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DIAMOND-LIKE CARBON (DLC) COATINGS: PRINCIPLES, PROPERTIES, APPLICATIONS, AND FUTURE PROSPECTS IN ADVANCED SURFACE ENGINEERING- A REVIEW

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ABSTRACT

Diamond-Like Carbon (DLC) coatings have evolved as one of the most important surface engineering solutions for increasing the tribological, mechanical, and chemical performance of engineering components. DLC coatings are a thin protective layer that combines high hardness, low friction, exceptional wear resistance, corrosion protection, and biocompatibility. A blend of sp^3 (diamond-like) and sp^2 (graphite-like) hybridization bonds makes up Diamond-Like Carbon (DLC), a metastable amorphous carbon compound. Whether the coating behaves more like graphite (soft, self-lubricating) or diamond (hard, wear-resistant) depends on the ratio of these bonds.This review presents the scientific principles of DLC coatings, deposition techniques, tribological behavior, industrial applications, advantages, limitations, and future research directions. Real-world applications in automotive systems, aerospace components, biomedical implants, manufacturing tools, and electronic devices are discussed. The study emphasizes the increasing significance of DLC coatings in Sustainable Engineering and Next-Generation Manufacturing. Amorphous materials with adjustable sp3 and sp2 bonding ratios are known as diamond-like carbon coatings. They are applied via various vapor deposition techniques to provide high hardness, low friction, and chemical inertness in industrial, biomedical, and electronic applications.

Keywords:- *Diamond-Like Carbon (DLC), Surface Engineering, Tribology, Wear Resistance, Friction Reduction, Thin Films, Protective Coatings, Advanced Manufacturing.*

1. INTRODUCTION

Surface degradation due to wear, friction, corrosion, and fatigue remains a major challenge in engineering systems. A significant proportion of component failures originate at the surface, even when the bulk material remains structurally sound. Surface engineering technologies therefore play a critical role in extending component life and improving system reliability. Among these technologies, Diamond-Like Carbon (DLC) coatings have attracted considerable attention because they provide exceptional surface properties without significantly altering the dimensions or weight of the substrate.

DLC coatings are amorphous carbon-based thin films containing varying proportions of sp2 (graphitic) and sp3 (diamond-like) carbon bonds. The presence of sp3 bonding imparts diamond-like hardness, while graphitic phases contribute to lubricity and low friction. This unique combination has enabled DLC coatings to become a preferred solution in numerous industrial sectors.

2. STRUCTURE AND CLASSIFICATION OF DLC COATINGS

DLC coatings are not a single material but a family of carbon-based coatings. Depending on composition, Fig. 1 shows DLC coatings

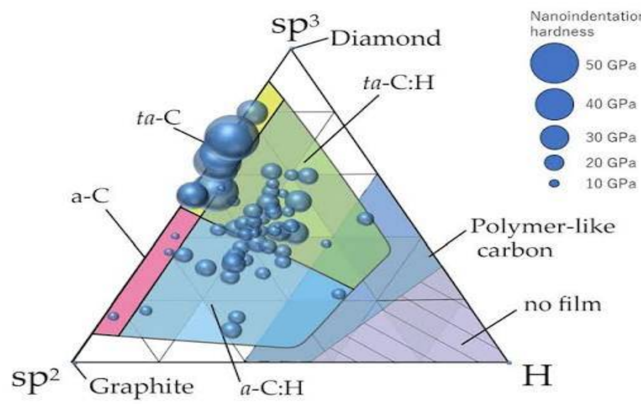

Fig.1

classified as hydrogenated amorphous carbon (a-C:H), tetrahedral amorphous carbon (ta-C), metal-doped DLC, and non-metal doped DLC such as silicon-doped DLC .Researchers have demonstrated that increasing the fraction of sp3 bonds generally enhances hardness and wear resistance, while dopants can improve thermal stability and coating adhesion.

Diamond-like carbon (DLC) coatings are defined as meta stable amorphous carbon materials characterized by a mixture of sp2 (graphitic) and sp3 (diamond-like) hybridized carbon [1][2][3][4].

The specific ratio between these phases dictates the material's properties: the sp3 phase contributes to high hardness, chemical inertness, and wear resistance, while the sp2 phase provides electrical conductivity and a low coefficient of friction [1][2].

These coatings are classified into several types based on their composition and bonding:

Hydrogenated amorphous carbon (a-C:H): Early versions of DLC coatings typically deposited via glow-discharge techniques [5].

Hydrogen-free amorphous carbon (a-C): Coatings often synthesized using cathodic vacuum arc evaporation (CVAE) [5].

Tetrahedrally-bonded hydrogen-free (ta-C): Monolithic coatings that provide the highest levels of hardness [5].

Doped/Alloyed DLC: Performance characteristics, such as thermal stability, electrical conductivity, and surface energy, are modified by incorporating non-metallic elements (H, N, Si, B, F, P, S) or metals (Cu, Ni, W, Ti, Mo, Si, Cr, Nb) [1][5].

DLC coatings are rarely used in pure form for demanding applications. Instead, they are engineered as **composite or nanocomposite systems** by incorporating various elements and nanoparticles:

Metal-Doped DLC (Me-DLC)
Nanocrystalline metal carbide precipitates embedded in an amorphous carbon matrix are

Dopant	Key Benefit
Tungsten (W)	Forms WSâ,, tribo-films for ultra-low friction; excellent impact resistance
Titanium (Ti)	Forms TiC precipitates; reduces stress and improves toughness
Chromium (Cr)	Exceptional oxidation stability; superior steel compatibility
Molybdenum (Mo)	Reduces residual stress; improves high-temperature performance
Nickel (Ni)	Suppresses interfacial oxidation/corrosion; stabilizes friction

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created by incorporating metals such as W, Ti, Mo, Cr, Ni, and Al into the carbon matrix. This improves adhesion, lowers internal tension, and increases heat stability up to about 500°C.

Non-Metal Doped DLC

To change surface energy, lower friction, and enhance environmental adaptability, elements like Si, N, F, B, and O are added:

Si-DLC: Preserves low friction (<0.1) in humid air while lowering surface energy and internal stress

F-DLC: Fluorination further lowers surface energy and micro-wear Superior high-temperature lubrication (400–500°C) is provided by B□C-DLC.

Nanoparticle-Incorporated DLC

Nanoparticle embedding onto DLC matrices is a recent development.

WO□/MoO□ nanoparticles: Achieve COF as low as 0.070–0.075 and improve adhesion (critical load increased from 25 N to 39 N).

TiO□ nanoparticles: Boosts antibacterial and photocatalytic capabilities

Ag particles: increases wear resistance by producing lubricious debris that is rich in silver.

Multilayer / Functionally Graded Composites

Functionally graded coatings, which progressively move from a metal interlayer (such as Cr or CrN) to the DLC top layer, are utilized to overcome weak adherence to metal substrates. Examples consist of:

Optimized for soft steel substrates, the CrN/W-DLC/DLC multilayer greatly increases wear resistance and adhesion.

Wear rates on stainless steel can be as low as $10^{-\ 1}$ $mm^3/(N \cdot m)$ with WC-Cr-DLC.

3.COMMON DEPOSITION TECHNIQUES INCLUDE:

Industrial production of DLC coatings commonly relies on Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and Plasma Enhanced Chemical Vapor Deposition (PECVD). PECVD has become particularly important because it enables deposition at relatively low temperatures and allows coating of complex geometries.

Method	Description	Typical Use
PACVD / PECVD	Plasma-assisted chemical vapor deposition; most common for a-C:H	Automotive, general industrial
PVD Sputtering	Physical vapor deposition; good for metal-doped DLC	Tool coatings, decorative
HiPIMS	High-power impulse magnetron sputtering; superior adhesion and density	High-performance applications
IBD	Ion beam deposition; produces high-spÂ³ ta-C	Ultra-hard coatings

The deposition process requires careful control of plasma energy, substrate preparation, chamber pressure, and precursor gas composition. Poor process control can lead to residual stresses, reduced adhesion, and premature coating failure.

The synthesis of DLC coatings primarily utilizes vacuum-based vapor deposition processes, which allow for the creation of conformal films even on complex geometries [2][6][3].

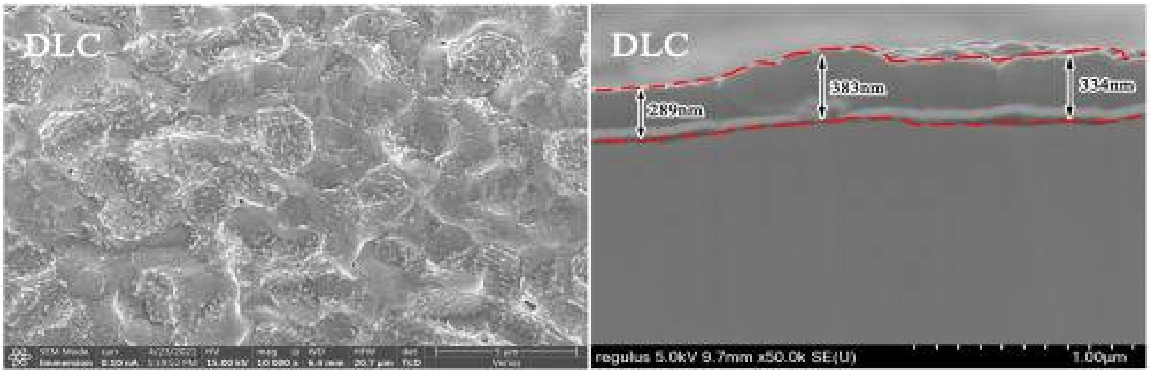
The choice of deposition method significantly influences the resulting crystallinity, surface morphology, and distribution of sp2 and sp3 bonds[7].

Chemical Vapor Deposition (CVD): Frequently used alongside physical vapor deposition to achieve specific tribological properties [2][8].

Plasma Enhanced Chemical Vapor Deposition (PECVD): A versatile and cost-effective method often utilized for automobile components; modifications like DC pulsed PECVD and ion/electron confinement have been developed to improve plasma density and film adhesion [1][6].

Physical Vapor Deposition (PVD): A primary vacuum-based technique for coating production [2][8].

Cathodic Vacuum Arc Evaporation (CVAE): Includes direct (DCVAE) and filtered (FCVAE) processes, alongside pulsed

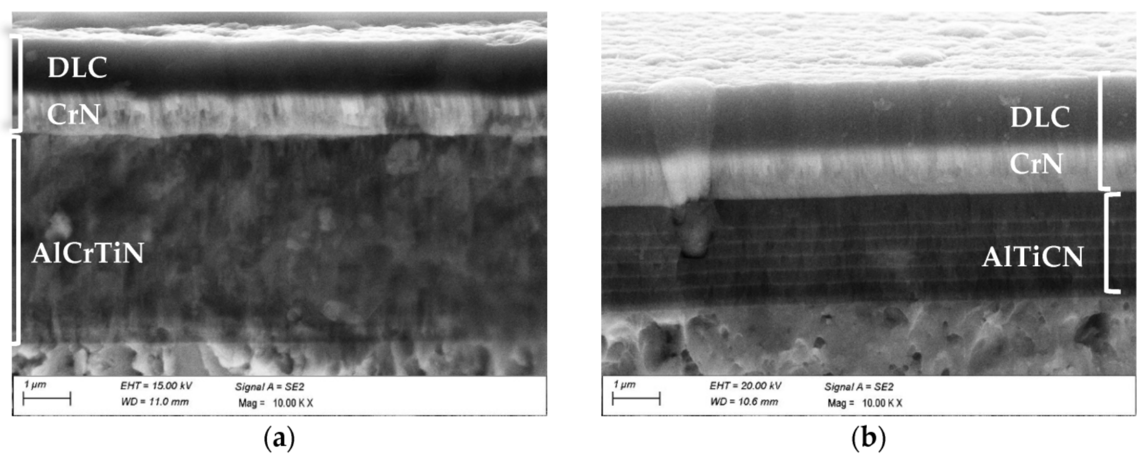


arc variations, to synthesize various hard a-C coatings [5].

Specialized techniques: Pulsed laser deposition (PLD), hollow-cathode-enhanced magnetron sputtering, and cathodic arc deposition with laser ignition of carbon plasma and plasma flow separation (CAD-LICPFS) [7].

DLC Film on 316L Stainless Steel (MPCVD) Surface morphology showing the granular DLC film structure. Right: Cross-sectional SEM revealing a uniform ~583 nm thick DLC coating on stainless steel substrate.

Multilayer Composite Coatings: DLC/CrN/AlCrTiN Cross-sectional SEM of functionally graded multilayer coatings. Left: DLC top layer over CrN interlayer on AlCrTiN base. Right: DLC/CrN/AlTiCN multilayer architecture demonstrating how



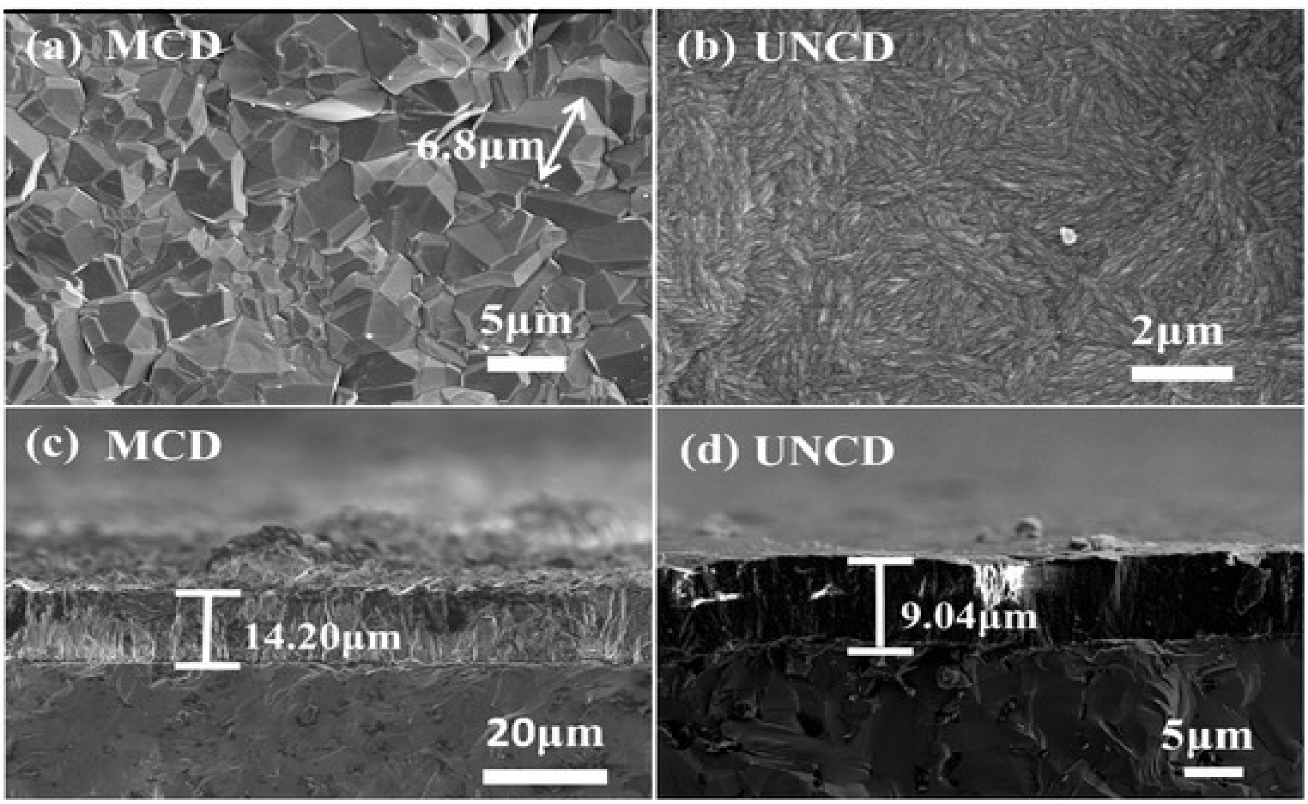
composite interlayers improve adhesion and performance.

Diamond/DLC Composite Coating (MCD vs UNCD)

Surface morphology of Microcrystalline Diamond (MCD) vs Ultra-Nanocrystalline Diamond (UNCD). Bottom: Cross-sections showing MCD (14.20 µm) and UNCD (9.04 µm) composite coating thicknesses.

4. TRIBOLOGICAL PROPERTIES

Tribology is the science of friction, wear, and lubrication between interacting surfaces. DLC coatings are among the most successful tribological materials developed in modern engineering. Their coefficient of friction can be significantly lower than conventional metallic surfaces, resulting in reduced heat generation and energy losses.



Numerous studies have reported substantial reductions in wear rates when DLC-coated components are compared with uncoated steel. The smooth surface morphology and high hardness minimize direct asperity contact, thereby reducing adhesive and abrasive wear mechanisms.

5. MECHANICAL AND CHEMICAL PROPERTIES

DLC coatings typically exhibit hardness values ranging from approximately 10 to 80 GPa depending on composition and deposition method. They also demonstrate excellent corrosion resistance because the coating acts as a barrier against moisture, oxygen,.

Another important characteristic is biocompatibility. Unlike many metallic coatings, DLC is generally chemically inert and well tolerated in biomedical environments, making it suitable for implantable devices and surgical tools.

DLC coatings are recognized for bridging the gap between diamond's extreme properties and industrial feasibility [3].

Property	Characteristics
Hardness	High mechanical hardness, with ta-C offering the highest values [2][4][5]
Friction	Ultra-low coefficient of friction, often < 0.1 [1][2][9].
Wear	Excellent resistance to tribological wear; typical rates ~ 7 x 10−17 m3/N.m [1][6]
Chemical	High corrosion resistance and chemical inertness [2][3][4].
Optical/Electronic	Optical transparency (IR range), high electrical resistance, and low dielectric constant [4][5][9].
Biocompatibility	Promotes cell growth and prevents substrate ion release [2][6].

They exhibit a unique combination of mechanical, chemical, and optical characteristics that make them highly valuable in demanding environments[9][10].

6. INDUSTRIAL APPLICATIONS AND CASE STUDIES

Their primary function in many applications is to mitigate friction and wear, thereby increasing the service life of components [1][5][9] The adaptability of DLC coatings allows their use across a wide range of sectors, from precision engineering to medicine [3][10].

Automotive Industry: Major automobile manufacturers such as Toyota, BMW, Volkswagen, and Mercedes-Benz employ DLC-coated components in fuel injection systems, valve train assemblies, piston pins, tappets, and cam followers. Used in engine parts and direct injection fuel systems to improve energy efficiency [1][8][5]

Aerospace Industry: DLC-coated bearings, actuators, and sliding components operate reliably under demanding mechanical and environmental conditions. Reduced wear contributes to longer maintenance intervals and improved operational safety.

Biomedical Applications: DLC coatings are used on orthopedic implants, artificial joints, dental tools, surgical instruments, and cardiovascular devices. Manufacturing Tools: DLC-coated cutting tools exhibit improved tool life and superior surface finish, particularly when machining aluminum alloys and non-ferrous materials. Employed for medical devices due to biocompatibility and the ability to be deposited at low temperatures on heat-sensitive materials like polymers [2][6][5].

Electronics: Hard-disk drives and micro-electromechanical systems (MEMS) utilize DLC coatings to protect miniature components from wear and surface damage. Utilized in magnetic storage disks, optical windows, micro-electromechanical devices (MEMs), and advanced optoelectronic devices [7][4][5][9].

7. DLC COATINGS IN BRAKE SYSTEMS

Recent research has increasingly explored DLC coatings for braking applications. Brake components operate under severe frictional and thermal conditions that promote wear and surface degradation. Application of DLC coatings on selected brake system components can reduce wear, improve surface durability, and enhance tribological performance.

For researchers investigating wear and friction of drum brakes, DLC coatings offer significant potential due to their hardness, low friction coefficient, and corrosion resistance. Silicon-doped DLC and multilayer DLC architectures have shown promising results in improving thermal stability and coating adhesion under demanding operating conditions.

8. ADVANTAGES AND LIMITATIONS

Advantages include high hardness, low friction, superior wear resistance, corrosion protection, improved energy efficiency, longer service life, and reduced maintenance requirements. DLC coatings can also contribute to sustainability by reducing lubricant consumption and minimizing material waste. However, challenges remain. High deposition costs, residual stress, adhesion difficulties, thickness limitations, and temperature sensitivity of some DLC variants continue to motivate research.

9. FUTURE RESEARCH DIRECTIONS

Future developments will focus on nanocomposite DLC coatings, multilayer structures, hybrid coatings, electric vehicles, hydrogen-resistant coatings, renewable energy systems, and space technologies. Artificial intelligence and machine learning are being integrated into coating process optimization and performance prediction. Research on silicon-doped DLC, tungsten-doped DLC, graphene-enhanced coatings, and nano-engineered multilayer systems aims to boost mechanical, thermal, and tribological properties.

Thermal Limitations: Above 400°C, the majority of DLC breaks down. To push this limit, research focuses on Si-doping and sp^3/sp^2 ratio tuning.

Adhesion to Substrates: Resolved by graded interlayers (Cr, CrN, WC), shot peening, and plasma nitriding.

Cost and Scalability: HiPIMS and hybrid deposition techniques are developing for large-scale manufacturing

AI/ML Optimization: DLC properties are predicted and optimized using computational materials science and machine learning.

10. CONCLUSION

Diamond-Like Carbon coatings represent a transformative technology in advanced surface engineering. Their ability to simultaneously provide hardness, wear resistance, low friction, corrosion protection, and biocompatibility has enabled widespread industrial adoption. Industries from automotive to aerospace, biomedical, manufacturing, and electronics have adopted DLC coatings for their versatility. Advances in deposition technology and material design will further expand DLC coatings' role in sustainable engineering and high-performance systems.

DLC coatings with composites represent one of the most versatile surface engineering solutions available today. By combining the **hardness of diamond** with the **lubricity of graphite** and enhancing the system through **metal doping, nanoparticle incorporation, and multilayer architectures**, these coatings deliver exceptional performance across automotive, aerospace, medical, and industrial applications. The field continues to evolve toward higher temperature stability, self-healing capabilities, and AI-driven design optimizatio

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