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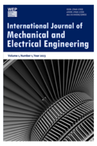

Research Status of Diamond-Like Carbon Coatings

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ABSTRACT

Diamond-like Carbon (DLC) coatings are amorphous carbon-based thin films composed of randomly mixed sp^1, sp^2, and sp^3 hybridized carbon. They combine the high hardness of diamond and the low friction property of graphite, with performance regulated by the sp^3/sp^2 ratio. Widely used in fields such as mechanical processing, they can address key issues in tool surface modification. This paper reviews its research status: in terms of structure, it includes two core models and two categories (a-C:H, a-C); preparation focuses on PVD (including HiPIMS) and CVD (PE-CVD); aiming at common issues like high internal stress, it summarizes optimization methods such as element doping, which requires balancing stress and hardness. The paper concludes with an outlook on the development trends of preparation technologies and application prospects in tools, providing a reference for industrial optimization.

KEYWORDS

Diamond-like Carbon (DLC) Coatings; Preparation Technology; Performance Optimization.

1. INTRODUCTION

Diamond-like Carbon (DLC) is an amorphous carbon with characteristics such as high hardness, stable chemical properties, low friction coefficient, and good biocompatibility, making it widely used in fields like biomedical engineering, aerospace, automotive parts, and electronic components. The sp^3 and sp^2 hybridized C—C bonds in DLC are the key determinants of its performance. Similarly, among substances containing a large number of C—C bonds, diamond with sp^3 bonds has a tetrahedral internal structure and extremely high hardness; while graphite, which has a planar regular hexagonal structure connected by sp^2 bonds and π bonds, features a layered structure with large interlayer spacing, weak interactions, easy sliding, and excellent lubricity [1], but its hardness is much lower than that of diamond. As amorphous carbon, DLC contains a certain amount of both sp^3 and sp^2 bonds, thus combining the properties of diamond and graphite. The higher the content of sp^3 bonds, the closer its characteristics are to diamond, with higher hardness, elastic modulus, and wear resistance; conversely, it is closer to graphite, with lower hardness and a smaller friction coefficient. In the field of mechanical processing, DLC coatings are often deposited on tool surfaces to improve cutting performance due to their excellent properties. Cutting tools such as cemented carbide tools, high-speed steel tools, and ceramic tools often face problems like insufficient hardness, high friction, excessive wear, and material adhesion during processing. However, DLC coatings, with their high hardness and good wear resistance, can effectively protect the tool substrate, enabling tools to meet the requirements of processing high-hardness materials and significantly extending their service life. The low friction coefficient of DLC coatings can effectively enhance the applicability of tools in dry cutting and reduce pollution caused by cutting fluids. In addition, DLC coatings have excellent anti-adhesion performance and strong chemical stability, which can effectively reduce material adhesion during tool processing. Therefore, DLC-coated tools are widely used in non-ferrous metal processing, composite material processing, and other fields.

Based on the service performance of DLC-coated tools, this paper summarizes and organizes the principles and processes of DLC coating preparation technologies, and introduces the performance characteristics and improvement methods of DLC coating materials. It also summarizes and prospects the development of DLC-coated tools.

2. CONCEPT AND STRUCTURE OF DIAMOND-LIKE CARBON (DLC) COATINGS

Diamond-like Carbon (DLC) coatings are a class of amorphous carbon-based thin film materials composed of randomly mixed diamond-type sp^3-hybridized carbon (sp^3-C), graphite-type sp^2-hybridized carbon (sp^2-C), and a small amount of sp^1-hybridized carbon. These coatings combine the high hardness of the diamond phase and the low friction property of the graphite phase, enabling the synergistic integration of the advantageous performances of the two phases. In the performance regulation mechanism of DLC films, the proportion of sp^3 bonds is the core factor determining their mechanical properties (such as microhardness, wear resistance, and friction reduction properties); while the content of sp^2 bonds mainly affects the physical functional properties of the films, including key indicators such as optical transmittance and electrical conductivity. Based on this structure-property relationship, the wide-range tunability of the comprehensive performance of DLC coatings can be achieved by regulating the relative ratio of sp^3/sp^2 hybridized carbon. This characteristic endows them with enormous application potential in fields such as mechanical processing and precision device protection, thereby making them a research hotspot in both academic and industrial circles.

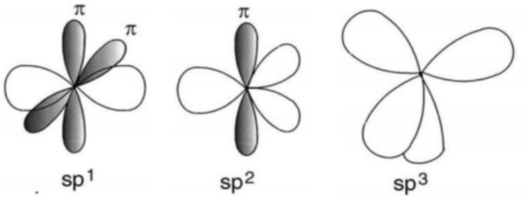

Figure 1. Schematic diagram of sp^1-C, sp^2-C, and sp^3-C

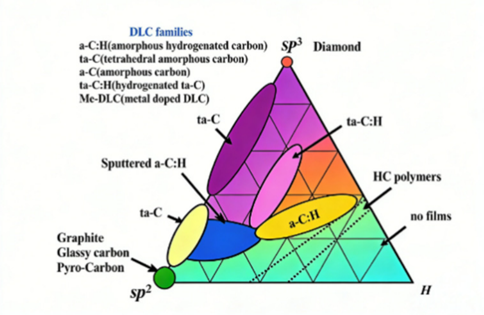

Figure 2. Ternary Phase Diagram of Amorphous Carbon [2]

The hybridization configurations of carbon in DLC coatings mainly include three types: sp^1-C, sp^2-C, and sp^3-C, with their hybrid orbital schematic diagram shown in Figure 1-1. Specifically, sp^1 hybridization involves the combination of one 2s orbital and one 2p orbital, forming two equivalent orbitals. The bonding electrons form σ bonds, while the remaining two 2p electrons constitute two independent π bonds. For sp^2 hybridization, one 2s orbital hybridizes with two 2p orbitals to generate three trigonal planar orbitals (with a bond angle of 120°), and strong σ bonds are formed through electron cloud overlap, leaving one 2p electron to form a weak π bond. In contrast, sp^3 hybridization is the complete hybridization of one 2s orbital and three 2p orbitals, resulting in four tetrahedral equivalent orbitals. The bonding electrons overlap to the maximum extent, forming extremely strong σ bonds without any unhybridized lone pair electrons. Jacob et al. [2] proposed that amorphous carbon films are mainly composed of sp^2-C, sp^3-C, and H atoms. Based on the relative contents of these three phases, the ternary phase diagram of amorphous carbon (as shown in Figure 2) was constructed. DLC coatings are generally classified into two categories: hydrogenated amorphous carbon films (a-C:H) and hydrogen-free amorphous carbon films (a-C). Different preparation processes will affect the relative contents of the three phases, thereby altering the structure and properties of the films.

Currently, there are two main structural models for DLC coatings: First is the fully constrained network model proposed by Angus and Jansen[3] , with its schematic diagram shown in Figure 3. Based on this carbon atom hybridization network model, carbon atoms in the irregular carbon network can form a fully cross-linked structure: when the number of constraints on carbon atoms equals the mechanical degrees of freedom, the network is regarded as a fully constrained state. As the coordination number increases, the number of covalent bonds in the network rises, reducing the total system energy; at the same time, the bond lengths and bond angles of C-C bonds undergo distortion, introducing additional strain energy into the system. If the energy reduction offsets the strain energy increment, the network reaches a thermodynamic equilibrium state. Based on this, the optimal average coordination number of carbon atoms can be defined, and thus the optimal sp^3/sp^2 bonding ratio in the film can be determined. When the number of constraints on carbon atoms exceeds the mechanical degrees of freedom, the coating system is in an over-constrained state, with significantly increased internal stress and hardness; conversely, when the number of constraints is less than the degrees of freedom, the system is under-constrained, resulting in low internal stress and hardness. Second is the two-phase structure model proposed by Robertson [4]. It holds that the first phase consists of independent clusters composed of sp^2-C, and the second phase is a three-dimensional network structure formed by sp^3-C and defects present in the coating. The first phase is embedded in the second phase and controls the optoelectronic properties of the coating, while the second phase, as the cluster boundary, determines the mechanical properties of the film. sp^2 hybridization exists in the form of graphite-like layered clusters, which can not only be embedded in the three-dimensional network structure but also connected to the terminals of the network structure as terminal groups to terminate the cross-linking of the second phase.

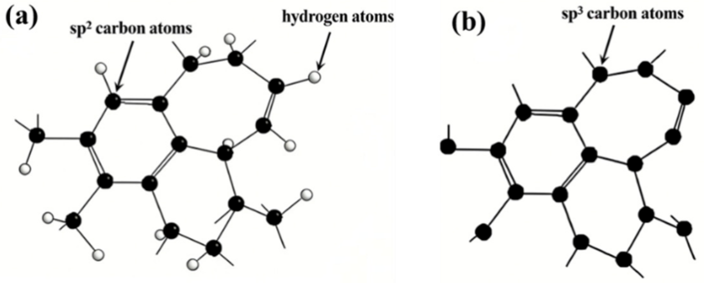

Figure 3. Two-Dimensional Structural Models of DLC Coatings: (a) a-C:H, (b) a-C [4]

3. PREPARATION METHODS OF DIAMOND-LIKE CARBON (DLC) COATINGS

Diamond-Like Carbon (DLC) coatings, as an amorphous carbon-based material, have become core surface functional coatings in fields such as high-end manufacturing, medical devices, and aerospace by virtue of their high hardness, ultra-low friction coefficient, and excellent chemical inertness[5]. However, their industrial application has long been restricted by three major bottlenecks: weak film-substrate adhesion, poor thermal stability, and high residual stress[6] . To break through these limitations, over the past two decades, researchers have promoted the evolution of DLC coating preparation technology from a single Physical Vapor Deposition (PVD) to composite processes and gradient structure design through measures such as innovating deposition processes, gradually realizing the targeted regulation of performance[7].

3.1. Physical Vapor Deposition

Physical Vapor Deposition (PVD) is a type of coating technology that, in a vacuum environment, vaporizes or ionizes solid target materials through physical means, and then deposits the target components on the substrate surface via vapor phase transport to form a coating. In the field of DLC coating preparation, the PVD technologies that have been extensively researched and widely applied in engineering mainly include Ion Beam Deposition (IBD), Magnetron Sputtering (MS), and Arc Ion Plating (AIP).

As shown in Figure 4(a), Ion Beam Deposition (IBD) is the earliest method adopted for DLC coating preparation. Its working principle is to strip carbon ions from a graphite cathode by means of high-voltage gas discharge and gas ion bombardment effects, and then accelerate the carbon ions through an electric field to deposit them on the negatively charged substrate surface. This technology boasts advantages such as precise regulation of carbon ion energy and concentration, low deposition temperature, low internal stress of the coating, and excellent film-substrate adhesion. However, limited by the shortcoming of low deposition efficiency, the application of traditional IBD technology in DLC coating preparation has gradually diminished.

Magnetron Sputtering (MS) is one of the commonly used methods for preparing DLC coatings. Its principle is to generate high-energy gas ions through gas glow discharge; these ions are accelerated by an electric field to bombard the solid carbon target. The surface particles of the carbon target gain energy, detach from the target surface into the gas phase, and finally deposit on the substrate, as shown in Figure 4(b). During this process, the magnetic field around the carbon target confines the secondary electrons generated during sputtering within a certain range, increasing the probability of their collision with gas molecules, thereby improving the target ionization rate [8]. Nevertheless, the target ionization rate of conventional magnetron sputtering technology is still relatively low, resulting in poor adhesion between the prepared DLC coatings and the substrate.

High Power Impulse Magnetron Sputtering (HiPIMS) features high pulse peak power (2-3 orders of magnitude higher than traditional magnetron sputtering) and low pulse duty cycle (0.5%-10%), which can achieve high target ionization rate and thus better coating performance [9]. It has been a widely researched DLC preparation method in recent years. Wang L. et al. [10] prepared nanocomposite WC-DLC coatings using HiPIMS. As the substrate bias increased from -40 V to -120 V, the columnar structure of the coating gradually decreased, fine-grained structures appeared, and the wear resistance improved; when the bias continued to increase to -200 V, the coating exhibited a lamellar structure, and the wear resistance deteriorated. Guo C.Q. et al. [11] studied the effect of bias voltage on the internal stress of Al-DLC coatings prepared by HiPIMS. The results showed that with the increase of bias voltage, the roughness decreased, while the sp^3 bond content and internal stress in DLC increased. Researchers attributed the increase in internal stress to the substrate temperature rise and film disorder caused by higher bias voltage.

Arc Ion Plating (AIP) for DLC coating preparation utilizes a cathodic arc source to generate plasma, which sustains the arc discharge between the cathode and the vacuum chamber. Controlled by a magnetic field, arc spots move on the surface of the solid carbon target, forming a molten pool and evaporating a large number of C atoms. The C atoms are ionized at high temperature, accelerate towards the substrate surface, and ultimately deposit to form a coating (see Figure 4(c)).A common issue with AIP technology is the unsatisfactory surface finish of the prepared coatings caused by the presence of large droplets. If a DC power supply is used for the cathodic arc source, the resistivity of the graphite target decreases with increasing temperature, causing the arc spots to linger at high-temperature areas for a long time and leading to local corrosion and deep pitting on the cathode surface[12], which further exacerbates the generation of large carbon droplets. Using a pulsed high-current power supply can increase the moving speed of the arc on the graphite surface, reduce the generation of large carbon droplets, and improve surface quality [13]. In addition, adding a magnetic filtering device to the arc equipment and adjusting the preparation process parameters can also reduce the deposition of large carbon droplets.Han Liang et al.[14]found that the current of the magnetic filter is an important process parameter affecting the sp^3 bond content of ta-C films; when an appropriate deposition bias is selected, a smaller magnetic filter current can increase the sp^3 content. Wang M. et al. [15]prepared DLC coatings on cemented carbide substrates using different substrate biases. The film thickness was approximately 600 nm and gradually decreased with increasing bias magnitude; under a bias of -200 V, an ultra-hard DLC coating with a hardness of 56.7 GPa and an elastic modulus of 721.1 GPa was obtained.

3.2. Chemical Vapor Deposition

The general process of preparing DLC coatings by Chemical Vapor Deposition (CVD) involves gaseous substances such as activated carbon source gases and inert gases undergoing a series of collisions and chemical reactions, followed by deposition on the substrate surface to form DLC coatings. Compared with PVD methods, CVD methods can more precisely control the proportion of reactants such as carbon sources and doping elements, and can deposit coatings on the surface of more complex parts [16]. DLC coatings prepared by CVD methods contain a large amount of hydrogen and are often used to fabricate hydrogenated DLC coatings. Currently, the most widely used CVD method for DLC coating preparation is Plasma-Enhanced Chemical Vapor Deposition (PE-CVD). Its basic principle is that gas glow discharge in a vacuum generates plasma; a large number of high-energy electrons in the plasma collide and react with various particles in the gas phase. The resulting positively charged active carbon-containing groups are accelerated to bombard the substrate under the attraction of the substrate's negative pressure, and nucleate and grow on the substrate surface (see Figure 5).Huang B. et al.[16]studied the preparation of Si-DLC coatings using PE-CVD technology and found that the deposition temperature affects the sp^3/sp^2 ratio of the coating. When the deposition temperature is between 60 ℃ and 120 ℃, the sp^3 bond content increases and the hardness improves; when the deposition temperature exceeds 120 ℃, the formation of metastable sp^3 bonds is inhibited, leading to a decrease in hardness. Xiong Wenwen et al. [17] deposited DLC coatings on silicon substrates using Radio Frequency Plasma-Enhanced Chemical Vapor Deposition (RF-PECVD). The research showed that the structure of the coating is closely related to the methane-argon flow ratio and the position of the substrate in the reaction chamber. Xu Shipeng et al. [18] adopted a self-designed optimized PE-CVD method, which combines a water-cooled radio frequency double-helix electrode with a planar electrode. This design increases the mean free path of ion movement, promotes ion bombardment, and thus significantly improves the coating quality.

4. PERFORMANCE OPTIMIZATION OF DIAMOND-LIKE CARBON (DLC) COATINGS

DLC coatings deposited by different preparation processes generally have several common defects. Among them, high internal stress and susceptibility to graphitization are the core inducements for the premature failure of DLC-coated tools under high-load and high-temperature service conditions. The exploration and optimization targeting these two key issues are the core directions to improve the comprehensive performance of DLC-coated tools (see Figure 1-6). The high internal stress of DLC coatings not only reduces the bonding strength between the coating and the substrate, shortens the service life of tools, but also restricts the achievable thickness of DLC coatings. Grigoriev S. et al. [19] found that when preparing DLC coatings on turning tools by arc ion plating technology, the coating would peel off due to excessively high internal stress when the coating thickness exceeds 1 μm. The internal stress of DLC coatings originates from three aspects: First, due to the significant difference between the low thermal expansion coefficient of DLC coatings and that of general substrates, the two shrink to different degrees during cooling, resulting in thermal stress inside the coating [20]; Second, during the deposition process, C atoms with lower energy cannot penetrate the surface and can only be adsorbed on the surface to grow in an sp^2 hybrid structure, while C atoms with higher incident energy penetrate the surface layer of the substrate through lattice gaps and stay in the subsurface layer as interstitial atoms. This increases the local density inside the coating and causes deformation, leading to an increase in the internal stress of the coating, which is the main source of internal stress; Third, the stress caused by structural defects such as impurities, vacancies, and stacking faults during the coating deposition process [21]. Methods to improve the internal stress of DLC coatings include element doping and adding transition layers.

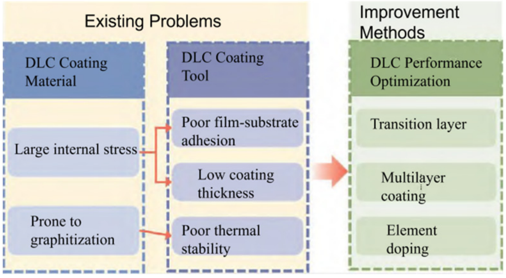

Figure 4. Existing Problems and Improvement Methods of DLC-Coated Tools

Doping modification is one of the simplest and most effective approaches. By incorporating a single element or compound, multiple elements or compounds, or a co-doping of elements and compounds into DLC coatings, it can reduce the residual stress of the coating, regulate the relative contents of sp^2-C, sp^3-C and H in the coating, and reshape the coating structure—thereby improving the mechanical and thermal stability of the coating. It is currently a research hotspot in the field of amorphous carbon coatings. The high internal stress of DLC coatings not only causes poor film-substrate adhesion of coated tools (which impairs tool life) but also limits the thickness of DLC coatings. When Grigoriev S. et al. [20] prepared DLC coatings on turning tools using arc ion plating technology, they found that when the coating thickness exceeds 1 μm, the coating will peel off due to excessively high internal stress. The internal stress of DLC coatings originates from three aspects:The large difference between the low thermal expansion coefficient of DLC coatings and that of ordinary substrates leads to inconsistent shrinkage during cooling, thus generating thermal stress inside the coating [22]. During deposition, C atoms with low energy cannot penetrate the surface and only adsorb on it to grow in an sp^2 hybrid structure; in contrast, C atoms with high incident energy penetrate the substrate surface layer through lattice gaps and stay in the subsurface layer as interstitial atoms. This increases the local density inside the coating and causes deformation, thereby raising the internal stress—which is the main source of internal stress [23].Stress caused by structural defects (such as impurities, vacancies, and stacking faults) during the coating deposition process[24]. Methods to improve the internal stress of DLC coatings include element doping and adding transition layers. Sharifahmadian O. et al. [25]prepared N-doped DLC coatings using CVD technology: the C-H bonds formed in the coating reduced the interconnection between C atoms, lowered the coating's internal stress, and improved film-substrate adhesion. Zhou Y. et al.[26]confirmed in the friction and wear test of DLC coatings that the DLC coating with an Al-TiN transition layer helps enhance film-substrate adhesion. DLC coatings exhibit graphitization at temperatures above ~350°C, resulting in poor thermal stability[27]. At high temperatures, the activity of particles in DLC coatings increases; beyond a certain temperature, the interaction of high-energy C-containing particles near the subsurface forms a thermal peak effect, causing internal structural relaxation—so the coating transforms from diamond characteristics to graphite characteristics[28]. Factors such as coating composition, structure, and thickness [29] all affect the graphitization of DLC coatings. In fact, the graphitization of DLC coating tools during cutting has two sides: on one hand, graphitized coatings can provide a low friction coefficient, reducing cutting force and cutting temperature [30-31]; on the other hand, excessively fast graphitization under overly high cutting temperatures reduces the coating's hardness, leading to rapid failure. The latter often restricts the application of DLC coating tools, so it is crucial to improve the thermal stability of DLC coatings and slow down the graphitization process. The doped elements can be divided into non-carbide-forming elements (e.g., Al, Cu, Ag, etc.) and carbide-forming elements (e.g., Cr, Ti, W, V, Zr, etc.). The former are embedded in the three-dimensional network structure of matrix carbon in the form of crystalline or amorphous nanoclusters, while the latter combine with matrix atoms to form hard carbides, which can alleviate coating stress and improve coating performance to a certain extent. Xu et al. [32]prepared Al-DLC coatings via a hybrid plasma system. Al atoms were solid-solved in the amorphous matrix, which greatly reduced the coating stress, and the coatings exhibited high film-substrate adhesion and wear resistance. Santiago et al.[33]incorporated Cr into DLC: when the Cr content reached 3 at.%, the coating showed better mechanical and tribological properties at high temperatures. Studies indicate that the stress in DLC coatings mainly originates from sp^3 C-C bonds, and most doped elements can promote the transformation of sp^3 bonds to sp^2 bonds, thus releasing the stress. However, the reduction of sp3 bonds also leads to a loss of hardness. Although carbophilic elements can form MeC hard phases to mitigate the hardness decrease, excessive or oversized MeC will destroy the integrity of the carbon network structure and reduce toughness. Therefore, element doping should be appropriate and not excessive. He et al.[34]doped Si into a-C:H coatings. Research showed that Si incorporation increased the sp3 bond content in the coating, and the internal stress decreased by at least 60% compared with undoped DLC coatings. Er et al.[35]prepared Si-DLC coatings (with Si contents of 0–15 at.%) by sputtering deposition: as the Si content increased, the graphitization temperature of the coating rose, and its thermal stability was enhanced.

5. SUMMARY

Diamond-like Carbon (DLC) coatings are a class of amorphous carbon-based thin film materials composed of randomly mixed sp^1, sp^2, and sp^3 hybridized carbon. They are characterized by combining the high hardness of the diamond phase and the low friction property of the graphite phase, with their performance mainly regulated by the ratio of sp^3/sp^2 hybridized carbon. DLC coatings are widely used in fields such as mechanical processing, biomedical engineering, and aerospace. Particularly in tool surface modification, they can effectively address issues like insufficient hardness, excessive wear, and material adhesion.This paper systematically reviews the research status of DLC coatings: In terms of structure and concept, it clarifies the essence of their hybrid configuration, introduces two core structural models (the fully constrained network model and the two-phase structure model), as well as the classification system of hydrogenated amorphous carbon films (a-C:H) and hydrogen-free amorphous carbon films (a-C). In terms of preparation methods, it focuses on elaborating Physical Vapor Deposition (PVD) technologies including Ion Beam Deposition, Magnetron Sputtering (including High Power Impulse Magnetron Sputtering, HiPIMS), and Arc Ion Plating, as well as Plasma-Enhanced Chemical Vapor Deposition (PE-CVD) under Chemical Vapor Deposition (CVD), analyzing the principles, advantages, and process optimization directions of each method. In terms of performance optimization, aiming at common issues of DLC coatings such as high internal stress, poor thermal stability, and weak film-substrate adhesion, it summarizes key improvement methods including element doping (divided into non-carbide-forming elements and carbide-forming elements), introduction of transition layers, and multi-layer coating design, and clarifies that doping needs to balance stress and hardness by regulating the sp^3/sp^2 conversion. Finally, this paper presents an outlook on the development trends of DLC coating preparation technologies and their application prospects in tools, providing a reference for their industrial optimization and expanded applications.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

[1] Lv Bolin, et al. Research Progress on Graphite's Tribological Properties, Lubrication Mechanism and Modification. Materials Report 29.19 (2015): 60-66.

[2] Jacob W, Möller W. On the structure of thin hydrocarbon films[J]. Applied Physics Letters, 1993, 63(13): 1771-1773.

[3] Angus J C, Jansen F. Dense ‘‘diamondlike’’hydrocarbons as random covalent networks[J]. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 1988, 6(3): 1778-1782.

[4] Robertson, J. Mechanical properties and coordinations of amorphous carbons[J]. Physical review letters, 1992,68(2): 220-223.

[5] Gao T, Li C, Wang Y, et al. Carbon fiber reinforced polymer in drilling: From damage mechanisms to suppression[J]. Composite Structures, 2022, 286: 115232.

[6] Grigoriev S N, Volosova M A, Fedorov S V, et al. The effectiveness of diamond-like carbon aC: H: Si coatings in increasing the cutting capability of radius End mills when machining heat-resistant nickel alloys[J]. Coatings, 2022, 12(2): 206.

[7] Erdemir A, Fontaine J, Donnet C. An overview of superlubricity in diamond-like carbon films[J]. Tribology of Diamond-Like Carbon Films: Fundamentals and Applications, 2008: 237-262.

[8] Zhu Guo. Multi-scale Simulation and Experimental Research on Physical Processes Related to Magnetron Sputtering Coating [D]. Wuhan: Huazhong University of Science and Technology, 2019.

[9] Wang Qimin, Zhang Xiaobo, Zhang Shihong, et al. Research Progress on Deposition of Hard Coatings by High-Power Pulse Magnetron Sputtering Technology [J]. Journal of Guangdong University of Technology, 2013, 30(4): 1-13.

[10] Wang L, Jin J, Zhu C, et al. Effects of HiPIMS pulse-length on plasma discharge and on the properties of WC-DLC coatings[J]. Applied surface science, 2019, 487: 526-538.

[11] Guo C Q, Li H Q, Peng Y L, et al. Residual stress and tribological behavior of hydrogen-free Al-DLC films prepared by HiPIMS under different bias voltages[J]. Surface and Coatings Technology, 2022, 445: 128713.

[12] Vetter J. 60 years of DLC coatings: historical highlights and technical review of cathodic arc processes to synthesize various DLC types, and their evolution for industrial applications[J]. Surface and Coatings Technology, 2014, 257: 213-240.

[13] Witke T, Schuelke T, Schultrich B, et al. Comparison of filtered high-current pulsed arc deposition (φ-HCA) with conventional vacuum arc methods[J]. Surface and coatings technology, 2000, 126(1): 81-88.

[14] Han Liang, Zhang Tao, Liu Delian. Process Optimization Study on the Deposition of Tetrahedral Amorphous Carbon Films with High Sp^3 Bond Content by Magnetic Filtration Cathode Arc Technology [J]. Journal of Vacuum Science and Technology, 2013 (3): 203-207.

[15] Wang M, Zhang L, Lin G. Improved mechanical and tribological properties of diamond-like carbon films by adjusting pulsed substrate bias[J]. Diamond and Related Materials, 2022, 130: 109402.

[16] Huang B, Liu L, Han S, et al. Effect of deposition temperature on the microstructure and tribological properties of Si-DLC coatings prepared by PECVD[J]. Diamond and Related Materials, 2022, 129: 109345.

[17] Xiong Wenwen, He Song, Zheng Songsheng, et al. Preparation of diamond-like carbon films by RF-PECVD method [J]. Journal of Materials Research, 2021, 35(2): 154-160.

[18] Xu Shipeng, Zhan Faqi, Zheng Yuehong, et al. Preparation and structure and mechanical properties of hydrogen-containing tetrahedral amorphous carbon films [J]. Journal of the Chinese Ceramic Society, 2022, 50(10): 2651-2656.

[19] Grigoriev S, Volosova M, Fyodorov S, et al. DLC-coating application to improve the durability of ceramic tools[J]. Journal of Materials Engineering and Performance, 2019, 28(7): 4415-4426.

[20] Zhang Ting, He Juan, Ren Ying, et al. Research Progress on Residual Stress of Diamond-like Carbon Films [J]. Materials Report, 2016, 30(1): 84-87, 95.

[21] Chen, Y, Mei F, Lin X, et al.The effect of carbon doping on microstructure, mechanical properties, wear resistance and cutting performance of AlTiCN coating[J]. Thin Solid Films 713 (2020): 138344.

[22] Sun De'en, Dong Hongming, Sam Zhang, et al. Review on the Reduction of Internal Stress in Doped Diamond Carbon Films [J]. Surface Technology, 2018, 47(06): 95-103.

[23] Robertson J. Deposition mechanisms for promoting sp3 bonding in diamond-like carbon[J]. Diamond and related materials, 1993, 2(5-7): 984-989.

[24] He X M, Walter K C, Nastasi M, et al. Investigation of Si-doped diamond-like carbon films synthesized by plasma immersion ion processing[J]. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2000, 18(5): 2143-2148.

[25] Sharifahmadian, Omid, and Farzad Mahboubi. "A comparative study of microstructural and tribological properties of N-DLC/DLC double layer and single layer coatings deposited by DC-pulsed PACVD process." Ceramics International 45.6 (2019): 7736-7742.

[26] Zhou Y, Ma W, Geng J, et al. Exploring long-run reciprocating Wear of diamond-like carbon coatings: Microstructural, morphological and tribological evolution[J]. Surface and Coatings Technology, 2021, 405: 126581.

[27] Nakazawa, Hideki, et al. "Tribological properties and thermal stability of hydrogenated, silicon/nitrogen-coincorporated diamond-like carbon films prepared by plasma-enhanced chemical vapor deposition." Japanese Journal of Applied Physics 55.12 (2016): 125501.

[28] Voevodin A A, Schneider J M, Rebholz C, et al. Multilayer composite ceramicmetal-DLC coatings for sliding wear applications[J]. Tribology international, 1996, 29(7): 559-570.

[29] Zhou Qiong, Huang Biao, Zhang Ergeng, et al. Research Status on Preparation of DLC Coatings and Measures for Improving Internal Stress and Thermal Stability [J]. Chinese Journal of Ceramics, 2019, 40(5): 555-564.

[30] Kumar C S, Majumder H, Khan A, et al. Applicability of DLC and WC/C low friction coatings on Al2O3/TiCN mixed ceramic cutting tools for dry machining of hardened 52100 steel[J]. Ceramics International, 2020, 46(8): 11889-11897.

[31] Wang Y, Xu J, Zhang J, et al. Tribochemical reactions and graphitization of diamond-like carbon against alumina give volcano-type temperature dependence of friction coefficients: A tight-binding quantum chemical molecular dynamics simulation[J]. Carbon, 2018, 133: 350-357.

[32] Xu W, Zhou K S, Lin S, et al. Structural properties of hydrogenated Al-doped diamond-like carbon films fabricated by a hybrid plasma system[J]. Diamond and related materials, 2018, 87: 177-185.

[33] Santiago J A, Fernández-Martínez I, Sánchez-López J C, et al. Tribomechanical properties of hard Cr-doped DLC coatings deposited by low-frequency HiPIMS[J]. Surface and Coatings Technology, 2020, 382: 124899.

[34] He X M, Walter K C, Nastasi M, et al. Investigation of Si-doped diamond-like carbon films synthesized by plasma immersion ion processing[J]. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2000, 18(5): 2143-2148.

[35] Er K H. Thermal stability of reactive sputtered silicon-doped diamond-like carbon films[J]. Journal of Ceramic Processing Research, 2013, 14(1): 134-138.