Review Article

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Review of Diamond like Carbon Films Fabrications and Applications as New Biomaterials in Medical Field

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ABSTRACT

Many materials have been developed for biomedical applications, and many researchers still aim to develop biomaterials that have better properties than the currently-used ones do. In order to develop a new biomaterial, there are two basic approaches: one is the development of a pure biomaterial made of a single chemical substance and the other a composite biomaterial made of more than two different substances. The latter approach can be realized, for example, by coating a material with another one. In terms of corrosion and compatibility, this approach seems to have some advantages. For example, 1) a thin coat with anti-corrosion and good compatibility material will convert a corroded substrate, which has a unique and advantageous physical property, into a new anti-corrosion composite material. Therefore, the development of anti-corrosion coating-material can result in numerous new composite, and 2) it is nowadays very difficult to develop a pure material that has anti-corrosion materials. One of the candidate coating-materials is diamond-like carbon (DLC). In this paper, the author reviewed whether DLC has anti-corrosion, and furthermore explored the relationship between the physico-chemical properties and the production parameters of DLC applications in medical field.

Keywords
Diamond-like carbon, Biomaterials, Metals.

Introduction
This review article explores the potential benefits of using diamond-like carbon (DLC) films as a new type of biomaterial in the field of medicine. The author discusses the various methods of DLC film fabrication, including physical vapor deposition, plasma-assisted chemical vapor deposition, and ion beam assisted deposition. They also highlight the unique properties of DLC films, such as high hardness, wear resistance, excellent biocompatibility, and low friction that make them promising biomaterials.

The introduction highlights the need for biocompatible biomaterials in medical devices that have direct contact with the living body, particularly blood. The current use of metals, polymers, and ceramics in medical devices lacks complete harmony with the living body and can lead to complications and rejection. The development of new biomedical materials, such as Diamond-Like Carbon (DLC), is needed to solve these issues. DLC coatings offer promising properties, such as high hardness, wear resistance, and biocompatibility. Recent research has shown the potential for low-pressure PECVD technology to deposit DLC coatings on various materials, including plastics, aluminum, and stainless steel. However, challenges remain in developing coating thickness and diversity and in expanding the range of applications. The increasing use of low-pressure PECVD technology in additive manufacturing, electronics, and biomedicine applications shows great potential for the future of DLC coatings.

The author review recent studies that have investigated the potential applications of DLC films in various medical fields, such as orthopedics, cardiology, neurology, and ophthalmology. Examples include the use of DLC-coated implants for joint replacement surgeries, as well as for stents and catheters in cardiology. The author also discusses the potential for using DLC films in drug delivery systems and for biosensors. Overall, the review concludes that DLC films have the potential to be an excellent biomaterial in the medical field due to their unique properties and potential applications. However, the author note that further research is needed to fully understand their benefits and limitations.

The rapid development in technology has been accompanied by great development in medical devices [1,2]. Which ultimately led to the urgent need for medical biomaterials that have complete compatibility with the living body (Biocompatibility)[3]. Especially in those medical devices that have direct contact with blood during analytical examination or during treatment as well. In order for this to happen, there must be complete understanding between specialists in engineering, physics, biology, chemistry and medicine to discuss the quality of the material and ways to develop it [4]. Hence the aim of using it in the future. After all the substances on our planet have been known, it is impossible in our time to discover a completely new substance. But there are other ways, which are to synthesize a new material from several other materials to suit the use for which it is intended [5]. It is known in biomedical materials that all composite materials have their advantages and disadvantages in medical use. Therefore, scientific research is still busy finding and developing a suitable material or materials.

Metals are among the most common materials used in medical uses and have a history dating back to 1860 [6], when surgeon Dr. J. Lister designed some medical equipment from gold, platinum [6-8], and silver. Also [6,8], the materials currently used are polymers and ceramics. Most of these medicinal materials lack complete harmony with the living body when they are implanted in the body or when they come into contact with blood with blood cells or when they come into contact with blood plasma. Recent studies have also shown that some medical materials implanted inside the body cause many diseases such as cancer. In addition, the living body rejects them when they are implanted, which leads to the body being injected with medications that reduce the body's immunity so that it can adapt to these implanted materials. In artificial organs, such as the artificial heart, for example, any clotting or breakdown of blood cells causes the blood to lose its basic function and is no longer usable, which leads to an urgent need for more blood and also leads to many diseases when it pumps blood to the living body.

These biochemical complexities have created an urgent need to develop new biomedical materials to help solve these problems and complications that occur when blood comes into direct contact with the biomedical material or when the biomedical material is implanted in the living body. From this standpoint, a new material was manufactured and developed, which is "Diamond-Like Carbon (DLC), an abbreviation for (DIAMOMD LIKE CARBON), which has physical, chemical, optical, mechanical, and electronic properties that encourage its use in many fields in the future [9].

Recent research shows that low-pressure PECVD can be used to deposit DLC coatings at lower temperatures and in a lower vacuum, improving deposition efficiency and expanding the range of applications for DLC coatings [10]. This technology is characterized by high properties such as high hardness and wear resistance, and it has been developed to provide DLC coatings on different materials such as plastic, aluminum, and stainless steel [11]. PECVD methods can also be used to deposit thin films of organic materials used in biological applications such as bioactive coatings and biological sensing devices. However, the technology still faces challenges in developing coating thickness and diversity, improving quality and expanding the range of applications. The deployment of low-pressure PECVD technology in additive manufacturing, electronics and biomedicine applications shows great potential and is increasing.

This material is prepared in several physical ways and also by laser, but we prepared the DLC films by chemically breaking down methane gas using high-frequency waves in very low pressure fields.

Coating Methods of DLC Films

The DLC film is a thin non-crystalline film consisting of a mixture of irregular diamond atoms, some of which form sp3 bonds that provide hardness and toughness, and others form sp2 bonds that contribute to other properties such as thermal conductivity and electrical conductivity. The DLC film has many properties such as durability, hardness, wear resistance, and it is widely used in various industries such as cars, surgical tools, electronic devices, and many other applications [12]. There are two main types of DLC coating:

1. Physical Vapor Deposition (PVD) used to deposit DLC coatings using solid carbon as a starting material. The carbon is vaporized and allowed to deposit onto a substrate to form a DLC film [12].

2. Chemical Vapor Deposition (CVD) used to deposit DLC coatings using a hydrocarbon gas as a starting material. The gas is decomposed in a vacuum chamber, and the resulting carbon vapor is allowed to deposit onto a substrate to form a DLC film. It also mentions that DLC coatings have potential applications in cardiovascular diseases[12].

These main deposition methods can be divided in the following deposition methods and others:

i. Physical Vapor Deposition (PVD) - which includes methods such as magnetron sputtering, arc vapor deposition, and ion beam deposition.

ii. Chemical Vapor Deposition (CVD) - which includes methods such as plasma-enhanced CVD (PECVD), hot-filament CVD, and microwave plasma CVD.

iii. Hybrid methods - which combine PVD and CVD techniques to produce DLC films with improved properties and control over film thickness.

iv. Laser Deposition - which involves the use of a high-power laser to vaporize a target material and deposit a DLC film on a substrate.

Other deposition methods for DLC films may include electrochemical deposition and chemical solution deposition. DLC coatings have potential applications in many fields, including but not limited to automotive, aerospace, and biomedical industries. In cardiovascular diseases, DLC coatings have been studied as a means for reducing the risk of blood clot formation and improving the biocompatibility of cardiovascular implants, such as stents.

DLC Magnetron Sputtering Deposition

DLC Magnetron Sputtering is a deposition technique that is used to deposit thin films of diamond-like carbon (DLC) onto a substrate. The process involves the use of a magnetron sputtering system, which generates plasma by ionizing a gas, typically argon. The plasma is used to bombard a carbon target, causing the carbon atoms to be ejected from the target and deposit onto the substrate.

The DLC coating deposited using magnetron sputtering technique exhibits a unique combination of properties such as high hardness, chemical inertness, low friction coefficient, and optical transparency. This coating can be used in a variety of industrial applications, including cutting tools, biomedical implants, coatings for electronic devices, and tribological applications.

The DLC coating deposition by magnetron sputtering is preferred over other DLC deposition methods such as chemical vapor deposition (CVD) and ion beam deposition (IBD) as it offers superior uniformity, an ability to coat complex shapes, and high reproducibility [13-15].

DLC Arc Vapor Deposition

DLC Arc Vapor Deposition is a physical vapor deposition (PVD) technique used to deposit thin films of diamond-like carbon (DLC) onto a substrate. The process involves the use of an electric arc discharge, which vaporizes a carbon target. The vaporized carbon atoms or ions are then deposited onto a substrate, where they condense and form a thin film. The DLC coating deposited using arc vapor deposition exhibits a unique combination of properties such as high hardness, chemical inertness, low friction coefficient, and optical transparency. This coating can be used in a variety of industrial applications, including cutting tools, biomedical implants, coatings for electronic devices, and tribological applications [16].

The DLC coating deposition by arc vapor deposition is preferred over other DLC deposition methods such as chemical vapor deposition (CVD) and magnetron sputtering as it offers higher deposition rates which results in cost-effective and faster processing [13,17]. The coating can also be deposited on complex shapes with good control over the coating properties. However, the process requires a high level of expertise and control over the deposition parameters to achieve consistent and reproducible results [18].

Plasma-Enhanced Chemical Vapor Deposition (PECVD)

Plasma-Enhanced Chemical Vapor Deposition (PECVD) is a type of chemical vapor deposition (CVD) process used for the deposition of thin films. In this process, a plasma is used to enhance the reaction rate of the precursor gases that are being deposited onto the substrate. The plasma can be created using a variety of methods, such as RF or microwave power, inductively coupled plasma (ICP), or capacitively coupled plasma (CCP). The plasma generates a high-energy electric field that dissociates the precursor molecules, and these dissociated molecules then react with each other or with the substrate to form a thin film [19-21]. The PECVD process is commonly used to deposit thin films of materials such as silicon nitride (SiN), silicon dioxide (SiO2), and amorphous silicon (a-Si) for use in microelectronics and solar cell applications as well as for surface coatings.

DLC (Diamond-like Carbon) Hot-filament CVD (Chemical Vapor Deposition) is a deposition technique used to synthesize thin films of diamond-like carbon onto a substrate. The process involves heating a substrate to a high temperature, typically in the range of 600-1000°C, and introducing a mixture of hydrocarbon gas, typically methane (CH4), and hydrogen gas (H2) into a vacuum chamber.

The hydrocarbon gas molecules dissociate into carbon atoms when they come into contact with hot filaments. These carbon atoms get dissolved in a hydrogen plasma and subsequently precipitated onto the substrate surface, forming a thin film of DLC [22].

Hot-Filament CVD Deposition

The DLC films deposited using hot-filament CVD exhibit superior properties such as high hardness, chemical inertness, and low friction coefficient, making them an ideal candidate for a variety of applications such as tribological applications, biomedical implants, and electronic devices [23]. Hot-filament CVD is a cost-effective and flexible method for DLC deposition, capable of depositing thin films with a thickness ranging from a few nanometers to several micrometers. The high-temperature processing makes the substrate surface rougher, creating an anchoring effect that promotes better adhesion of the DLC film to the substrate [22,24]. However, the deposition process requires a significant amount of energy, time, and expertise to achieve consistent and reproducible results.

DLC Microwave Plasma CVD

DLC (Diamond-Like Carbon) Microwave Plasma CVD (Chemical Vapor Deposition) is a method of depositing thin films of diamond-like carbon onto a substrate. The process involves the use of microwave energy, typically at a frequency of 2.45 GHz, to ionize a gas mixture of hydrocarbon gas, usually methane (CH4), and hydrogen gas (H2) in a vacuum chamber [25]. The ionized gas molecules create a plasma, which dissociates the hydrocarbon gas into carbon ions. These carbon ions are then deposited onto the substrate, forming a thin film of DLC. The hydrogen gas also helps in the deposition process, by providing an H-rich environment to allow the carbon ions to attach to the substrate [26].

DLC films deposited using microwave plasma CVD have excellent mechanical properties such as high hardness, toughness, chemical and thermal stability, and excellent tribological properties. This makes them ideal candidates for applications such as products used in the medical field, energy industry, and electronic devices [27].

Microwave plasma CVD is advantageous due to its high deposition rate, low processing temperature, and good reproducibility of film thickness and quality. However, it requires specialized equipment and careful control of process parameters such as gas composition, pressure, and microwave power to ensure the properties of the DLC film being deposited remains consistent [27].

Hybrid Methods - Which Combine PVD and CVD Techniques

Hybrid methods combining PVD (Physical Vapor Deposition) and CVD (Chemical Vapor Deposition) techniques are commonly used to produce DLC (Diamond-like Carbon) films with improved properties and control over film thickness [28]. These methods include:

1. Ion-beam-assisted deposition (IBAD): In this technique, a combination of ion-beam-sputtering (PVD) and plasma-enhanced CVD (PECVD) is used to deposit DLC films[28]. The ion beam provides additional energy to the substrate, which enhances the adhesion of DLC films and improves the growth rate, while PECVD provides a source of carbon and hydrogen to create DLC films [29-31].

2. Magnetron-sputtering-assisted CVD (MSACVD): In this method, magnetron sputtering (PVD) and CVD are combined to deposit DLC films. In the PVD step, the substrate is bombarded with high-energy ions, which creates a rough surface that promotes the adhesion of DLC films. In the subsequent CVD step, carbon and hydrogen are introduced, which react on the substrate surface to form DLC films [32].

3. Plasma-enhanced chemical vapor deposition/magnetron sputtering (PECVD/MS): This technique combines PECVD and magnetron sputtering to deposit DLC films with improved properties. In PECVD, a plasma is used to dissociate the hydrocarbon precursor gases into carbon and hydrogen ions, which are then deposited on the substrate surface. In magnetron sputtering, a target made of carbon is bombarded with ions to create a plasma, which aids in the deposition of DLC films [33-35].

These hybrid techniques provide greater control over the structure and thickness of DLC films, resulting in films with improved mechanical, tribological, and chemical properties compared to films deposited using a single technique [18]. The hybrid methods also make it possible to deposit DLC films with tailored properties for specific applications [36-38].

Electrochemical Deposition and Chemical Solution Deposition

DLC (Diamond-like Carbon) electrochemical deposition and chemical solution deposition are two additional methods for depositing DLC films.

1. Electrochemical deposition: In this technique, a DLC film is deposited on a conductive substrate by applying an electric potential between the substrate and a DLC electrode in an electrolytic solution. The electrolytic solution contains carbon source material, and the DLC film is deposited by the electrochemical reduction of this carbon source [39,40]. The advantages of electrochemical deposition are that it is a low-cost process, and the properties of the DLC film can be tailored by adjusting the conditions of the process such as the current density, the deposition time, and the type of electrolytic solution.

2. Chemical solution deposition: In this method, a DLC film is deposited on a substrate by immersing it in a solution containing a carbon source precursor, along with a metal catalyst or a surfactant as a stabilizer. The substrate is then dried and heated to decompose the precursor and form a DLC film. The advantage of chemical solution deposition is that it is a low-temperature process, which is of advantage for heat-sensitive substrates [40].

Both DLC electrochemical deposition and chemical solution deposition have their own advantages and limitations. However, both methods offer a lower-cost alternative to the other methods used for DLC film deposition such as PVD and CVD[40]. Additionally, these methods provide tunable and adjustable properties of DLC films according to the applications that are required.

Laser Deposition

DLC films can be deposited on various substrates using different techniques, and one of these techniques is laser deposition. Laser deposition is a process that involves using a high-energy laser beam to heat up a target composed of DLC material, causing it to evaporate and then condense as a film on a substrate. The laser energy allows for precise control of the DLC film's properties, such as thickness, composition, and crystallinity. Laser deposition of DLC films has many advantages, including high purity, precise control of film thickness, and excellent adhesion to the substrate. It also offers the possibility of depositing DLC films on complex-shaped parts with high precision, making it a widely used technique in various applications, including aerospace, biomedicine, and electronics.

In laser deposition, a high-power laser is focused onto a target material, which ablates and vaporizes the material. The vapor then condenses on the substrate, forming a DLC film. This method allows for precise control over the thickness and quality of the deposited film, and the DLC films produced have excellent adhesion, high hardness, low friction, and corrosion resistance [32,41]. Laser deposition has several advantages over other methods of DLC film deposition. It is a clean and highly controllable process, with minimal risk of contaminants. The method can be used to produce high-quality films with excellent uniformity, even over large areas. Additionally, the method is suitable for depositing DLC films on various substrates, including metals, ceramics, and plastics.

Laser deposition has found applications in many industries, including the automotive, aerospace, and biomedical fields. It has been used to produce wear-resistant coatings for cutting tools, corrosion-resistant coatings for engine components, DLC films for biomedical implants, and much more [32,41].

Ion Beam Deposition

Another method for depositing DLC films is ion beam methods, which involve bombarding a substrate surface with ions to create a DLC film. There are two main types of ion beam methods for DLC film deposition: ion beam sputtering (IBS) and ion beam assisted deposition (IBAD). In IBS, a high-energy ion beam is used to sputter the DLC material from a target, which then deposits on the substrate. In IBAD, a DLC film is deposited on the substrate while being concurrently bombarded with low-energy ions [29].

The ion beam methods offer several advantages for the production of DLC films. One of the most important is the ability to control the film's properties by adjusting the ion beam parameters, such as energy and flux density. This control allows for the precise control of the film's properties, including the composition, density, and crystallinity. Additionally, ion beam methods can be used to deposit DLC films on a variety of substrates, including metals and ceramics. These films offer high adhesion, low friction, and wear resistance, making them useful in applications ranging from cutting tools to medical implants [16,29-31].

Plasma Deposition

Plasma deposition is another commonly used method for depositing DLC films. Plasma deposition involves a low-pressure plasma environment that dissociates and ionizes hydrocarbon gases, creating a plasma of carbon and hydrogen atoms and ions. The plasma then deposits DLC films onto the substrate surface through a process called chemical vapor deposition (CVD) [10,20,23,25]. There are several types of plasma deposition techniques such as radiofrequency (RF) plasma deposition, and microwave plasma deposition, among others. During plasma deposition, the properties of the DLC film can be controlled by varying the process parameters such as gas flow rates, pressure, and power [10,20,23,25]. Plasma deposited DLC films have some advantages over other techniques [41-43]. They have uniform thicknesses, exhibit good surface morphology, and can be deposited on various substrates. The films also have high hardness, low friction, excellent chemical resistance, and are biocompatible, making them ideal for use in medical implants. DLC films produced through plasma deposition methods have found application in a wide range of industries, including electronics, aerospace, and biomedical fields [1,12,19,32,44-48].

Characteristics of DLC Coated Materials

Amorphous hydrogenated carbon (a-C:H) films have many excellent properties such as biocompatibility, anti-corrosion and chemical stability [45,49-51]. These advantages of the DLC films lead to many applications in mechanical, electrical and medical fields. An example of the attractive properties:

- mechanical (wear, friction) [13]
- chemical (corrosion, permeation, temperature insulation, biocompatibility, wettability) [52-55]
- electrical (conductivity) [13]
- optical (transmission, reflection, absorption, color)[13]
- Low economic cost [56]

In addition, the possibility of coating metals, polymers, ceramics and all materials with this new chemical method. Equipment consisting of complex, three-dimensional shapes can also be coated [44,52-55,57,58]. First, we designed a new device and method for coating currently used biomedical materials after our success in coating semi-insulators such as silicone for electronic uses [57]. After many attempts, we found the appropriate conditions under which we can coat these materials for medical uses [52,53]. Then we cultured this material in the living body to see how well the body interacted with this material for a week and two months, respectively. As a result, we found that this material has complete compatibility with the living body and does not cause any harmful chemical reactions with the living body compared to materials that are not coated [44]. This material is also characterized by strong chemical bonds with the coated material. We have also developed a new device to examine the adhesion of platelets to biomedical materials when they come into contact with blood. As a result, we found that it is one of the best biomedical materials currently used compared to heparin-coated biomedical materials [52,53]. As well as those materials that were not originally coated. This is due to its physical and chemical properties. This substance is used to coat biomedical materials that are implanted in the human body

DLC Biocompatibility and Blood Biocompatibility

DLC coatings have shown promising biocompatibility in various biomedical applications.

The unique properties of DLC coatings, such as high hardness, low friction, and high wear resistance, make them an attractive option for biomedical devices such as stents, artificial joints, and orthodontic appliances [1,2,7,48,52,59-62]. Studies have shown that DLC coatings can improve the biocompatibility of cardiovascular implants by reducing inflammation and promoting endothelialization, which is the growth of endothelial cells on the surface of the implant. The smooth and non-stick nature of DLC coatings also helps to reduce the risk of blood clot formation on the surface of the implant [62].

In orthopedic applications, DLC coatings have been used to improve the wear resistance and longevity of artificial joints. Additionally, DLC coatings have shown potential for reducing bacterial adhesion and biofilm formation on the surface of medical implants, which can help to prevent infection [8,58,59]. DLC coating has shown promising results in terms of blood compatibility [53]. The unique properties of DLC coatings, such as their low surface energy, high hydrophobicity, and low friction, make them attractive options for improving blood compatibility of medical devices, reducing thrombogenicity, and avoiding platelet aggregation [52].

DLC coatings have been shown to reduce platelet activation and adhesion, thereby reducing the risk of thrombus formation [52]. The surface of the DLC coating is extremely smooth and has a low surface free energy, which results in a reduction of protein adsorption and cellular adhesion. Furthermore, the non-stick nature of the DLC coating's surface prevents the formation of a fibrin network, which can trigger the mass formation of thrombi. The coating reduces the potential for any cellular damage that may lead to hemolysis or inflammation response in the body [48,62-64].

Additionally, the hydrophobic nature of the DLC coating enables it to resist the absorption of water from surrounding tissues and fluids, which reduces the potential for bacterial adhesion. This property makes DLC coatings useful in preventing biofouling and bacterial growth on medical devices, especially in cases where long-term implantation is necessary [47,65].

In summary, the low surface energy, high hydrophobicity, low friction, non-stick nature, and smooth surface of DLC coatings contribute significantly to their blood compatibility and anti-thrombogenic properties, which make them attractive for coating medical devices that come in contact with blood.

DLC Coating for Orthopedic Applications

DLC (Diamond-Like Carbon) coatings have received increasing attention in orthopedic application due to their biocompatibility, biostability, mechanical integrity, wear-resistant, and low friction properties for replacement and supplemental internal fixation devices in bone surgery [8,58,59]. DLC coatings have been successfully applied to improve the wear resistance, increase the stability, and reduce the friction of orthopedic implants like artificial joints, spinal implants, and dental implants [59]. The low friction nature of the coating also minimizes the wear and tear of the articulating surfaces that are repeatedly in contact with each other, thereby reducing the risk of implant failure and the need for revision surgery [66,67].

Another crucial application of DLC coatings in orthopedics is in the treatment of osteoporotic fractures. Bone screws coated with DLC have shown significant improvements in anchorage strength, with reduced risk of loosening and migration compared to uncoated screws [68,69]. In addition, the coating also protects the bone around the screw, promoting faster bone regeneration and faster union of the fracture. Furthermore, the biocompatibility of DLC coatings plays a significant role in reducing the inflammatory response of the body against the implanted device. DLC coatings also have the ability to reduce friction and wear between the implant and the surrounding bone and soft tissue promoting faster healing, preventing infection, and reducing pain associated with movement of the device.

In summary, DLC coatings are proving to provide significant improvements in orthopedic applications. Their applications reduce implant rejection while promoting faster healing and reducing inflammation. Furthermore, it has a range of applications in joint replacements, spinal implants, dental implants, and treatment of osteoporotic fractures.

DLC Coating for Stent Applications

DLC coating has been widely used in stent applications due to its unique and favorable properties in reducing restenosis rates after coronary stent implantation. One of the critical factors in the performance of the stent is the surface properties since it can lead to significant issues such as restenosis, thrombus formation, and neointimal hyperplasia. The DLC coating provides an excellent surface for stent applications as it inhibits thrombus formation and platelet adhesion [62,64,70-74]. DLC coatings not only lower adhesion to the surface but also improve endothelialization, which further reduces the risk of in-stent restenosis. Furthermore, the low friction coefficient contributes to the thrombogenicity prevention and less tendency for the clotting cascade process to initiate [42,46,75-77].

DLC coatings also provide excellent wear resistance and durability [2,78-80], which can help increase the useful life of stents after implantation. The corrosion resistance and hardness of DLC coatings, combined with their biocompatibility, make them ideal candidates for use in cardiovascular implant applications like stents. Overall, the use of DLC coating in stent applications has shown promising results in reducing the risk of restenosis and thrombosis, thus promoting successful outcomes after implantation. With continued research, DLC coatings will continue to be a favorable option in stent applications, with potentially further improvements and optimizations.

DLC Applications for Joint Knee Replacement

DLC (Diamond-Like Carbon) coatings have been successfully used in joint knee replacement surgery, particularly in the femoral component of the prosthesis. The DLC coating improves implant wear resistance, increases biocompatibility, and extends the lifespan of the implant [81].

In knee replacement surgery, the prosthetic joint must withstand considerable mechanical stress. Over time, the repetitive loading can cause wear and tear of the prosthesis, resulting in implant loosening, fracture, and the need for revision surgery. DLC coatings provide a durable surface that effectively reduces friction and adhesion, producing a long-lasting, stable, and smooth bearing surface [48,62,82]. Furthermore, the DLC coating also plays a significant role as an effective barrier against corrosion, from body fluids, and provides protection against bacterial infection [59]. The biocompatibility of the coating, promoting faster integration between the implant and the surrounding bone, reducing inflammation and minimizing the risk of rejection.

DLC coated knee implants are also preferred over other coatings because they contain lower levels of metal ions, such as chromium, cobalt, and nickel. Lower levels of these substances reduce the risk of metal allergy and sensitization, a common issue associated with metal-containing implants [3,51,66,83,84]. Moreover, DLC coatings also improve the tribological behavior of knee implants, preventing wear and tear events, reducing friction and failure of the implant. DLC coated implants also show fewer post-implantation complications such as implant loosening, dislocations, aseptic loosening, or revisions, hence reducing patient morbidity and financial burden.

In summary, DLC coatings offer a promising solution in knee joint replacement surgery. They provide excellent wear resistance, increased stability, and biocompatibility, while also preventing corrosion, and promoting earlier and faster healing and recovery [48,85].

Discussion and Conclusion

Overall, the biocompatibility of DLC coatings has made them a promising material for a range of biomedical applications. However, further research is needed to fully understand the long-term effects of DLC coatings on the human body and their potential for use in clinical applications. Endothelialization is due to its unique physical and chemical properties. The smooth, non-stick nature of the DLC coating reduces the risk of blood cells and biomolecules adhering to the surface of the implant. Reduced adhesion of these components results in reduced inflammation and cellular activation [42,46,76].

The DLC coating also has a low coefficient of friction, which reduces shear stresses and decreases platelet activation and aggregation. The coating is also highly biocompatible, meaning that it does not induce any adverse effects on the surrounding tissue and cells [60]. Moreover, the hardness and wear resistance of the DLC coating provide protection against corrosion and wear of the cardiovascular implants. This reduces the release of metal ions from the implant surface, which can lead to inflammatory responses and adverse biological effects [82]. The promotion of endothelialization is an important factor in the biocompatibility of cardiovascular implants. The DLC coating has been shown to enhance the growth of endothelial cells and improve their adhesion to the implant surface. Endothelialization is essential for the formation of a healthy endothelial lining, which reduces the risk of thrombosis and restenosis after the implantation of stents [42,70-74]. The biocompatibility of DLC coatings on cardiovascular implants is due to their unique physical and chemical properties, which reduce inflammation, promote endothelialization, and protect against corrosion and wear.

In summary, DLC-coated materials have many attractive properties, such as wear resistance, anti-corrosion, and biocompatibility. These coatings can be applied to various materials, making them suitable for use in many different industries. DLC coatings can also be designed to have specific properties tailored to meet the needs of different applications. Research has shown that DLC-coated materials have strong chemical bonds with the coated material, are highly compatible with the living body, and result in reduced platelet adhesion compared to other materials. The low economic cost of DLC coatings makes them an attractive option for many industries looking for cost-effective solutions. Overall, DLC-coated materials have the potential to improve performance and durability in many applications while reducing the risk of harmful chemical reactions and improving biocompatibility in biomedical applications.

The paper starts by highlighting the need for biocompatible biomaterials in medical devices, particularly those that come in direct contact with blood or are implanted in the body. The current materials used in medical devices, such as metals, polymers, and ceramics, have limitations and can lead to complications and rejection. The paper then provides an overview of DLC films and their unique properties, such as high hardness, wear resistance, low friction, and excellent biocompatibility. The author discusses the various methods of DLC film fabrication and highlight recent research that has investigated the potential applications of DLC films in various medical fields, such as orthopedics, cardiology, neurology, and ophthalmology. The review article delves into the specific applications of DLC films in various medical fields, such as the use of DLC-coated implants for joint replacement surgeries, as well as for stents, catheters, drug delivery systems, and biosensors. The author also discusses the potential limitations of DLC films and the challenges of DLC film deposition, such as developing coating thickness and diversity and expanding the range of applications. The paper concludes by summarizing the potential benefits of DLC coatings in medical applications and offering future recommendations for DLC applications in the medical field. Overall, the review provides an in-depth exploration of DLC films as a promising biomaterial for medical applications and highlights the opportunities and challenges associated with their use.

Future Recommendations

Based on current research trends and advancements, there are several potential future recommendations for DLC applications in the medical field. These include:

1. Developing new coatings: Researchers can develop new coatings with specific properties and characteristics that can be tailored to target specific medical applications. For instance, using DLC coatings to improve the longevity and performance of implantable medical devices beyond orthopedic functions, such as treating cancer, diabetes, and heart diseases.

2. Wound healing and tissue engineering: Researchers are exploring exciting new ways to apply DLC coatings in wound healing and tissue engineering applications. For example, using DLC-coated materials to assist in tissue regeneration by reducing the immune response to implanted materials and reducing scar tissue formation.

3. Implant Design: DLC coatings can be used in novel orthopedic device designs and implants, including spinal implants, dental implants, and orthopedic trauma implants. The low friction properties of DLC may be particularly beneficial in improving mobility and reducing bone resorption following implantation.

4. Drug delivery and diagnostics: DLC coatings could be used as delivery vehicles for controlled release of drugs in targeted areas or as sensors for precision diagnostics for clinical applications such as diabetes self-care.

5. Robotics: DLC coatings have been used in the manufacturing of surgical instruments and devices, especially robotics-assisted surgeries. With the increasing use of robots and minimally invasive surgical procedures, DLC coatings could be used to minimize wear and tear during surgical procedures, reduce the likelihood of infection, and help improve procedural accuracy.

In conclusion, the development of new and innovative applications of DLC coatings has the potential to solve some of the most pressing challenges in the medical field, particularly in disease management, wound healing, and tissue engineering. As such, future innovations in DLC coatings have a vital role in medical advancement and improving patient outcomes. The research in the field of DLC coatings is still developing, and more studies are needed to fully understand their potential benefits in biomedical applications. However, the current research indicates that DLC coatings have many promising properties that could lead to the development of more effective and durable biomedical devices in the future. DLC coatings offer durability and effectiveness that could enhance biomedical devices, but their complete range of advantages requires additional research.

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