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INFLUENCE OF CARBURIZING ON SURFACE LAYER OF M50 NIL STEEL FOR BEARING APPLICATIONS

M50Nil steel is a low carbon alloy steel known for its strength, toughness, and superior wear and corrosion resistance at high temperatures. These beneficial properties lead to its widespread use in the aerospace industry. This study aims to clarify how different carburization temperatures and tempering processes affect the mechanical properties of carburized M50NiL steel. The carburization was performed in the pit furnace for three different durations (1, 1.5, and 3 hours) at temperature range of 880°C to 940°C. To fully understand the behavior of M50Nil steel during carburization, a range of temperatures from 880 to 940°C was used for the treatment. The surface layers were characterized by using EDS, X-ray diffraction (XRD), and Vickers microhardness testing. The EDS analysis of carburized samples usually shows a higher carbon concentration in the carburized layer than in the base material. The carburized specimen contained only the ε-fe3n phase, indicating that carbon in the furnace atmosphere helped stabilize ε-fe3n instead of the γ'-fe4n phase. The microhardness of carburized sample surfaces at different temperatures ranged from 480 to 855 Hv. The steel carburized at 880°C for 1.5 hours showed excellent surface hardness of 855 HV and a case depth of 204.00 μm. Carbon coating greatly enhances surface hardness, creating a thin outer layer with excellent wear resistance. The cbz 940 sample tempered for 1.5 hours showed lower wear rates than the untreated specimen. Potentiodynamic polarization tests in a 3.5% NaCl saline solution were performed to assess the corrosion resistance of the steel samples. Comparing the results, steel carburized at lower temperatures showed better corrosion resistance. The results show that as carburizing temperatures rise, the proportions of γ' phases and larger submicron precipitates also increase, which is linked to a higher presence of large primary carbides.

Keywords: Carburizing; M50 NiL; Corrosion; Wear; Hardness; EDS; XRD

1. Introduction

Carburizing, commonly referred to as case hardening, is a thermochemical diffusion method that modifies the chemical makeup of the outer layer of steel. This is accomplished by subjecting the steel to a carbon-rich environment at high temperatures for a specific duration. Carbon atoms from the atmosphere seep into the surface of the steel, forming a layer rich in carbon. The main goal of carburizing is to improve the mechanical characteristics of the steel, especially its hardness at the surface. Increasing the carbon content on the surface enhances the steel's hardness and improves its resistance to wear and fatigue [1]. This is particularly advantageous in scenarios where steel parts face abrasive environments or significant loads. The carburizing process consists of multiple phases. Initially, the steel parts are cleaned to eliminate any impurities. Next, the components are put into a furnace or a sealed chamber along with a carbon-rich substance referred to as a carburizing agent, like charcoal or gas. The furnace reaches temperatures between 850 and 950 degrees Celsius, permitting the carbon atoms to penetrate the steel's surface. The carburizing process can take anywhere from a few hours to a few days, depending on the level of surface hardness required [2].

Carburizing (CBZ) stands apart from other heat treatment methods, like quenching and tempering, due to its particular emphasis on enhancing the surface of the steel [3]. Quenching and tempering change the overall characteristics of the steel, while carburizing focuses mainly on the outer surface. In contrast to quenching, which quickly cools steel to achieve specific hardness levels, carburizing emphasizes changing the chemical makeup of the outer layer through the diffusion of carbon. This carburizing technique affects the surface of steels in various ways. Primarily, it enhances the surface hardness, which enhances the steel's resistance to wear and deformation. This is especially beneficial in uses like gears, bearings, and shafts, where steel parts face significant loads and contact stresses [4]. Additionally,

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carburizing enhances the fatigue strength of the steel, increasing its resistance to repeated loading. This is essential in scenarios where steel parts experience repetitive stress, as it aids in avoiding early breakdown. Besides improving hardness and fatigue strength, carburizing can also boost the surface's ability to resist corrosion. The layer enriched with carbon formed during the carburizing process acts as a protective shield, helping to inhibit the penetration of corrosive elements into the steel, which ultimately prolongs its durability. It's important to mention that the thickness of this carburized layer can be regulated by modifying the temperature, duration, and carbon levels throughout the process. This enables manufacturers to customize the carburizing process to suit particular needs regarding component thickness, load capacity, and wear resistance [5].

Carburizing is a critical treatment for M50 NiL steel due to its capacity to enhance mechanical properties and wear resistance, thereby rendering it suitable for high-demand applications. The carburizing process entails the introduction of carbon into the surface of the steel, which substantially augments hardness and micro structural attributes. Carburizing significantly elevates surface hardness, with research indicating that hardness values can attain up to 1202 HV following composite carburizing-nitriding procedures [6]. This process modifies the microstructure, facilitating the formation of austenite that subsequently transforms into martensite upon tempering, thereby creating a carbon concentration gradient that bolsters mechanical properties. The presence of substantial primary carbides facilitates nitrogen diffusion during subsequent nitriding processes, thereby optimizing the hardening procedure [7]. The synergistic combination of carburizing with additional treatments, such as nitriding, yields a self-lubricating layer that mitigates friction and wear, thereby transitioning the wear mechanism from an abrasive nature to an adhesive one. Conversely, despite the notable improvements in the properties of M50 NiL steel afforded by carburizing, it is imperative to judiciously balance the treatment parameters to prevent excessive brittleness, which may result from excessively high hardness levels. Carburizing steels permit an integrated functional design, enabling the tailoring of materials to fulfill specific performance criteria. This design flexibility can culminate in more efficient and effective bearing solutions in aerospace applications, employing the gas carburization method that markedly enhances the surface hardness and wear resistance of M50 NiL bearing steel. Such enhancements contribute to an extended service life for bearings utilized across diverse applications, thereby reducing maintenance costs and minimizing downtime. Carburizing steels facilitate an integrated functional design, allowing for the customization of materials to meet distinct performance specifications. This adaptability in design can result in more efficient and effective bearing solutions within aerospace applications.

The objective of this study is to investigate the effect of carbide substrate on M50 NiL Steel for high temperature bearing applications. Particularly focuses on response of raw material to various suitable temperatures and durations of carburizing treatment where it plays important role in enhancing surface and mechanical properties of bearing steels by inducing carbon through Gas carburizing process to enhanced bearing performance.

1.1. Role of Carburizing in enhancing Steel properties

Carburizing greatly improves the performance of M50 NiL steel by increasing its hardness and wear resistance while preserving the toughness of its core. This heat treatment method entails introducing carbon into the surface of low carbon steel, which is essential for attaining the desired mechanical characteristics. M50 nil steel particularly benefits from carburizing, as this process facilitates the creation of a microstructure with a specific carbide density, which is crucial for improving wear resistance and minimizing pitting [8]. The carburizing process not only enhances the hardness of the surface but also preserves the toughness of the steel's core, making it ideal for high-demand applications like gears and bearings [9]. By choosing a carburizing grade material, manufacturers can enhance the microstructure to attain a volume fraction of carbides in the hardened matrix of at least 20%, greatly prolonging the lifespan of the steel component [10]. Carburizing is an essential process for enhancing the performance properties of M50 Nil steel in demanding conditions [11].

Carburizing is a heat treatment technique that increases the surface hardness of low carbon steel by introducing carbon into it, all while preserving a resilient core [12]. This technique is a type of case hardening that focuses on toughening the outer layer of steel components while maintaining a softer and more malleable core [13]. There are various methods for carburizing, such as pack carburizing, gas carburizing, and liquid carburizing. Pack carburizing is a process where steel parts are enclosed in a carbon-rich medium and heated to promote the diffusion of carbon into the material. On the other hand, gas carburizing employs an atmosphere enriched with carbon-bearing gases, enabling fine-tuned management of carbon potential and diffusion rates. Liquid carburizing involves immersing low carbon steel in a high-carbon liquid that facilitates the absorption of carbon into the surface. Each technique offers its own benefits: pack carburizing tends to be more straightforward and economical, gas carburizing provides improved control and consistency, whereas liquid carburizing can reach elevated carbon levels rapidly. Ultimately, the selection of a method is determined by the particular needs of the application, including the required hardness, depth of carbon penetration, and efficiency of production [14].

Carburizing greatly improves the performance of bearing steels by enhancing fatigue resistance and toughness, essential qualities for components that experience dynamic loads. The carburizing process creates advantageous surface compressive residual stresses and alters the hardness distribution, resulting in improved fatigue strength [15]. The connection between case depth and component size is crucial in assessing the toughness of steel, a property that can be improved by alloying with elements such as nickel. Besides these advantages, carburizing also enhances the overall hardness of the steel, which is crucial for resisting wear.This is especially important when evaluating various surface treatment techniques; for example, both austenitic and ferritic nitrocarburizing produce a thin compound layer with hardness values ranging from 800 to 1000 HV [16]. However, austenitic nitrocarburizing offers a thicker compound layer and greater penetration, which leads to enhanced characteristics for bearing uses. In general, the incorporation of carburizing.

Carburized M50 NiL steel is extensively utilized in the production of gears, shafts, and various components due to its exceptional strength and remarkable wear resistance. The high carbon martensitic structure of carburized M50 NiL steel enhances its surface hardness and contributes to the material's toughness, rendering it particularly suitable for applications in the aerospace and automotive industries. This type of steel is capable of enduring substantial stress and fatigue which makes it highly appropriate for high-performance gears integrated into premium automobile applications.

2. Materials and methods

2.1. Material

M50 Nil steel is a high-performance alloy distinguished by its superior mechanical properties, making it essential for a wide range of industrial applications [17]. The surface characteristics of M50 Nil steel are extremely crucial because they have a direct effect on its wear resistance, hardness, and overall performance [18]. By grasping the composition, the elements affecting surface characteristics, and cutting-edge techniques for enhancement, manufacturers and engineers can fully harness the capabilities of M50 nil steel in challenging applications [19]. A M50 Nil steel rod, roughly 25 mm in diameter, was cut into 6 mm thick discs utilizing a band saw. Subsequently, a surface finishing procedure was carried out with a removal allowance of 0.5 mm, leading to samples that are 5 mm thick. The samples were subsequently processed using electrical discharge machining (EDM), resulting in the creation of three parallel samples from a single piece, each measuring 10 mm × 10 mm × 5 mm^3, appropriate for a range of mechanical testing procedures. TABLE 1 illustrates the chemical composition of M50NiL steel. In this study, samples of M50Nil steel measuring 10×10×5 mm^3 were used.

TABLE 1

M50NiL steel (wt.%) Composition

C	Cr	Mo	Ni	V	Mn	Si	Fe
0.12	4.1	4.0	3.2	1.1	0.1	0.1	Balance

2.2. Gas Carburizing

Gas carburizing is a technique for hardening surfaces where the outer layer of components is infused with carbon within a gaseous environment rich in carbon, as shown in Fig. 1. The procedure starts by thoroughly cleaning all samples in ethanol to achieve the best surface quality. The components are then gently heated in a neutral environment to achieve temperatures between 880°C and 940°C, in accordance with the intended carburizing specifications. Once the specified temperature is reached, the furnace is filled with an appropriate gas, like propane, butane, or methane, establishing conditions that favor carbon diffusion. In this phase, the components are carefully maintained at the designated temperature for an adequate duration, permitting carbon atoms to infiltrate the surface and create a hardened layer, which improves the material's wear resistance and longevity. After the carburizing phase, the specimens are subjected to a regulated cooling process in a protective environment created by the cold chamber [20].

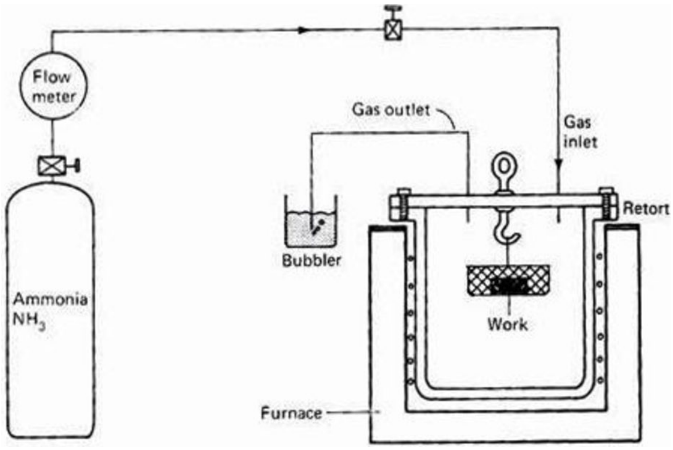


Fig. 1. Gas carburizing furnace [1]

All samples underwent ultrasonic cleaning in ethanol prior to the carburizing process. The study focused on the temperature of M50Nil steel, examining four carburizing temperatures: 880°C, 900°C, 920°C, and 940°C. The durations chosen for the investigation were 60 minutes (1 hour), 90 minutes (1.5 hours), and 180 minutes (3 hours). Carburizing is a heat treatment method aimed at increasing the surface hardness of ferrous metal components, especially those made of case-hardened steel. This process starts by warming a furnace to temperatures above 593°C and introducing the ferrous components into an environment that controls carbon potential, ensuring it remains at a minimum of 0.5%. The carburizing gas, rich in carbon, is introduced to elevate the surface carbon levels beyond the targeted amount. After the initial carburization phase, a diffusion treatment is carried out using a carburizing gas that has a lower carbon content. This step is crucial for attaining the desired depth of carbon penetration. This process of carburization followed by diffusion treatment is repeated until the desired carbon depth is achieved, enabling accurate management of the material's characteristics. Moreover, the supplementary gas introduced into the furnace is essential for supplying a source of free carbon, which significantly improves the carburizing effect overall. This methodical approach guarantees that the end product fulfills particular hardness and durability standards, making it appropriate for a range of uses. A valuable gas is introduced into the process chamber together with the air. The enriching gas is a carbon-containing substance that can be broken down to yield free carbon. In one aspect of the invention, the process involves heating the furnace's process chamber to a temperature exceeding approximately 593°C. The parts intended for carburizing are introduced into this chamber, where a carrier gas is supplied to create an atmosphere with a carbon potential of at least 0.5%. Additionally, air is introduced into the chamber to increase the carbon potential of the atmosphere by at least 0.1%, after which the carburized parts are removed from the furnace [21].

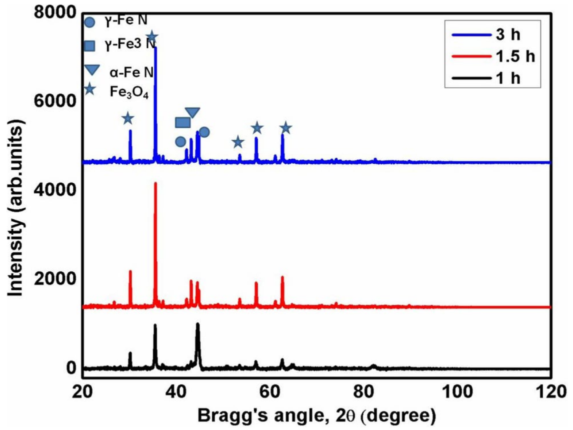
The study on M50 NiL steel identifies specific carburization temperatures that yield optimal mechanical properties and investigates carburization temperatures between 880°C and 940°C, This range is critical as it influences the formation of various micro structural phases and the overall mechanical properties of the steel and also explored the Higher Temperatures and their effects on M50 NiL steel, While temperatures up to 940°C were explored, the literature indicates that although higher temperatures can enhance certain properties, they may also lead to increased brittleness and reduced fatigue resistance. Therefore, while 940°C can be beneficial, it may not be optimal for all applications. The research reveals that carburizing at lower temperatures can enhance corrosion resistance, which is a critical factor for materials used in bearing applications. The findings indicate that the corrosion rates of carburized specimens are significantly lower than those of untreated steel, showcasing the effectiveness of carburization in improving material longevity. It provides a glance how varying treatment conditions can lead to different outcomes in terms of mechanical properties, which is essential for optimizing material selection for specific applications.

3. Results and discussions

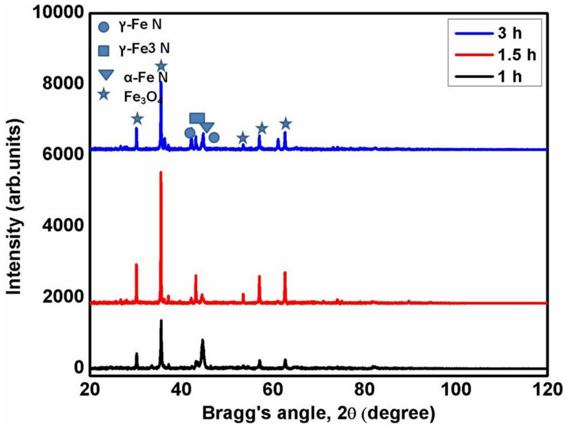
3.1. Phase Structure and Microstructure (XRD & SEM)

Utilizing the X-ray diffraction (Bruker AXS, D8 Advance X-ray Diffraction system) with Cu-Kα radiation ($\lambda = 0.15406$ nm) in the range of angles 20-120° at 40 kV and 30 mA with 0.02° interval step mode, the phase structure of the carburized surface was examined.

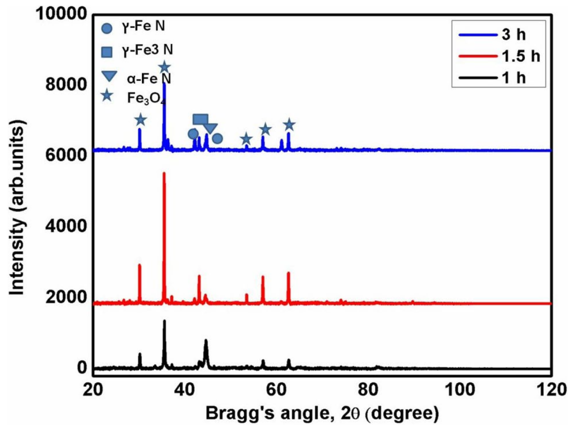
Fig. 2(a-d) illustrates the XRD Profile pertaining to both before and after carburizing of M50NiL samples. The phase constitution of the layers on M50NiL steel is contingent upon the carburizing temperature and duration. As demonstrated in the figure, the phases identified in the untreated sample are predominantly characterized by the α-Fe (ferrite) phase, accompanied by



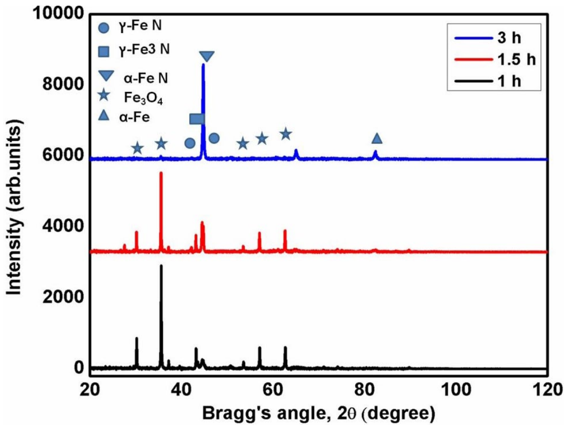
(a) XRD plot for CBZ 880°C



(b) XRD plot for CBZ 900°C



(c) XRD plot for CBZ 920°C



(d) XRD plot for CBZ 940°C

Fig. 2(a-d). XRD Profiles for Carburized samples (880°C to 940°C) lesser quantities of ε-Fe and γ-Fe (austenite phase). Conversely, the carburizing process engenders the emergence of novel phases, which evolve in correlation with the carburizing temperature.

Fig. 2(a) presents the X-ray patterns of the carburized samples subjected to temperature of 800°C. XRD analysis indicated that all carburized layers primarily consist of Fe_3O_4, α-Fe N, γ-Fe N, in addition to a minor presence of γ-Fe_3 N for the CBZ 800 specimens. The principal phases generated during the carburizing process encompass iron oxide (Fe_3O_4) and iron nitrides (α-Fe N and γ-Fe N). At the relatively lower treatment temperature of 800°C, a more substantial quantity of Fe_3O_4 and γ-Fe N was detected. With the extension of treatment duration, the diffraction intensity of Fe_3O_4 and γ-Fe N exhibited an increase, whereas the intensity of γ-Fe_3 N diminished. The compound layer exerts a significant influence on the friction and wear characteristics, thereby necessitating adjustments to the carburizing temperature to optimize these properties. Prolonged carburizing durations facilitate an augmented formation of Fe_3O_4 and α-Fe N, while the content of γ-Fe_3 N experiences a decline. Extended carburizing promotes the diffusion of enhanced quantities of carbon and nitrogen, thereby stabilizing these phases. The progression of these phases contributes to the enhancement of surface properties, including hardness and wear resistance, given that nitrides exhibit superior hardness and wear-resistance compared to pure iron. The XRD analysis reveals an increased number of sharp peaks corresponding to fully developed nitride (γ-FeN, γ-Fe_3N) and oxide (Fe_3O_4) phases. The specimen Cbz800°C at 03hr demonstrates optimized hardness and wear resistance owing to the complete formation of iron nitrides (γ-FeN, γ-Fe_3N), albeit at the expense of heightened brittleness and diminished fatigue resistance. The presence of Fe_3O_4 suggests some degree of oxidation, which may confer slight improvements in corrosion resistance, yet could also precipitate material embrittlement.

At treatment temperature of 900°C, an increased quantity of Fe_3O_4 and α-FeN was detected in the Cbz900°C at 01 hr sample as shown in Fig. 2(b). With the escalation of treatment duration, the diffraction intensity corresponding to Fe_3O_4 exhibited an increase, whereas the intensity associated with α-FeN diminished. This reduction is attributed to the gradual emergence and proliferation of alternative phases, such as Fe_3O_4, which progressively assert dominance over time. The intensity of the γ-Fe_3N phase escalates at 1.5 hours of carburizing, subsequently experiencing a decline at the 3-hour mark. The attenuation of the γ-Fe_3N phase at 3 hours can be ascribed to its transformation into the more thermodynamically stable γ-Fe_4N phase as carburizing time extends. Carburizing at 900°C facilitates the generation of iron nitrides, with the degree of nitride synthesis amplifying in correlation with the duration of carburizing. The X-ray diffraction (XRD) analysis reveals a pronounced presence of the Fe_3O_4 phase in the CBZ900°C at 03 hr specimen, likely resulting from oxidative processes occurring during extended carburizing at 900°C, whereby atmospheric oxygen interacts with the iron surface. The existence of a pronounced Fe_3O_4 phase bolsters surface oxidation resistance; however, it may compromise toughness and fatigue resilience due to the inherently brittle characteristics of oxide layers. Evidently, the compound layer predominantly comprises Fe_3O_4, γ-Fe_3N, γ-FeN, along with α-FeN. The generation of these nitrides contributes to enhanced surface hardness and wear resistance, given that nitrides exhibit superior hardness and wear resistance in comparison to pure iron.

From Fig. 2(c) At an elevated treatment temperature of 920°C, a substantial quantity of Fe_3O_4 was identified in the CBZ920°C at 1.5 hr sample. This phenomenon is likely attributable to the extended exposure, which fosters extensive oxidation during the carburizing process, culminating in the formation of a robust oxide layer (Fe_3O_4). The heightened temperature and prolonged duration augment the interaction of oxygen with the steel surface, culminating in significant oxidation, which may detrimentally impact the mechanical properties of the material and augment surface brittleness. As the treatment duration extended, the diffraction intensity associated with Fe_3O_4 intensified, whereas the α-FeN phase exhibited a decline. At the 1.5-hour mark, a discernible increment in the γ-Fe_3N phase was noted. As the carburizing treatment duration at 920°C progressed, the diffraction intensity of the γ-FeN phase intensified, attaining a maximum at the 3-hour interval. Furthermore, the presence of Fe_3O_4 notably escalated following 1.5 hours, concomitant with the establishment of predominant nitride layers. Analysis of the diffraction patterns reveals marked variations in the peak intensities of γ-FeN and the iron oxide (Fe_3O_4), underscoring the gradual formation of these phases over time. The intensity peaks pertaining to γ-FeN generally exhibit an increase in correlation with extended treatment time. The subtle broadening of peaks may signify the presence of stress or strain within the layer as a consequence of prolonged carburizing.

Fig. 2(d) illustrates the x-ray diffraction patterns of the carburized specimens subjected to a temperature of 940°C. X-ray diffraction (XRD) analysis indicated that the carburized layers predominantly comprise Fe_3O_4 and α-Fe, in conjunction with minor quantities of γ-Fe_3N and γ'-Fe_4N for the analyzed samples. The emergence of these nitrides and oxides contributes to an enhancement in surface hardness and wear resistance, as nitrides exhibit superior hardness and wear resistance relative to pure iron. The alterations in phase composition with varying carburizing durations underscore the dynamic characteristics of the carburizing process, which significantly influences the microstructural attributes and mechanical properties of the treated material. As the duration of the carburizing treatment was extended beyond 1.5 hours, particularly at the 3-hour mark, a substantial decrease in the diffraction intensity of the Fe_3O_4 phase was visible, while the α-FeN phase became increasingly prominent, alongside the novel emergence of α-Fe phase. The reduction in Fe_3O_4 intensity implies a decline in surface oxidation, likely attributable to enhanced nitrogen diffusion, which serves to stabilize the nitride phases. The reinforcement of α-FeN at extended durations is indicative of deeper nitrogen penetration, thereby facilitating the formation of stable nitrides. Moreover, the appearance of the α-Fe phase suggests a partial decomposition of Fe_3O_4, as nitrides begin to take precedence, thereby augmenting surface hardness and wear resistance. The increase in Fe_3O_4

formation suggests a more pronounced oxidation phenomenon at lengthier carburizing intervals. Oxides such as Fe_3O_4 can confer some degree of corrosion resistance; however, they may also impair ductility and toughness. Extended carburizing at 940°C fosters the conversion of γ-Fe_3N to the more stable γ-FeN phase, as evidenced by the heightened intensity peaks associated with this phase. As the treatment duration is prolonged, the predominance of the γ-Fe_3N phase becomes evident, particularly after a period of 3 hours. This phase is recognized for its high hardness and wear resistance, signifying that the carburized surface will exhibit improved mechanical properties following extended treatment. The α-Fe peak, indicative of the ferrite phase, demonstrates an increasing intensity as the carburizing duration diminishes, thereby suggesting that nitrogen diffusion is less effective during shorter treating intervals.

3.2. EDS Analysis of Carburized Samples

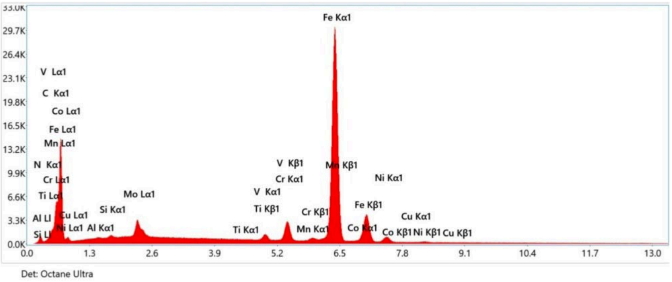
Fig. 3(a) indicates untreated sample EDS details and TABLE 2 shows the EDS results in value of the carburized layer of the significant M50 NiL specimens. The EDS analysis of the steel subjected to carburizing at 880°C for an hour showed changes in elemental composition as shown in Fig. 3(b). Carbon content increased from 9.9 wt.% to 12.6 wt.%, forming a carbon-enriched case that enhanced surface hardness and wear resistance. Nitrogen content rose to 4.1 wt.%, aiding in nitride formation for increased hardness. Iron decreased to 64.7 wt.%, establishing a carburized layer. Aluminium enrichment to 8.5 wt.% enhanced carbide formation, while chromium reduction to 2.6 wt.% may impact corrosion resistance. Cobalt content increased to 1.3 wt.%, with titanium absent. Molybdenum and nickel decreased, while manganese and silicon remained stable. A 1.5-hour carburizing process at 880°C increased carbon content to 15.4 wt.%, further enhancing hardness and wear resistance. Nitrogen content also rose, along with a decrease in iron content to 66.9 wt.%. Chromium content declined as well. Molybdenum and vanadium concentrations changed, affecting alloy properties. Cobalt concentration increased due to carbon affinity, while nickel remained constant. A three-hour carburization process at 880°C heightened carbon content to 16.2 wt.%, leading to improved mechanical properties and wear resistance. Nitrogen and cobalt concentrations increased, while iron and chromium content decreased. Minor changes in manganese and vanadium were noted, along with reductions in molybdenum and nickel concentrations. Overall, the carburization process significantly altered the steel's composition, enhancing its mechanical properties and wear resistance.

The Energy Dispersive Spectroscopy (EDS) analysis conducted on a sample carburized at 900°C for 1 hour revealed significant changes in elemental composition in Fig. 3(c). Carbon content increased from 9.9 wt.% to 11.6 wt.%, leading to a carbon-enriched layer that enhances surface hardness and wear resistance. Nitrogen content also rose to 2.8 wt.%, potentially forming nitrides that could further improve material properties. However, a decrease in iron content to 72.8 wt.% and chromium content to 3.1 wt.% might impact corrosion resistance. Notably, cobalt content increased to 1.6 wt.%, while molybdenum and nickel content decreased. Carburizing the sample at 900°C for 1.5 hours increased carbon content to 12.8 wt.%, demonstrating successful diffusion and improved surface characteristics. Nitrogen content rose to 2.1 wt.%, enhancing mechanical properties. Chromium content decreased to 2.9 wt.%, affecting overall properties, while cobalt content increased to 1.5 wt.% due to its affinity for carbon absorption. After a three-hour carburizing process, carbon content reached 14.6 wt.%, improving hardness, wear resistance, and mechanical strength. The incorporation of nitrogen at 4.7 wt.% may enhance durability but could lead to embrittlement. Cobalt concentration increased to 1.2 wt.%, further enhancing properties. Iron content reduced to 67.1 wt.%, with chromium content decreasing to 3.3 wt.%. Minor changes in manganese and vanadium content were observed. Molybdenum and nickel content increased, potentially strengthening the alloy's microstructure.

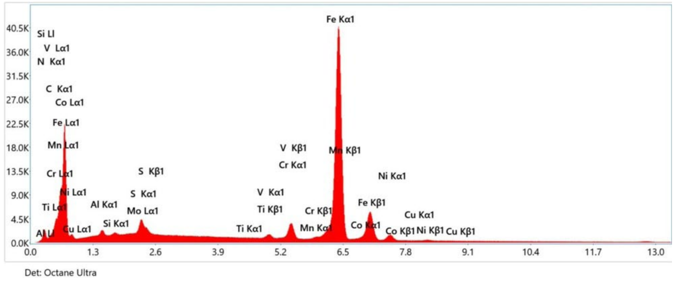
TABLE 2

EDS analysis of Carburized M50NiL

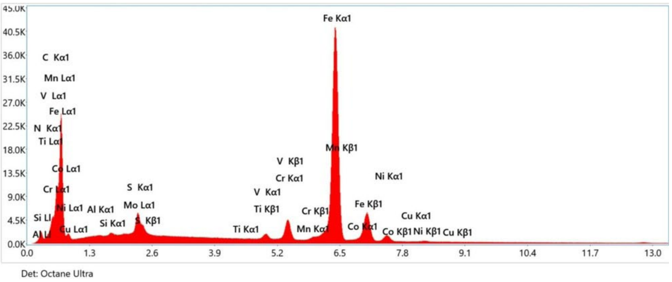
Element (wt. %)	**Untreated**	**Cbz880 at 3 hr**	**Cbz 900 at 3 hr**	**Cbz 920 at 1 hr**	**Cbz 940 at 3 hr**
Carbon (C)	*9.9*	16.2	14.6	11.1	29.6
Nitrogen (N)	0.0	4.3	4.7	1.2	9.0
Aluminium (Al)	*0.1*	0.7	0.2	0.0	0.3
Silicon (Si)	*0.2*	0.2	0.3	0.1	0.6
Sulphur (S)	*0.0*	0.0	0.0	0.0	0.0
Titanium (Ti)	*0.1*	0.1	0.0	0.1	0.1
Vanadium (V)	*1.1*	0.7	0.9	1.0	0.9
Chromium (Cr)	*3.6*	2.6	3.3	3.4	2.7
Manganese (Mn)	*0.3*	0.2	0.2	0.4	0.2
Iron (Fe)	*76.4*	67.6	67.1	75.0	47.9
Cobalt (Co)	*0.9*	1.4	1.2	1.6	1.0
Nickel (Ni)	*2.8*	2.7	2.9	2.7	3.4
Copper (Cu)	*0.1*	0.1	0.1	0.2	0.2
Molybdenum (Mo)	*4.2*	3.0	4.4	3.2	3.9



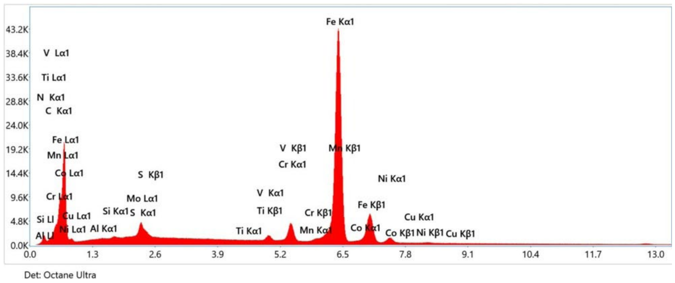
(a) Untreated



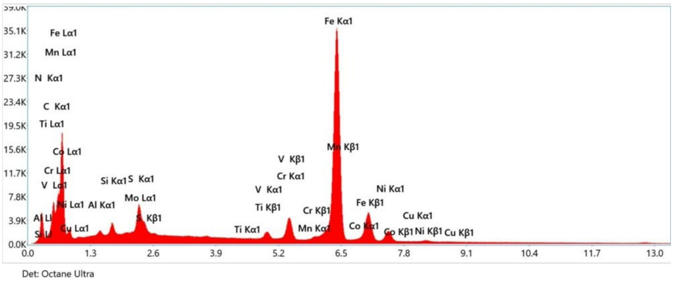
(b) Cbz 880°C at 03 hr



(c) Cbz 900°C at 03 hr



(d) Cbz 920°C at 1 hr



(e) Cbz 940°C at 03 hr

Fig. 3(a-e). EDS analysis of Carburized M50NiL specimens at 880°C, 900°C, 920°C ,940°C for 1,1.5 and 3 hr or 60 min, 90 min, 180 min

The EDS analysis of a steel sample carburized at 920°C for 1 hour revealed significant changes in elemental composition in Fig. 3(d). The increase in carbon content from 9.9 wt.% to 11.1 wt.% indicated successful carbon diffusion, leading to a carbon-enriched case that enhanced surface hardness and wear resistance. Nitrogen absorption (0 wt.% to 1.2 wt.%) may produce nitrides, further improving hardness and wear resistance, while a reduction in iron and chromium content implied surface modification to form a carburized layer. Cobalt content rose to 1.6 wt.%, enhancing hardness, strength, and corrosion resistance. Similarly, a sample carburized at 920°C for 1.5 hours showed a carbon content rise to 10.2 wt.%, demonstrating effective carbon diffusion and improvement in surface properties. The inclusion of nitrogen (2.0 wt.%) further enhanced mechanical properties, while a reduction in iron content (73.3 wt.%) highlighted carbon migration to surface layers. Changes in chromium, nickel, and vanadium content may impact alloy properties. A three-hour carburizing process at 920°C led to a carbon content increase to 11.0 wt.%, boosting attributes like hardness, wear resistance, and mechanical strength. Nitrogen inclusion (1.6 wt.%) and cobalt rise (1.6 wt.%) may enhance mechanical properties, with careful adjustments to iron, chromium, and other elements maintaining a controlled transformation process. Overall, these carburizing processes aimed to optimize elemental compositions for enhanced performance and durability in challenging applications, with modifications like carbon enrichment, nitrogen absorption, and alloy adjustments improving material properties like hardness, wear resistance, and strength.

In Fig. 3(e) The carburizing process at 940°C for one hour enhances steel by increasing carbon content to 18.0 wt.%, improving hardness and wear resistance. Carbon atoms infiltrate the surface layers, displacing some iron atoms and absorbing nitrogen, potentially forming nitrides to boost material properties. Silicon, chromium, nickel, molybdenum, and vanadium content changes during carburizing, affecting alloy properties. Energy Dispersive Spectroscopy (EDS) analysis at 940°C for 1.5 hours shows alterations in carbon, nitrogen, and iron content, potentially due to decarburization. Nitrogen assimilation at a lower rate relative to carbon could be due to solubility constraints. Manganese presence implies a controlled transformation process. The process at 940°C for three hours results in a substantial increase in carbon content to 29.6 wt.%, reducing iron content significantly due to carbon substitution. Nitrogen introduction and increased cobalt content may fortify mechanical properties. Reduction in chromium content and minor variations in silicon and vanadium suggest a controlled process. Changes in molybdenum and nickel content may influence alloy properties. The modifications observed through these processes are essential for achieving desired mechanical properties, including hardness and wear resistance, by facilitating carbon diffusion and elemental transformations in the steel.

3.3. Surface Mechanical Properties (Hardness and Corrosion, Wear)

3.3.1. Micro hardness

From the conducted hardness testing experiment, it has been observed that the untreated M50NiL steel displays a relatively low hardness value of 297.5 HV, necessitating the implementation of carburizing and heat treatment processes for substantial enhancement of hardness. The hardness measurements of the carburized specimens, subjected to a temperature range of 880°C to 940°C and soaking durations between 1 hour and 3 hours, are delineated in Fig. 4. The surface hardness of the samples exhibited variation in accordance with alterations in carburizing temperature and soaking duration, while the hardness values were recorded within the range of 480-855 HV. In the carburizing procedure at 880°C, the specimen Cbz880°C at 01 hr shows a hardness of 572.6 HV, increasing significantly to 855.1 HV at 1.5 hr due to carbon diffusion, leading to a hardened surface layer. The specimen Cbz880°C at 03 hr retains a high hardness of 854.5 HV, indicating saturation of the carburizing process and peak hardness achieved. The specimen Cbz900°C at 01 hr has a hardness of 480.6 HV, rising to 684.0 HV at 1.5 hr, and reaching 743.1 HV at 03 hr, attributed to the progressive carbon atom diffusion into the substrate. Increased treatment duration results in enhanced absorption of carbon, leading to a thicker carburized layer and improved surface hardness. For specimens at 920°C, hardness variations arise from several factors, with Cbz920°C at 01 hr showing 727.6 HV due to initial carbon diffusion. The hardness decrease at 1.5 hr to 681.54 HV may be due to saturation of carbon or microstructural changes from prolonged high temperatures. At 03hr, the hardness increases to 712.6 HV, indicating further carbon diffusion and densification of the carburized layer.In the carburizing process at Cbz940°C, hardness starts at 615.3 HV for 1 hour, rising to 638.0 HV at 1.5 hours, and reaching 667.8 HV at 3 hours, reflecting the effects of temperature and time on hardness. Elevated temperatures enhance carbon diffusion into the steel matrix, increasing carbon concentration in the surface layer and forming hard iron carbides.

3.3.2. Corrosion Resistance Behaviour

Fig. 5(a-d) presents the potentiodynamic polarization curves for the carburized samples subjected to testing at a temperature of 880°C for durations of 1, 1.5, and 3 hours, respectively; the corresponding electrochemical parameters, namely *Ecorr*, *Icorr*,

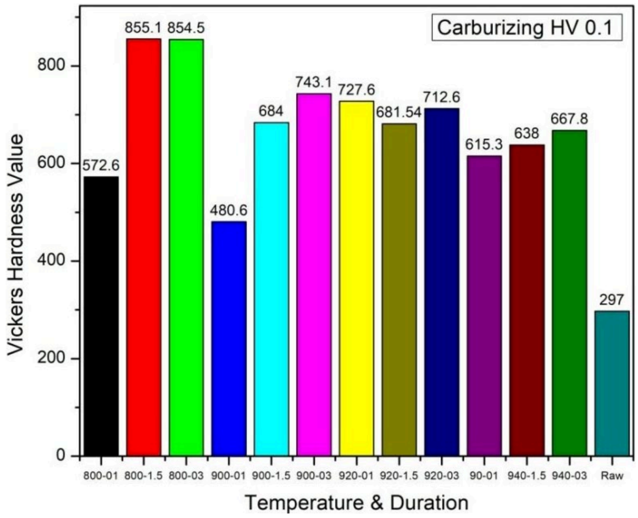
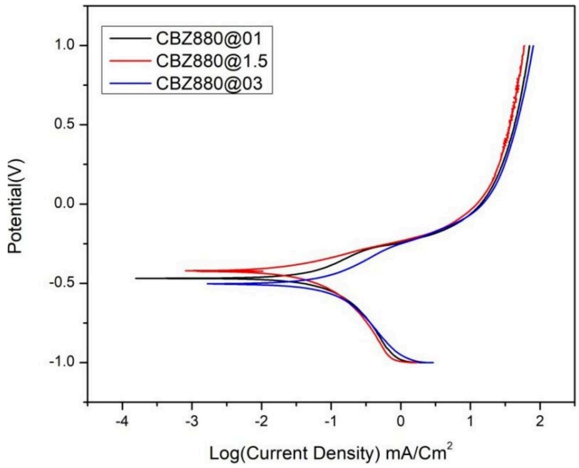


Fig. 4. Hardness Profile for Carburized samples

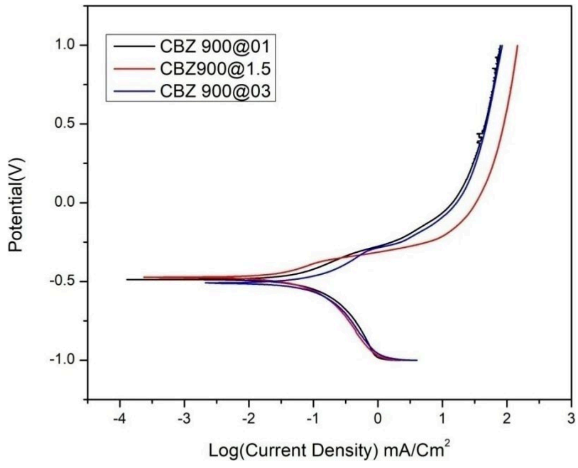
Rp, and the corrosion rate, are enumerated below. And Fig. 6 shows corrosion rate of carburized samples.

The Tafel plot 5(a) shows that all three specimens exhibit a potential decrease between –0.4V and –0.55V. Sample Cbz880°C for 1 hour displays reduced passive region and increased dissolution tendency, with higher corrosion current density (86.076 μA) and lower corrosion potential (*Ecorr*: –468.912 mV) indicating inferior corrosion resistance compared to other samples. Compared to Cbz880°C for 1.5 hours, this sample shows faster anodic kinetics with lower polarization resistance (*Rp*) of 819 Ω, resulting in a higher corrosion rate of 39.4321 mpy. A higher gas flow rate leads to a more positive corrosion potential (*Ecorr*) in Cbz880°C for 1 hour and a more negative open circuit voltage (OCV) of –0.49 V, suggesting increased thermodynamic driving force for corrosion. The Tafel slope in Fig. 6(a) suggests a wider passive range due to the development of a thicker protective carbon-rich layer, resulting in lower corrosion current density (86.076 μA) with higher polarization resistance (*Rp*) of 1418 Ω and reduced corrosion rate of 11.7734 mpy, indicating improved corrosion resistance. The carburizing process enhances *Rp*, leading to higher *Ecorr* of –468.912 mV compared to untreated steel. Cbz880 at 03hr demonstrates a balance between corrosion resistance and vulnerability, with a more negative *Ecorr* of –496.079 mV indicating higher susceptibility to corrosion. The recorded *Rp* of 596 Ω and corrosion rate of 32.9756 mpy imply some level of corrosion control compared to other carburized specimens. This material shows delicate equilibrium between corrosion resistance and susceptibility.

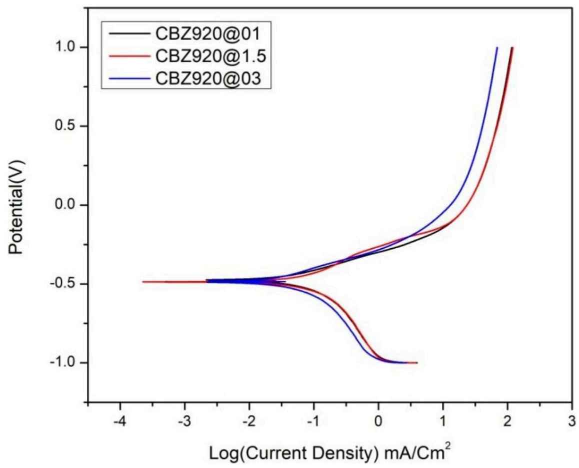
The analysis from Fig. 6 shows that the Cbz900°C at 01 hour sample has a reduced passive region and experiences progressive dissolution similar to the Cbz900°C at 03 hour sample. The corrosion potential is more negative at –487.547 mV, indicating a higher susceptibility to corrosion compared to other carburized steels. However, there is a polarization resistance (*Rp*) of 637 Ω, suggesting the presence of a partially effective passive layer hindering further corrosion. The corrosion rate is 39.4399 mpy, with a corrosion current (*Icorr*) of 88.478µA, balancing corrosion resistance and susceptibility. The Tafel slope in Fig. 5(b) suggests a strong passive range due to a robust carbon-rich layer acting as a barrier. Increased flow rates improve carbon diffusion, reducing the corrosion current density to 34.356 µA. This leads to a higher *Rp* of 918 Ω, indicating better corrosion resistance



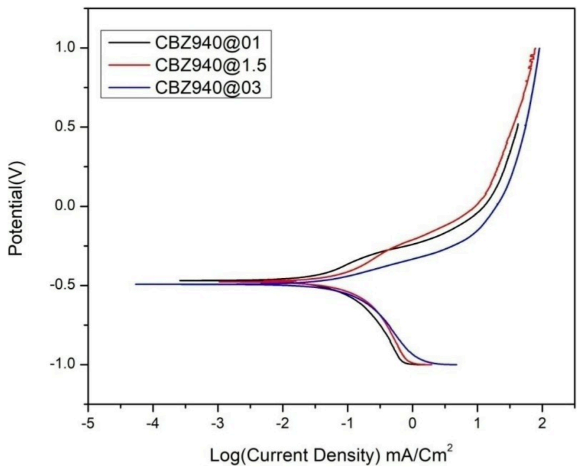
a) Tafel plot for CBZ 880°C



b) Tafel plot for CBZ 900°C



c) Tfel plot for CBZ 920°C



d) Tafel plot for CBZ 940°C

Fig. 5(a-d). Tafel plots of Carburized samples at 880, 900, 920 and 940°C for 1,1.5 and 3 h respectively

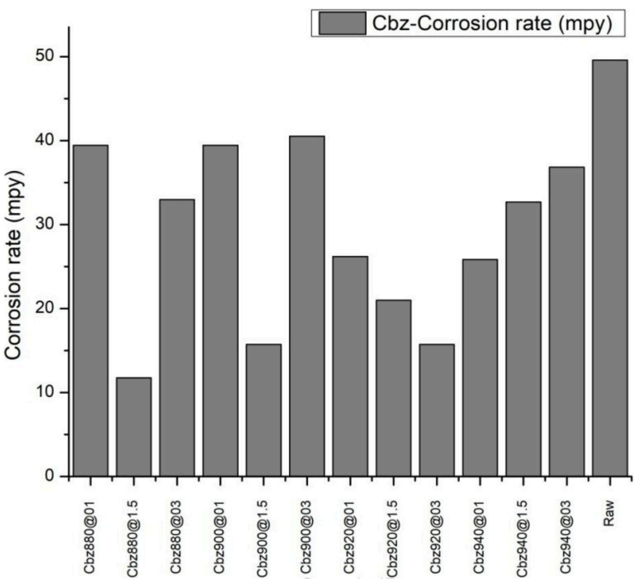


Fig. 6. Corrosion rate for Raw and Carburized Samples

with a lower corrosion rate of 15.7388 mpy. An increase in carbon content enhances corrosion resistance, shown by a positive shift in *Ecorr* to –473.614 mV. Compared to untreated steel, carburized steels exhibit significantly reduced corrosion rates. In contrast, the Cbz900°C at 03 hr sample shows inferior corrosion resistance with a higher corrosion rate of 40.5325 mpy and decreased *Rp* of 492 Ω, indicating accelerated anodic kinetics. The OCV of –0.52 V in carburized specimens implies a stronger driving force for corrosion.

The Cbz920°C at 01 hr specimen experiences significant corrosion in a NaCl solution, with a high corrosion current density of 57.168 µA and a low corrosion potential of –475.099 mV, indicating poor corrosion resistance. In comparison, the Cbz920°C at 03 hr specimen shows faster corrosion kinetics with a lower polarization resistance of 707 Ω and a corrosion rate of 26.1891 mpy, reflecting decreased corrosion resistance. The gas flow rate affects the corrosion potential, shifting it towards more positive values. The Cbz920°C at 1.5 hr steel demonstrates a balance between corrosion resistance and susceptibility, with an Open Circuit Potential (OCV) of –0.47 V and a corrosion potential of –482.471 mV. Despite a slightly higher corrosion rate of 20.9846 mpy, the material displays some level of corrosion control compared to other carburized specimens. The Tafel slope In Fig. 5(c) indicates a denser carbon-rich layer acting as a protective barrier, resulting in improved corrosion resistance with reduced current density and higher polarization resistance. Overall, carburizing enhances resistance to corrosion by increasing the Rp value and shifting the *Ecorr* to more positive values, indicating improved corrosion resistance compared to untreated steel. The carburized steels also exhibit significantly lower corrosion rates than untreated steel, showing improvements in corrosion resistance.

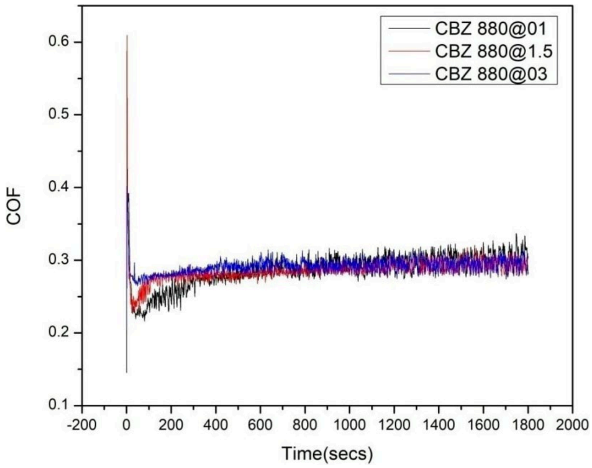
Fig. 5(d) shows that a carbon-rich layer can enhance corrosion resistance by creating a protective barrier. Higher flow rates during carburization improve carbon diffusion, leading to a lower corrosion rate of 25.8538 mpy and a decreased corrosion current density (*Icorr*) of 56.436 μA. However, surface imperfections or impurities may reduce the polarization resistance (*Rp*) to 103 Ω. Increasing the carbon content in steel can improve corrosion resistance, as seen in a shift in the corrosion potential (*Ecorr*) to –468.856 mV compared to untreated steel. Carburized steels exhibit significantly lower corrosion rates compared to untreated steel, with the carburized steel Cbz940°C showing enhanced resistance. Cbz940°C at 1 hr displays a moderately noble corrosion potential, while Cbz940°C at 1.5 hours exhibits interaction between corrosion resistance and vulnerability, with a lower Rp of 624 Ω and a corrosion rate of 32.6787 mpy. The Cbz940°C at 03 hours sample, on the other hand, exhibits inferior corrosion resistance, with a higher *Icorr* of 80.419 μA and a lower *Ecorr* of –492.654 mV. The gas flow rate influences the corrosion potential behavior. The open circuit voltage (OCV) values indicate the thermodynamic driving force for corrosion in the carburized samples.

3.3.3. Wear Resistance

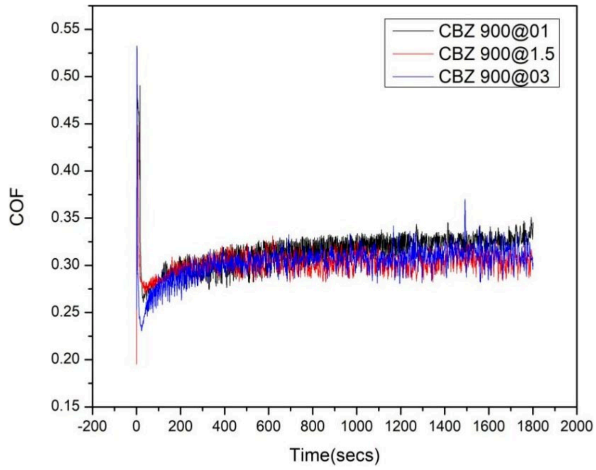
The wear rate of carburized specimens exhibits substantial variability across diverse treatment conditions, thereby reflecting the influence of carburization on wear resistance. The untreated specimen, characterized by a wear rate of 0.52×10^{-6} g/m, manifests the highest wear volume (0.798×10^{-3} mm^3/m) and the lowest wear resistance (909090.909×10^{-3} Nm/mm^3), thus indicating inadequate wear performance. The specimen treated at 880°C for 1 hour demonstrates ameliorated wear behavior, evidenced by a diminished wear rate of 0.47×10^{-6} g/m and a wear volume of 0.389×10^{-3} mm^3/m, which can be ascribed to the development of a more robust surface layer. An increase in the carburization duration to 1.5 hours at 880°C further reduces the wear volume to 0.294×10^{-3} mm^3/m and markedly enhances wear resistance to 2500000.000×10^{-3} Nm/mm^3, attributable to the deeper diffusion of carbon and augmented hardness. However, extending the treatment duration to 3 hours at 880°C results in a slight increase in the wear volume to 0.261×10^{-3} mm^3/m and sustains a wear rate of 0.47×10^{-6} g/m, thereby suggesting an optimal treatment duration for maximizing wear resistance while preserving surface integrity. These fluctuations underscore the pivotal role of carburization parameters in customizing the wear characteristics of steel components. In comparison to the untreated specimen, the friction coefficients of the carburized specimens are lower during the initial phase, subsequently rising to a stable condition. From Fig. 7(a),The friction coefficients for the 1, 1.5, and 3 hour carburized samples are approximately 0.2867, 0.3196, and 0.2900, respectively. The friction coefficient of the carburized specimens exhibits a decreasing trend initially before increasing with prolonged treatment duration. The 1 hour carburized specimen presents the lowest friction coefficient.

The wear rates of carburized specimens exhibit substantial variability across differing treatment conditions, thereby reflecting the influence of carburization on wear resistance. The specimen treated at 900°C for 1 hour demonstrates a wear rate of 0.97×10^{-6} g/m and a wear volume of 0.943×10^{-3} mm^3/m, indicating a moderate enhancement in wear performance relative to untreated specimens. An increase in the carburization duration to 1.5 hours at 900°C results in a significant reduction of the wear rate to 0.30×10^{-6} g/m and a wear volume of 0.200×10^{-3} mm^3/m, which suggests improved wear resistance as a result of deeper carbon diffusion and augmented surface hardness. Prolonging the treatment duration to 3 hours at 900°C yields a wear rate of 0.47×10^{-6} g/m and a wear volume of 0.426×10^{-3} mm^3/m, indicating a balance between diffusion depth and surface hardness, albeit exhibiting slightly higher wear compared to the 1.5-hour treatment. These findings underscore the pivotal role of carburization parameters in optimizing wear characteristics, with the treatment at 900°C for 1.5 hours yielding the best wear resistance, as evidenced by the lowest wear rate and volume loss. From Fig. 7(b),The coefficients of friction for the samples carburized for durations of 1, 1.5, and 3 hours are approximately 0.3148, 0.302, and 0.3029, respectively. This trend illustrates a decrease in the friction coefficient with an increase in treatment duration from 1 to 1.5 hours, likely attributable to optimal carbon diffusion and surface hardening. However, extending the treatment duration to 3 hours results in a slight increase in the friction coefficient, suggesting that excessive treatment may marginally compromise the surface properties. The carburized sample treated for 1.5 hours exhibits the lowest coefficient of friction.

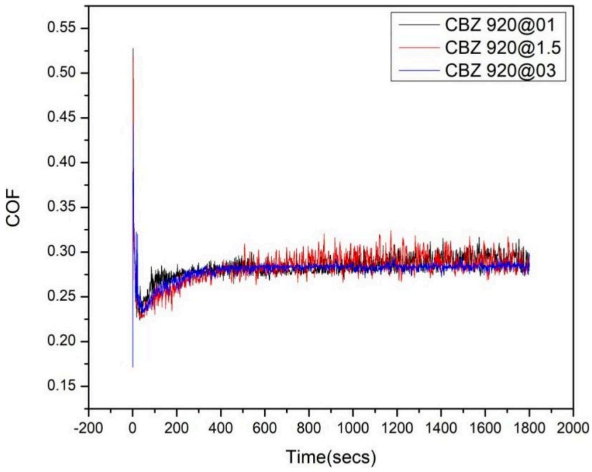
The wear rates of the carburized specimens exhibit substantial variability across diverse treatment conditions, underscoring the influence of carburization on wear resistance. The specimen treated at 920°C for 1 hour displays a wear rate of 0.47×10^{-6} g/m and a wear volume of 0.306×10^{-3} mm^3/m, signifying a moderate enhancement in wear performance relative to untreated specimens. Prolonging the carburization time to 1.5 hours at 920°C sustains a comparable wear rate of 0.47×10^{-6} g/m but elevates the wear volume to 0.316×10^{-3} mm^3/m, suggesting improved wear resistance attributable to deeper carbon diffusion and augmented surface hardness. Extending the treatment duration



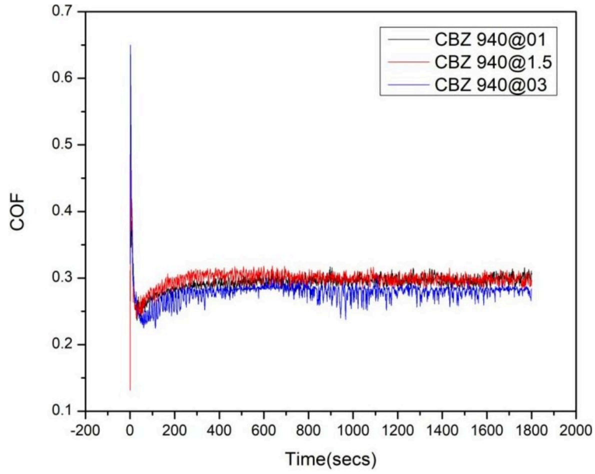
a) COF for Cbz 880°C



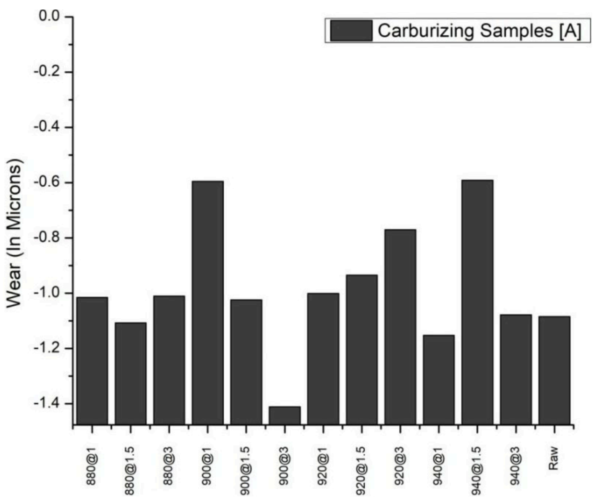
b) COF for Cbz 900°C



c) COF for Cbz 920°C



d) COF for Cbz 940°C



e) WR for Carburized samples

Fig. 7(a-e). COF of the specimens treated at 1, 1.5 and 3 h for different Carburizing temperatures (a) 880°C (b) 900°C (c) 920°C (d) 940°C (e) Wear rates(WR) of untreated and Carburized samples

to 3 hours at 920°C yields a wear rate of 0.38×10^{-6} g/m and a wear volume of 0.242×10^{-3} mm^3/m, thereby exhibiting the most proficient wear resistance among the evaluated conditions. These outcomes accentuate the pivotal significance of carburization parameters in the optimization of wear characteristics, with the treatment at 920°C for 3 hours yielding the lowest wear rate and volume loss. In comparison to the untreated specimen, the friction coefficients of the carburized specimens are initially lower, subsequently increasing to attain a steady state. From Fig. 7(c),The friction coefficients for the 1, 1.5, and 3-hour carburized specimens are approximately 0.2831, 0.2823, and 0.3029, respectively. The friction coefficient of the carburized specimens initially decreases and then rises with the extension of treatment duration. The 1.5-hour carburized specimen exhibits the lowest friction coefficient.

The wear rate of carburized specimens exhibits substantial variation across diverse treatment conditions, underscoring the influence of carburization on wear resistance. The specimen treated at 940°C for 1 hour manifests a wear rate of 0.58×10^{-6} g/m and a wear volume of 0.432×10^{-3} mm^3/m, signifying a moderate enhancement in wear performance relative to untreated specimens. Prolonging the carburization duration to 1.5 hours at 940°C results in a significant reduction of the wear rate to 0.27×10^{-6} g/m and the wear volume to 0.214×10^{-3} mm^3/m, indicating improved wear resistance attributed to deeper carbon diffusion and increased surface hardness, thereby demonstrating the most favorable wear resistance among the evaluated conditions. Extending the treatment period to 3 hours at 940°C culminates in a wear rate of 0.72×10^{-6} g/m and a wear volume of 0.485×10^{-3} mm^3/m. These outcomes highlight the essential role of carburization parameters in optimizing wear properties, with the treatment at 940°C for 1.5 hours yielding the minimal wear rate and volume loss. In comparison to that of the untreated specimen, the friction coefficients of the carburized specimens are lower during the initial phase, subsequently increasing to a steady state. The friction coefficients for the 1, 1.5, and 3-hour carburized specimens are approximately 0.293, 0.2977, and 0.2785, respectively. From Fig. 7(d), The friction coefficient of the carburized specimens initially declines before rising with the extension of treatment time. The 3-hour carburized specimen exhibits the lowest friction coefficient.

4. Conclusion

M50 NiL steel specimens with different temperatures ranging form 880°C to 940°C with duration of 1, 1.5, 3 hrs are investigated to identify the phase structure, micro structural changes, wear, corrosion and micro hardness, and from these observations the major outcomes are as follows:

a) The Carburized layer comprises a diffusion layer consists, phases such as α-FeN, γ-FeN, and γ-Fe3N, along with Fe_3O_4, are generated on the surface layer of M50 NiL. Moreover, substantial concentrations of carbon are observed in CBZ at a temperature of 940°C over a duration of 03 hours in EDS.

b) The micro hardness of M50 NiL Carburized specimens subjected to a temperature of 800°C for a period of 1.5 hours is recorded at 855 HV, which is two times greater than that of the untreated specimen, which measures 294 HV, a difference that may be attributed to the significant presence of large primary carbides during the assessment.

c) The wear resistance and friction coefficient of M50 NiL carburized specimens treated at 940°C for 1.5 hours indicate a minimal wear rate of 0.27×10^{-6} g/m (–0.59132) alongside a friction coefficient of 0.2977, in contrast to the untreated sample which exhibits a wear rate of 0.52×10^{-6} g/m (–1.08422) and a friction coefficient of 0.5773.

d) Corrosion resistance behaviour of M50 NiL carburized sample is significantly improved for 880°C at 1.5 hours, the specimen showed a corrosion rate of 11.773 mpy, significantly lower than the untreated sample's rate of 49.577 mpy. In Future dual treatments like carburizing and nitriding may indicate growth in microstructure and mechanical properties and also optimization process may suggest suitable parameters to attain desirable results.

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