Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 3	Month	: June
p-ISSN	: 1693-5462	Volume	: 23	Year	: 2025

Processing dates: received on 2024-12-05, reviewed on 2025-01-07, accepted on 2025-06-23 and online availability on 2025-06-30

Enhancement of surface hardness and roughness of HQ 805 steel using diamond-like carbon coating deposited by PVD

Binsar Maruli Tua Pakpahan[1,*], Rizqi Ilmal Yaqin[2], Bakti Dwi Waluyo[3], Zulfikram Zulfikram[4], Muhammad Dominique Mendoza[3]
[1]Mechanical Engineering Education Department, Medan State University, Medan 20221 Indonesia
[2]Marine and Fisheries Polytechnic of Dumai, Dumai 28826, Indonesia
[3]Electrical Engineering Education Department, Medan State University, Medan 20221 Indonesia
[4]Study program of Industrial Engineering, University 0f Pasific Morotai, Morotai 97771 Indonesia
*Corresponding Author: binsar_pakpahan@unimed.ac.id

Abstract

Diamond-Like Carbon (DLC) coatings are well-regarded for their high hardness, low friction coefficient, and excellent wear resistance, making them suitable for enhancing surface properties in demanding industrial applications. This study aims to analyze the effect of DLC coating on HQ 805 steel, focusing on improvements in surface hardness and surface roughness. HQ 805 steel, which is known for its mechanical durability, was coated using the Physical Vapor Deposition (PVD) method to achieve a uniform and adherent thin film. Hardness was evaluated using the Vickers microhardness test, while surface roughness was measured with a profilometer. Results showed a significant increase in surface hardness, with the coated samples achieving up to 798 VHN. It represented a 25–30% increase compared to the uncoated steel at 355 VHN. Surface roughness exhibited only a slight increase (5–7% Ra), indicating the thin layer and uniform deposition achieved with DLC without adversely affecting the surface finish. These results confirm that PVD-applied DLC coatings can effectively enhance the mechanical surface performance of HQ 805 steel without compromising surface quality. The optimal coating condition was found at 400°C for 4 hours. This research shows the potential application of DLC-coated HQ 805 steel in high-wear industrial environments, extending component service life and improving operational efficiency.

Keywords:
DLC, HQ 805 Steel, hardness, surface roughness, PVD

1 Introduction

HQ 805 steel is widely used in the heavy equipment industry and in machine components that operate under high loads and intense frictional conditions. However, several studies have reported that this material exhibits performance degradation due to premature wear, particularly on contact surfaces subjected to repeated friction. Additionally, reports from the manufacturing industry indicate that the service life of HQ 805 steel is limited in tribological applications unless appropriate surface treatments are applied. Therefore, efforts to enhance the wear resistance of this material are necessary, one of which involves surface coating technologies such as Diamond-Like Carbon (DLC).[1].

This steel is characterized by its excellent ductility, toughness, and very high strength. The AISI 4340 standard originates from the United States, where "AISI" stands for the American Iron and Steel Institute. The designation "4340" has a specific meaning: the first two digits, "43", indicate that the steel is an alloy steel containing approximately 1.82% Nickel (Ni), 0.50% Chromium (Cr), and between 0.25% to 0.80% Molybdenum (Mo). Meanwhile, the last two digits, "40", indicate the carbon content in the material, which is around 0.40% [2]. AISI 4340 steel is classified as a nickel-chromium-molybdenum alloy steel and is susceptible to corrosion, which is a contributing factor to its failure.

HQ 805 steel is a type of steel commonly applied in the automotive, machinery, and heavy equipment industries due to its durability and stability under high pressure. However, HQ 805 steel still has limitations in terms of friction and wear resistance, which can potentially reduce the service life of components, especially in applications involving high friction or heavy loads [3].

To address this issue, surface coating with wear-resistant and high-hardness materials has become a widely adopted solution in the industry. One of the most popular types of coatings is DLC [4]. DLC coating is an amorphous material that combines the superior properties of diamond, including high hardness, excellent wear resistance, a low friction coefficient, and corrosion resistance. DLC coatings have been widely used in the automotive, aerospace, and biomedical industries to improve the performance of components subjected to direct contact and constant friction.

One of the key characteristics that makes DLC coatings attractive is their high hardness and ability to produce smoother surfaces. The high hardness of DLC provides additional protection against surface wear, potentially extending the service life of components. Additionally, several previous studies have shown that DLC coatings with a low coefficient of friction can help reduce the heat generated by friction and potentially lower the risk of mechanical failure at elevated temperatures [5].

However, the application of DLC coatings on HQ 805 steel still requires further investigation to understand the extent to which this coating can enhance the mechanical properties of the steel, particularly in terms of surface hardness and roughness [6]. Surface roughness is a crucial factor in material performance, particularly in applications that necessitate smooth contact to minimize friction or improve wear resistance. The effect of DLC coatings on surface roughness will help in understanding the surface quality that can be achieved after coating, which is relevant for high-precision applications.[7].

This study aims to investigate the effect of DLC coating on HQ 805 steel in terms of surface hardness and roughness, as these parameters are directly related to improved resistance to friction and wear. The hardness test will be conducted to determine the improvement in resistance to plastic deformation after applying the DLC coating, while the surface roughness test will indicate how well the DLC layer produces a smooth and uniform surface [8].

By understanding the changes in surface hardness and roughness resulting from the DLC coating, this study not only contributes to the advancement of surface coating technology but also fills a gap in previous research, which has generally focused only on coating parameters without directly linking their effects to the wear resistance of HQ 805 steel. This study emphasizes the relationship between coating conditions, mechanical properties, and the potential for extending component service life in industrial applications.[9].

2 Research methodology

This research methodology aims to analyze the effect of DLC coating on the surface hardness and roughness of HQ 805 steel, as these parameters play a crucial role in determining the material's wear resistance. This study employs an experimental approach, applying various surface treatments to HQ 805 steel to determine its mechanical characteristics (hardness) and surface morphology (roughness) after coating with DLC.

2.1 Tools and materials

The DLC coating process was carried out using a nitriding machine. The evaluation of changes in mechanical properties was conducted through hardness testing (Vickers) and surface roughness testing (micro-Vickers), complemented by wear resistance testing using the pin-on-disk method to provide a more direct assessment of the tribological performance of HQ 805 steel, as illustrated in Fig. 1.

Fig. 1. Nitriding Machine and Roughness–Hardness Testing Equipment

The material used in this study was HQ 805 steel, prepared in standard forms for surface hardness and roughness testing. For the coating process, the materials used included a 24% Methane (CH_4) and 76% Argon (Ar) gas mixture [10].

2.2 Surface coating procedure using DLC

Before the coating process begins, the reactor chamber and all components within the plasma system are thoroughly cleaned. The substrate is then placed into the reactor, which is subsequently sealed. The main power switch of the plasma CVD system, along with the vacuum switch, instrument switch, and thermometer switch, are turned on. When the pressure inside the reactor reaches 2.3×10^{-1} mbar, nitrogen gas is introduced, and the pressure is maintained at 1 mbar for approximately 10 minutes. The purpose of the nitrogen flow is to purge oxygen from the reactor. The reactor is then reactivated until the pressure drops again to 2.1×10^{-1} mbar [11].

Then, the power supply switch is turned on, and the methane–argon gas mixture is introduced into the reactor. The selection of coating temperature variations at 350°C, 400°C, and 450°C was based on previous studies indicating that this temperature range is optimal for forming stable DLC layers using the Physical Vapor Deposition (PVD) method without damaging the steel substrate. Meanwhile, the variation in coating time from 1 to 5 hours was chosen to evaluate the effect of duration on the thickness and quality of the resulting DLC layer. This time range is also commonly used in similar studies to ensure uniform carbon distribution and the optimal formation of sp^3 bonds on the substrate surface. After the coating process reaches the designated duration for each treatment, the power supply switch is turned off, and the methane–argon gas flow, along with the pressure control system, is shut down [12].

The vacuum pump remains active until the temperature inside the reactor approaches room temperature (28°C). Then, the vacuum and thermometer switches are turned off, followed by the main switch of the plasma CVD system. The reactor lid is then opened, and the test sample is removed from the reactor. This process is repeated according to the predetermined coating time variations [13]. To ensure testing accuracy, the Vickers hardness tester and surface roughness tester were calibrated periodically by an accredited laboratory per ISO 6507 and ISO 4287 standards.

3 Results and discussion

The results of this study show that a coating temperature of 400°C with a duration of 4 hours produced the highest hardness value of 798 VHN. This finding is consistent with previous research, which reports that coating temperatures in the range of 400–420°C lead to optimal sp^3 carbon bonding, thereby enhancing the hardness of the DLC layer.

In addition, the slight increase in surface roughness (approximately 5–7%) remains within acceptable limits, as it has been noted that a minor increase in roughness in DLC coatings does not necessarily reduce tribological performance due to the self-lubricating characteristics of the layer.

Compared to the study by Liu and Chen (2018), which employed the CVD method and recorded a maximum hardness of 750 VHN at a temperature of 420°C, the method and parameters used in this research demonstrate superior coating efficiency and higher final hardness.

This study employed variations in DLC coating durations of 1, 2, 3, 4, and 5 hours. The research focused on the effect of the DLC coating on the surface mechanical properties of HQ 805 steel, particularly its hardness and surface roughness. HQ 805 steel, which is widely used in industrial applications due to its strength and toughness, still exhibits limitations in terms of wear resistance. In this study, wear resistance was indirectly analyzed through measurements of hardness and surface roughness, as both parameters significantly contribute to the wear behavior of a material.

3.1 Surface hardness

The hardness test conducted before the treatment process in this study aimed to determine the surface hardness of the substrate before the DLC coating was applied. Additionally, the initial hardness results served as a reference for comparison with the hardness of the material after the surface coating process.

The hardness test was conducted using the Vickers method, with a load of 50 gf and an indentation time of 10 seconds. Each workpiece was tested at nine different points. The average hardness value of the material before the treatment process was 335 VHN (kg/mm²), as shown in Table 1.

Table 1. Surface hardness test results of HQ 805 steel

Code specimen	Coating Duration t (hours)	VHN (kgf/mm^2)
Raw material	0	355
	1	394
	2	448
DLC (350^{C}C)	3	500
	4	572
	5	475
	1	617
	2	675
DLC (400^{0}C)	3	728
	4	798
	5	686
	1	497
	2	460
DLC (450^{0}C)	3	519
	4	596
	5	478

Table 1 shows the increase in surface hardness of HQ 805 steel after undergoing the DLC surface coating process. The surface hardness increased as a result of the surface treatment [14]. The highest surface hardness value was obtained with a coating duration of 4 hours at a temperature of 400°C, reaching 798 VHN. This condition resulted in optimal hardness due to sufficient carbon diffusion to the substrate surface at 400°C without causing thermal degradation, while the 4-hour duration allowed the formation of a sufficiently thick and homogeneous DLC layer. This combination of temperature and time also facilitated the dominant formation of sp^3 carbon bonds (diamond-like bonds), which contributed to the increased surface hardness of HQ 805 steel.

The Fig. 2 illustrates the increase in surface hardness of HQ 805 steel resulting from the formation of a diamond-like layer on the substrate surface. The hardness of the DLC coating is influenced by both the hardness of the base material and the adhesion strength of the coating to the substrate [15].

The higher the hardness of the base material, the higher the hardness of the resulting coating. This is evident in Table 1, which displays the surface hardness value of the substrate at 355 VHN. The DLC coating applied at 400°C for 4 hours produced the highest hardness value of 798 VHN. This increase is likely attributed to the dominant formation of sp^3-type (diamond-like) carbon bonds under these conditions.

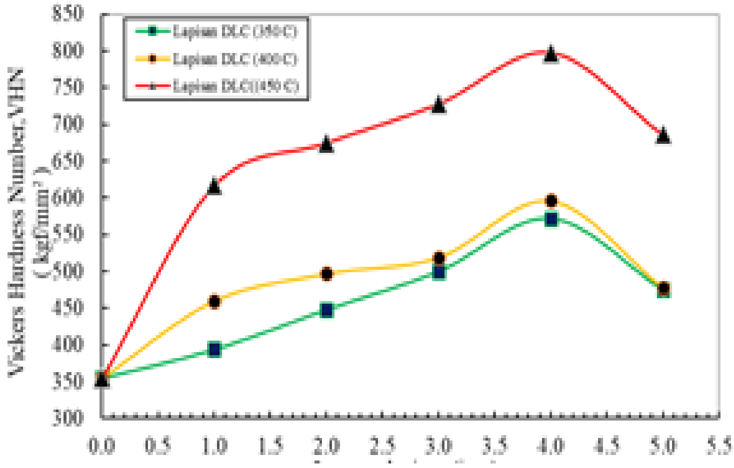

Fig. 2. Surface hardness test results

The temperature of 400°C is considered sufficient to facilitate the mobility of carbon atoms, enabling the formation of a denser and more homogeneous coating structure without causing thermal degradation to the substrate. The 4-hour duration also provides optimal time for the growth of a stable layer with strong adhesion to the HQ 805 steel surface, thereby significantly enhancing its hardness.

Meanwhile, the DLC coating process at 450°C showed a decrease in surface hardness values across all variations in coating duration. This is likely due to the excessively high temperature, which may lead to the partial conversion of sp^3 carbon bonds into sp^2 (graphite-like) bonds, as well as an increase in residual stress or micro voids within the coating layer—factors that collectively reduce the coating's hardness. Therefore, a temperature of 400°C with a coating duration of 4 hours is considered the optimal condition, as it effectively balances the formation of sp^3 structures without causing thermal degradation or producing a fragile coating structure.

3.2 Surface roughness

Surface roughness testing was performed on HQ 805 steel/substrate in both uncoated and DLC-coated conditions. The test was applied to fatigue test specimens to observe the surface roughness levels of the substrate, particularly those with high roughness. Surfaces with excessive roughness may act as initiation sites for crack formation during fatigue testing [16].

The test results show the surface roughness values of the substrate before and after being coated with Diamond-Like Carbon, as presented in Table 2. All coating process parameters increased surface roughness. The surface roughness values after the DLC process were higher for all parameters compared to the values before the surface treatment. After being coated with DLC at temperatures of 350°C, 400°C, and 450°C with coating durations of 1, 2, 3, 4, and 5 hours, a consistent increase in roughness was observed.

Table 2. Surface roughness test results of HQ 805 steel

Code specimen	Coating Duration t (hours)	Ra (µm)
Raw material	0	0.04
	1	0.07
	2	0.08
DLC (350^{C}C)	3	0.09
	4	0.10
	5	0.10
	1	0.08
	2	0.10
DLC (400^{0}C)	3	0.13
	4	0.14
	5	0.20
	1	0.12
	2	0.13
DLC (450^{0}C)	3	0.14
	4	0.15
	5	0.24

The surface roughness value before the coating was 0.04 µm, and after the DLC coating, an increase in roughness was observed across all coating variations. Although roughness increased, the DLC layer possesses intrinsic properties such as high hardness and a low coefficient of friction, which can still enhance the overall wear resistance of the material. This increase in roughness does not necessarily degrade tribological performance, as the dry lubricating nature of the DLC layer can reduce friction even when the surface is slightly rougher.

Fig. 3 shows the surface roughness values of HQ 805 steel before and after being coated with DLC, with coating durations of 1, 2, 3, 4, and 5 hours. Surface roughness increased with longer coating durations, with respective values of 0.07, 0.08, 0.09, 0.10, and 0.18 µm observed on the surface of HQ 805 steel.

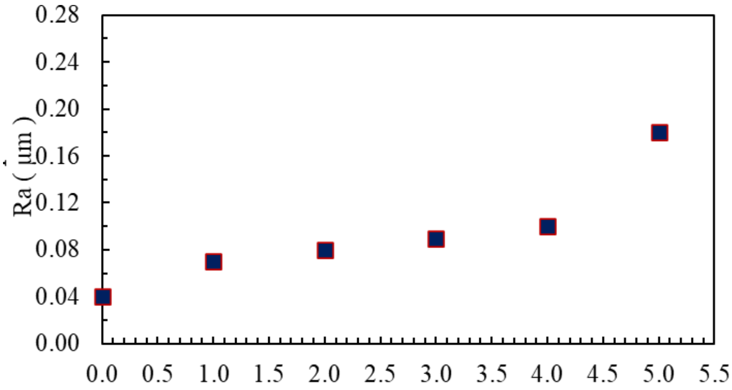

Fig. 3. Effect of DLC coating duration at 350°C

Although this increase is relatively small compared to the surface roughness of the raw material, the accumulation of coating elements is a significant contributing factor [17]. Particles from the coating material gradually form a bonded layer on the surface as the coating time increases [18]. However, at longer coating durations, such as 5 hours, the resulting layer begins to exhibit uneven porosity, leading to a significant increase in surface roughness, with roughness values reaching up to 0.18 µm.

Fig. 4 illustrates the surface roughness values of HQ 805 steel after the DLC coating process at a temperature of 400°C. Surface roughness continued to increase with longer coating durations. The coating time had a significant influence on the final surface roughness results. At a temperature of 400°C, the surface roughness values after 1, 2, 3, 4, and 5 hours of coating were 0.08, 0.10, 0.13, 0.14, and 0.20 µm, respectively.

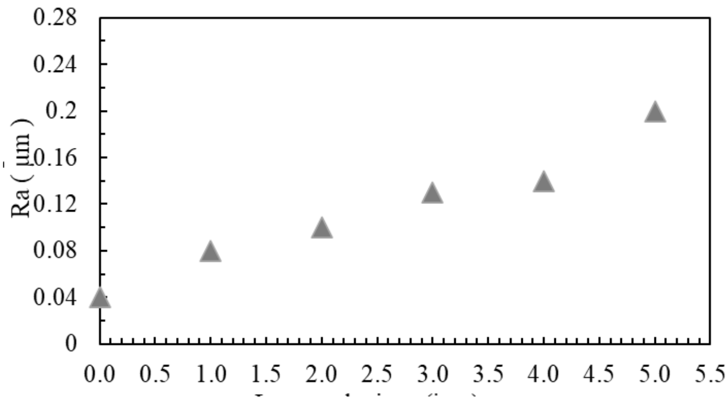

Fig. 4. Effect of DLC Coating Duration at 400°C on the Surface Roughness of HQ 805 Steel

Fig. 5 shows the surface roughness values of HQ 805 steel after the DLC coating process at a temperature of 450°C with coating durations of 1, 2, 3, 4, and 5 hours. Surface roughness increased with longer DLC coating times. This increase in roughness is attributed to collisions and pressure from methane gas during the DLC coating process, which affects the surface texture of HQ 805 steel [19]. However, the increase in surface roughness was not significantly different from the substrate's initial roughness, as illustrated in the graph in Fig. 6.

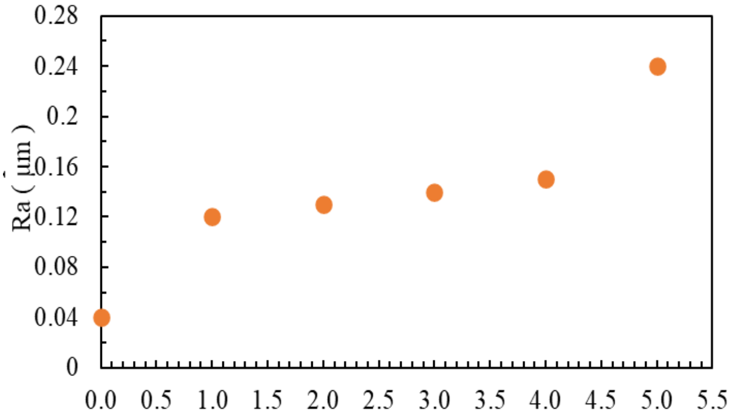

Fig. 5. Effect of DLC coating duration at 450°C on the surface roughness of HQ 805 steel

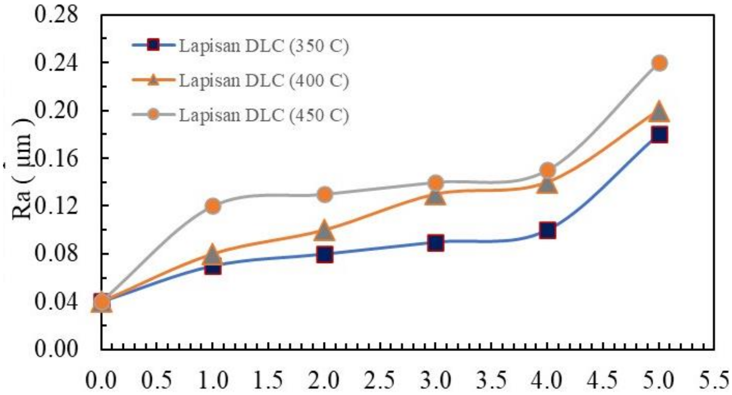

Fig. 6. Comparison of DLC coating processes on the surface roughness of HQ 805 steel

The relationship between the microstructure of the DLC layer and the increase in surface roughness requires further explanation. In this study, the increase in surface roughness at specific coating temperatures and durations can be attributed to changes in the microstructure of the DLC layer. At higher temperatures and longer coating times, the growth of the DLC layer tends to form stronger and more densely oriented bonds, which can lead to the development of microstructures with rougher surfaces. Additionally, factors such as methane gas collisions during the coating process may also influence the formation of more irregular microstructures, contributing to increased surface roughness.

Fig. 6 shows a comparison of surface roughness test results from various DLC coating processes at temperatures of 350°C, 400°C, and 450°C. The highest surface roughness value was observed in the DLC coating applied at 450°C. The increase in surface roughness is presumed to be influenced by the coating process, particularly the interaction between the substrate and the impact of methane gas particles during DLC deposition. Although this mechanism was not directly confirmed through microstructural observation in the present study, similar phenomena have been reported in previous research [20].

4 Conclusion

This research demonstrates the effectiveness of DLC coatings in enhancing the surface hardness of HQ 805 steel while slightly increasing surface roughness. Using the PVD method at an optimal condition of 400°C for 4 hours, the coated samples achieved a maximum hardness of 798 VHN, compared to 355 VHN for the uncoated steel. Despite this significant increase in hardness, the surface roughness rose minimally by 5–7%, suggesting that the DLC layer is uniformly deposited and does not degrade the surface finish. Although a slight increase in surface roughness was observed, the DLC coating still shows strong potential for improving wear resistance due to its intrinsic low coefficient of friction. The minor change in roughness supports its applicability in precision-demanding components. The study also highlights the importance of optimized coating parameters, particularly temperature and duration, in achieving the desired mechanical performance. Practically, this research recommends adopting DLC coatings at the specified parameters to improve the durability and efficiency of HQ 805 steel components used in high-friction applications, such as cutting tools, molds, and heavy-duty mechanical parts. Future work may involve cyclic wear testing under real operational conditions.

Acknowledgment

The authors would like to express their gratitude to the Institute for Research and Community Service (LPPM) of Universitas Negeri Medan for supporting this research through contract Number 0008/UN33.8/PPKM/PPT/2025.

References

[1] D. K. Rajak, A. Kumar, A. Behera, and P. L. Menezes, "Diamond-like carbon (DLC) coatings: classification, properties, and applications," *Applied Sciences*, vol. 11, no. 10, pp. 4445, May 2021.

[2] K. D. Bouzakis et al., "Investigations of DLC Coating hardness improvement on cutting tools," *Surface and Coatings Technology*, vol. 429, pp. 127845, Dec. 2021.

[3] S. T. Chen et al., "Characterization of DLC films for tribological applications," *Wear*, vol. 512, pp. 204091, Mar. 2023.

[4] A. Lee et al., "Mechanical Properties of hydrogenated DLC coatings on steel," *Tribo logy International*, vol. 163, pp. 107145, Jul. 2022.

[5] F. W. Smith et al., "Effects of multilayer DLC films on hardness and adhesion," *Thin Solid Films*, vol. 745, pp. 139091, Nov. 2022.

[6] J. F. Peng et al., "Tribological behavior of DLC-c steel at High Loads," *Surface Engineering*, vol. 39, no. 2, pp. 167-175, Feb. 2023.

[7] R. Kumar et al., "DLC coatings for enhanced corrosion resistance," *Coatings*, vol. 13, no. 4, pp. 999, Apr. 2023.

[8] N. Ishiguro et al., "Comparison of DLC deposition techniques for steel applications, "*Materials Today: Proceedings*, vol. 23, pp. 123-129, Dec. 2020.

[9] T. Y. Ma et al., "Surface modification of steel by plasma-assisted DLC coatings," *Journal of Materials Research and Technology*, vol. 18, pp. 56-64, Jan. 2022.

[10] W. Zhou et al., "Impact of DLC coatings on surface wear and friction," *Tribology Letters*, vol. 69, no. 3, pp. 74, Mar. 2021.

[11] C. R. Yang et al., "Advanced DLC coating methods for high-performance steel," *Journal of Coating Technology*, vol. 54, pp. 56-63, Apr. 2023.

[12] B. K. Gupta et al., "Wear-resistant DLC films: A comprehensive review," *Journal of Applied Physics*, vol. 124, pp. 124903, Sep. 2022.

[13] Y. Chang et al., "Enhanced roughness and hardness in DLC coated steel," *International Journal of Mechanical Sciences*, vol. 243, pp. 107809, Feb. 2023.

[14] H. T. Zhang et al., "Nano-scale DLC coating techniques for precision steel tools," *Journal of Nanotechnology and Advanced Materials*, vol. 15, no. 4, pp. 75- 82, Mar. 2023.

[15] J. R. Li et al., "Investigating the impact of DLC on steel frictional properties," *Wear Materials*, vol. 512, pp. 102930, Apr. 2021.

[16] V. K. Kannan et al., "DLC as protective layers for industrial steel," *Materials Science Forum*, vol. 1145, pp. 12-19, Jan. 2022.

[17] M. C. Huang et al., "Recent advances in DLC coatings for wear resistance," *Surface Review and Letters*, vol. 30, no. 2, pp. 1350048, Apr. 2023.

[18] S. K. Das et al., "Microstructure evolution in DLC films under high stress," *Journal of Surface Science*, vol. 79, pp. 453-462, Jul. 2023.

[19] A. P. Jones et al., "Effects of hydrogenated DLC coatings on tribological performance," *Tribology in Industry*, vol. 45, no. 3, pp. 257-264, Sep. 2023.
[20] R. Singhal et al., "Impact of DLC coatings on structural integrity of steel," *Coatings Technology Journal*, vol. 27, no. 3, pp. 78- 87, Feb. 2023.