with increasing carburizing temperature. In this equation, $D(T)$ is the diffusion coefficient at temperature T, D_0 is the pre-exponential factor, Q is the activation energy, R is the gas constant, and T is the absolute temperature.

To model the enrichment of carbon on the surface of AISI 316L during treatment, an empirical temperature-dependent expression is adopted [32], [33]:

$$C_s(T) = C_0 + k\, exp(\alpha T) \quad (4)$$

Equation (4) shows that this relationship supports the observed increase in surface carbon concentration at higher carburizing temperatures. Here, $C_s(T)$ represents the surface carbon concentration after carburizing, C_0 is the initial carbon concentration, and k and α are empirical constants related to the carburizing condition.

The increase in hardness resulting from increasing carbon content is expressed through a linear correlation, as shown in (5) [32], [33]:

$$HV_s = mC_s + c \quad (5)$$

This indicates that higher surface carbon content contributes proportionally to the increase in hardness. In this equation, HV_s is the surface hardness, C_s is the surface carbon concentration, while m and c are empirical constants.

The decrease in hardness from the surface toward the substrate interior is further associated with the effective diffusion depth, as expressed in (6) [34], [35]:

$$HV(\alpha) = HV_{core} + L \cdot d \quad (6)$$

Equation (6) indicates that the hardness gradient follows the degree of carbon penetration. The hardened region is influenced by the diffusion layer depth, while the inner substrate tends to maintain hardness values close to the core hardness. In this research, these mathematical models are not used for numerical simulation but serve as a theoretical foundation to interpret the experimental results obtained at carburizing temperatures of 600 °C, 700 °C, and 800 °C, particularly with respect to diffusion depth, surface carbon content, and hardness evolution.

III. RESULTS AND DISCUSSION

A. Chemical Composition Test

Table 2 presents the surface carbon content of AISI 316L stainless steel after pack carburizing at different temperatures. The untreated specimen (A1/TP) exhibited an average surface carbon content of 0.22%, which was used as the initial reference for surface evaluation. After carburizing at 600 °C, the carbon content increased to 0.55%, then to 0.61% at 700 °C, and reached the highest value of 0.80% at 800 °C. These findings indicate that increasing the carburizing temperature enhances carbon uptake on the surface of AISI 316L stainless steel. It should be noted that the carbon content measured in the untreated specimen represents the surface composition under the present testing conditions and may differ from the nominal bulk composition of the base material.

TABLE 2.
CARBON CONTENT COMPOSITION

Sample Code	Temperature °C	Surface Carbon Content (%)			Average Surface Carbon Content (%)
A1	TP	0.21	0.23	0.22	0.22
A2	600	0.56	0.57	0.54	0.55
A3	700	0.63	0.61	0.59	0.61
A4	800	0.79	0.81	0.81	0.80

The progressive increase in surface carbon content can be attributed to improved diffusion kinetics at higher carburizing temperatures [35], [36]. During pack carburizing, carbon species generated from Alaban wood charcoal diffuse toward the steel surface, while eggshell powder may act as an activator that supports the formation of active carbon species. The concentration gradient between the carbon-rich carburizing medium and the steel surface becomes the main driving force for carbon diffusion into the near-surface region. Higher temperatures provide greater thermal energy, increase the mobility of carbon atoms, and enhance diffusion into the substrate [33]. This behavior is consistent with the relationship expressed in (4), which shows that surface carbon concentration increases with carburizing temperature. The chemical composition results are also supported by microstructural observations, as specimens treated at higher temperatures showed darker and more distinct modified surface regions, indicating a higher degree of carbon enrichment [7], [11], [37].

The carbon levels obtained in this study are in agreement with previous reports on the thermochemical treatment of austenitic stainless steels, where higher carburizing temperatures generally produced greater carbon diffusion and surface carbon contents in the range of 0.7–0.8% [7], [31], [38]. Therefore, the value of 0.80% obtained at 800 °C confirms the effectiveness of the selected carburizing parameters. In addition, the carburizing medium consisting of 70% Alaban wood charcoal and 30% eggshell powder demonstrated good potential as a sustainable alternative to conventional carburizing agents. From an engineering perspective, the increase in surface carbon content is important because it may contribute to improved surface hardness and durability, particularly for AISI 316L components intended for electromedical device applications.

B. Microstructure

Figure 3 shows the microstructures of untreated and carburized AISI 316L stainless steel at different carburizing temperatures. The untreated specimen exhibited a relatively uniform austenitic microstructure with clear grain boundaries and no visible carbon-rich modified layer.

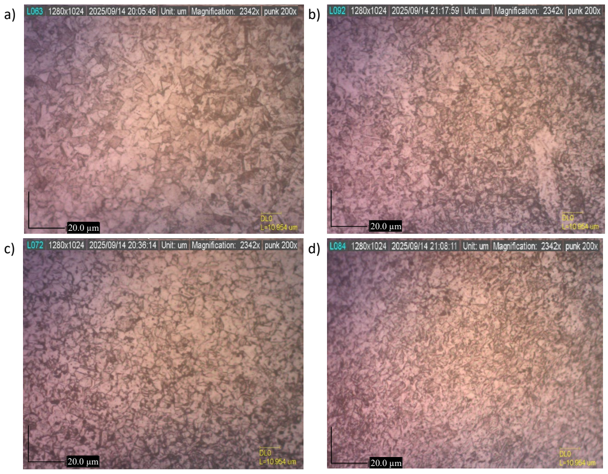

Figure 3. Microstructure of stainless steel before and after carburizing a.) Untreated, b.) 600 °C, c.) 700 °C, and d.) 800°C.

After carburizing at 600 °C, a thin and slightly darker layer began to appear near the surface, indicating the initial stage of carbon diffusion into the austenitic matrix. At 700 °C, the modified layer became clearer, thicker, and more continuous. The specimen treated at 800 °C showed the most pronounced surface modification, with a deeper and more uniform dark layer, indicating the highest carbon enrichment and diffusion depth.

The progressive increase in the thickness and clarity of the modified surface layer can be attributed to enhanced diffusion kinetics at higher carburizing temperatures [35], [36]. Higher temperatures provide greater thermal energy, increase carbon atom mobility, and accelerate carbon diffusion from the Alaban wood charcoal–eggshell medium into the near-surface region of the steel. This behavior is consistent with the diffusion mechanism represented by (2) and (3), where increasing temperature increases the diffusion coefficient and promotes deeper carbon penetration. The microstructural results are also in agreement with the chemical composition test, which showed that the surface carbon content increased from 0.55% at 600 °C to 0.80% at 800 °C.

These findings are consistent with previous studies on the carburizing of austenitic stainless steels, which reported that higher carburizing temperatures promote greater carbon diffusion, thicker modified layers, and more significant surface modification [39], [40], [41], [42]. In the present study, Alaban wood charcoal acted as the carbon source, while eggshell powder may support the formation of active carbon-containing species during heating, thereby assisting the carburizing reaction at the steel surface. This confirms that the 70% Alaban wood charcoal and 30% eggshell powder mixture has potential as a bio-based carburizing medium for modifying the surface of AISI 316L stainless steel.

From an engineering perspective, the formation of a thicker and more uniform carbon-rich modified layer is important because it may improve surface stability and resistance to localized surface damage. This is relevant for AISI 316L components used in electromedical devices, where repeated handling, contact, light friction, and cleaning may gradually affect the surface condition of the material. Therefore, the microstructural results support the potential use of bio-based pack carburizing to improve the surface durability of AISI 316L for electromedical device applications.

C. Surface Hardness

Figure 4 shows the surface hardness of the untreated and carburized AISI 316L specimens. The untreated sample (TP) exhibited the lowest hardness value, approximately 327 HV, which represents the initial hardness of the base material before thermochemical treatment. After carburizing at 600 °C, the surface hardness increased to about 341 HV, indicating that carbon enrichment had begun to strengthen the near-surface region. At 700 °C, the hardness increased slightly to approximately 343 HV, while the highest hardness was obtained at 800 °C, reaching about 346 HV. This gradual increase confirms that higher carburizing temperatures promote surface hardening of AISI 316L stainless steel.

The increase in hardness can be explained by the enhanced diffusion of carbon atoms at higher carburizing temperatures [11], [33]. During pack carburizing, carbon species generated from the Alaban wood charcoal diffuse toward the steel surface, while eggshell powder may support the formation of active carbon-bearing species during the process. As the temperature increases, the thermal energy available for atomic movement also increases, allowing more carbon atoms to diffuse into the near-surface region [22], [43]. This produces a carbon-enriched modified layer, as confirmed by the chemical composition and microstructural observations. The higher carbon concentration contributes to surface strengthening, mainly through solid-solution strengthening and the formation of a harder carbon-rich surface region. Therefore, the increase in hardness is directly related to the higher carbon uptake and clearer modified layer observed at higher carburizing temperatures. This relationship is also consistent with (5), which indicates that an increase in surface carbon concentration corresponds to an increase in hardness.

The hardness trend obtained in this study is consistent with previous studies on the thermochemical treatment of austenitic stainless steels, where carburizing generally increases surface hardness due to carbon diffusion into the surface layer [1], [2], [44]. However, the magnitude of hardness improvement may vary depending on the carburizing temperature, holding time, carbon source, activator material, and initial condition of the stainless steel substrate [3], [6], [18], [23], [43]. Compared with conventional carburizing treatments that

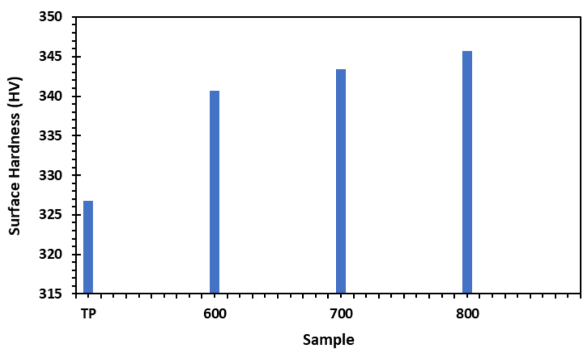

Figure 4. Surface Hardness of AISI 316L Steel.

commonly use industrial carburizing agents, the present study demonstrates that a bio-based carburizing medium consisting of 70% Alaban wood charcoal and 30% eggshell powder can also improve the surface hardness of AISI 316L. This finding indicates that agricultural and biological waste-derived materials can be used as alternative carburizing media for surface engineering applications.

From an engineering perspective, the increase in hardness from 327 HV to 346 HV is important because it indicates improved resistance to local plastic deformation, light wear, and repeated surface contact. Although the increase is moderate, it shows that the bio-based pack carburizing treatment can enhance the surface durability of AISI 316L without changing the bulk material. This improvement is particularly relevant for electromedical device components, which often experience repeated handling, positioning, cleaning, and mechanical contact during operation. Therefore, the hardness results support the potential application of the proposed sustainable carburizing treatment for improving the service performance and surface durability of AISI 316L components used in electromedical devices [19], [20].

D. Carbon Diffusion Thickness

Figure 5 presents cross-sectional micrographs that illustrate the formation of the carbon diffusion layer in AISI 316L stainless steel after pack carburizing at different temperatures. In the untreated sample, no clear diffusion layer can be seen, and the microstructure remains fairly uniform from the surface to the inner region. This shows that no thermochemical surface change occurred. Thus, this condition represents the initial microstructural state of the material before the carburizing process.

After carburizing at 600 °C, a visible diffusion layer appears near the surface with an average thickness of about 10.0 µm, showing the early entry of carbon into the austenitic matrix. At 700 °C, the diffusion layer becomes thicker and more even, with a thickness of around 11.7 to 13.0 µm. This suggests that carbon transport and retention in the near-surface area become more effective. The sample treated at 800 °C shows the clearest and thickest diffusion layer, ranging from about 14.6 to 16.7 µm, which indicates the deepest carbon penetration among all treatment temperatures.

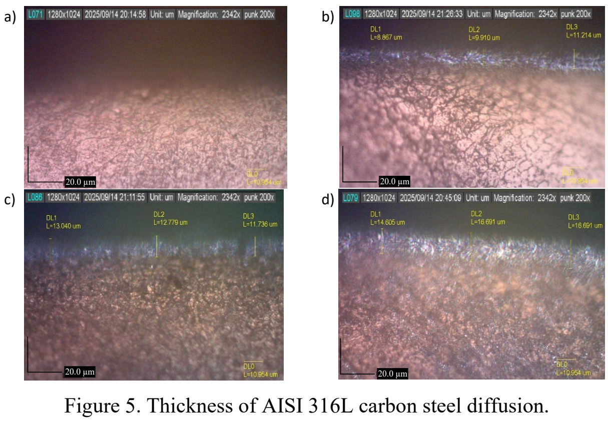

Figure 5. Thickness of AISI 316L carbon steel diffusion.

The gradual rise in diffusion layer thickness as the temperature increases confirms that carburizing temperature has a strong effect on carbon movement into AISI 316L [14], [44], [45]. This finding is in line with the relationships presented in (2) and (3), which explain that diffusion depth is controlled by both holding time and the diffusion coefficient, which changes with temperature. The same trend is also supported by the chemical composition and microstructural findings, which revealed greater surface carbon enrichment and more obvious modified layers at higher temperatures. Compared with previous carburizing studies on austenitic stainless steels, the diffusion layer thickness obtained in this work is comparable to, and in some cases slightly higher than, the commonly reported diffusion depth range for carburized stainless steel surfaces [9], [34]. This comparison indicates that the use of 70% Alaban wood charcoal and 30% eggshell powder was effective in supplying active carbon species during pack carburizing. Unlike several conventional carburizing media that rely on commercial carbon sources or chemical activators, the bio-based carburizing medium used in this study was able to produce a continuous and measurable carbon-enriched surface layer. Therefore, the present results not only confirm the effectiveness of the proposed carburizing medium but also show that locally available natural materials can provide a competitive alternative for surface modification of AISI 316L stainless steel.

From an engineering point of view, a thicker and more continuous diffusion layer is important because it reflects a more stable modified surface zone that can provide higher surface hardness and better resistance to localized damage [46]. For metallic parts used in electromedical devices, this is especially important during repeated contact, light friction, and regular handling, where surface stability has a direct effect on service life. Therefore, the diffusion thickness results further confirm the potential of the proposed bio-based carburizing treatment as a sustainable surface engineering method for AISI 316L components in electromedical devices.

E. Hardness Distribution

Figure 6 presents the hardness distribution of carburized AISI 316L stainless steel from the surface down to a depth of 0.9 mm. All samples show a steady reduction in hardness as the distance from the surface increases. This pattern reflects the common gradient effect of diffusion-based surface hardening. It shows that carburizing mainly changed the outer layer, while the inner part of the material kept hardness values close to those of the untreated base metal.

At the surface (0 mm), the sample treated at 800 °C had the highest hardness, reaching about 345 HV. It was followed by the 700 °C sample with around 343 HV and the 600 °C sample with about 340 HV. As the depth increased, the hardness of all samples gradually dropped. At around 0.8–0.9 mm, the hardness curves became close to each other, and the values nearly matched the original hardness of the substrate. Among all conditions, the 800 °C sample kept a higher hardness over a deeper region,

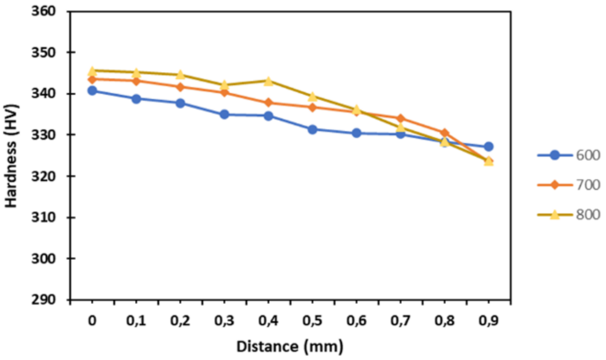

Figure 6. Hardness distribution of AISI 316L steel.

which suggests a thicker and more effective hardened layer. In contrast, the 600 °C sample showed the fastest drop in hardness, which is in line with more limited carbon diffusion.

This hardness gradient matches the diffusion behavior described in the earlier sections. A higher carburizing temperature encouraged more carbon absorption, produced thicker diffusion zones, and caused clearer microstructural changes [11], [14], [44], [46]. These factors led to stronger hardening at the surface. This result is also in agreement with (6), which links the hardness profile to the depth of carbon penetration in the material. The findings are similar to those reported in earlier studies on low-temperature carburizing of austenitic stainless steels, where hardness decreases progressively from the hardened surface to the unaffected core [18], [47], [48], [49].

From an engineering point of view, a gradient-hardened structure offers a valuable advantage because it provides a hard surface together with a tougher inner core. This combination is important for metal parts used in electromedical devices, which must resist repeated contact, light sliding, and localized mechanical loading without becoming too brittle. Therefore, the hardness distribution results suggest that the proposed bio-based carburizing treatment can create a tougher and more wear-resistant surface on AISI 316L while preserving the mechanical strength of the substrate for electromedical device applications.

IV. Conclusion

This study shows that a bio-based carburizing medium made of 70% Alaban wood charcoal and 30% eggshell powder can effectively improve the surface properties of AISI 316L stainless steel. Carburizing at temperatures of 600–800 °C increased the surface carbon content from 0.55% to 0.80%, raised the surface hardness from 341 HV to 346 HV, and formed diffusion layers with thicknesses reaching 16.7 μm. These findings confirm that higher carburizing temperatures allow carbon to diffuse more effectively and gradually strengthen the modified surface area. The microstructure analysis showed the formation of a darker and more uniform carbon-rich layer as the treatment temperature increased, which suggests stronger thermochemical changes at higher temperatures. The overall results from chemical composition, microstructure, surface hardness, and hardness distribution clearly indicate that treatment at 800 °C gave the best surface improvement among all tested conditions.

From an engineering point of view, the higher surface hardness and thicker diffusion layer suggest good potential for improving the surface durability of AISI 316L, especially for metal parts used in electromedical devices that experience repeated contact, light friction, and regular handling. Besides its technical benefits, the use of waste-based carburizing materials also provides a sustainable and low-cost surface engineering method. Therefore, this proposed treatment can be considered a promising alternative for improving the durability of AISI 316L components in biomedical and electromedical applications.

Declarations

Conflict of Interest

The authors have declared that no competing interests exist.

Declaration of Generative AI Use

Generative AI and AI-assisted technologies in the writing process: During the preparation of this manuscript, the authors used ChatGPT solely for language editing, grammar correction, readability improvement, and refinement of academic wording. The tool was not used to generate the research concept, methodology, experimental data, results, analysis, interpretation, or scientific conclusions. After using this tool, the authors carefully reviewed, revised, and approved the final manuscript and took full responsibility for the content of the publication.

CRediT Authorship Contribution

Muhammad Akbar Hariyono designed the concept and main ideas of this research, was responsible for fundraising, conducted carbonization experiments and data collection, and drafted the initial manuscript. Galih Persada played a role in developing the methodological design and provided technical support in material characterization. Ahmad Robittah supervised the overall research process and validated the experimental results. A'yan Sabittah managed data curation, compiled visualizations in the form of tables and figures, and conducted critical review and final editing of the manuscript. All authors have read and approved the final version of the manuscript and are responsible for the accuracy and integrity of the publication's content.

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