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Review

Diamond-Like Carbons for 3-D-Printed Biomedical Components

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Highlights

What are the main findings?

- DLC enables independent tuning of surface properties in AM biomedical components.
- DLCs improve wear and biological response.
- Performance depends on composition, structure, and deposition method.

What are the implications of the main findings?

- DLC coating becomes a key design tool, not just a post-treatment method.
- Specific DLC coating selection remains a key challenge to be solved.
- Future work requires long-term in vivo validation.

Abstract

Diamond-like carbon (DLC) coatings are increasingly explored as a practical route to enhance the surface performance of biomedical implants and tissue engineering scaffolds, particularly when combined with additive manufacturing. Rather than serving only as protective layers, DLC coatings allow for independent tuning of surface properties without modifying the bulk structure, which is especially relevant for complex 3D-printed components. This flexibility is often what makes them attractive for biomedical design. This review is structured around two main application areas: DLC coatings for prosthetic implants and DLC coatings for tissue engineering scaffolds. Within this context, the influence of DLC structure (e.g., sp^2/sp^3 bonding, hydrogen content, and doping) on mechanical, tribological, and biological behavior is discussed. Particular attention is given to additively manufactured metallic implants and porous scaffolds, where large surface area and internal architectures complicate coating uniformity and adhesion. Reports show that DLC coatings can improve corrosion resistance, reduce wear, and influence biological responses, such as antibacterial activity and cell interactions. Several challenges remain to be solved, especially in achieving uniform coating penetration in porous networks and in ensuring long-term stability under physiological conditions. The combination of additive manufacturing and DLC coatings has been shown to offer the potential to become an enabling technology for next-generation biomedical devices.

Keywords: biomedical applications; surface engineering; 3D printing

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1. Introduction

The use of biomedical implants and tissue engineering scaffolds has become a central part of modern healthcare, enabling the treatment of a wide range of conditions that would otherwise significantly impair quality of life. From orthopedic joint replacements to cardiovascular devices and dental restorations, these technologies are now routinely used in clinical practice [1–4]. Their increasing importance is closely linked to demographic changes, as well as the growing prevalence of chronic diseases, both of which continue to place substantial pressure on healthcare systems worldwide [5,6].

In parallel with these developments, the demand for advanced biomaterials has steadily increased. Orthopedic applications, in particular, account for a large share of implant use, mainly driven by age-related degeneration and musculoskeletal disorders [6]. At the same time, global aging trends indicate that this demand is likely to intensify in the coming decades, reinforcing the need for materials capable of long-term performance and reliable biocompatibility [7]. In this context, tissue engineering has attracted increasing attention, shifting the focus away from simple replacement toward the regeneration of damaged tissues [8–11]. At the same time, materials used in biomedical devices have to cope with quite demanding conditions, as they must work reliably inside the body while being well tolerated, avoiding unwanted reactions, and maintaining their mechanical and chemical stability over long periods [5].

One of the most significant technological advances supporting this transition is additive manufacturing. By enabling the layer-by-layer fabrication of complex geometries directly from digital models, additive techniques offer unprecedented control over structural features, including pore size, interconnectivity, and overall architecture [12,13]. These characteristics are especially important in biomedical applications, where mechanical behavior and biological performance are closely connected [14–17]. As illustrated schematically in Figure 1, a variety of additive manufacturing techniques, including fused deposition modeling (FDM), stereolithography (SLA), and powder-bed fusion processes, can be employed to fabricate prototypes with tailored geometries and hierarchical structures. Compared with conventional manufacturing approaches, these techniques provide greater flexibility in designing porous architectures that facilitate tissue integration and mass transport [18–20].

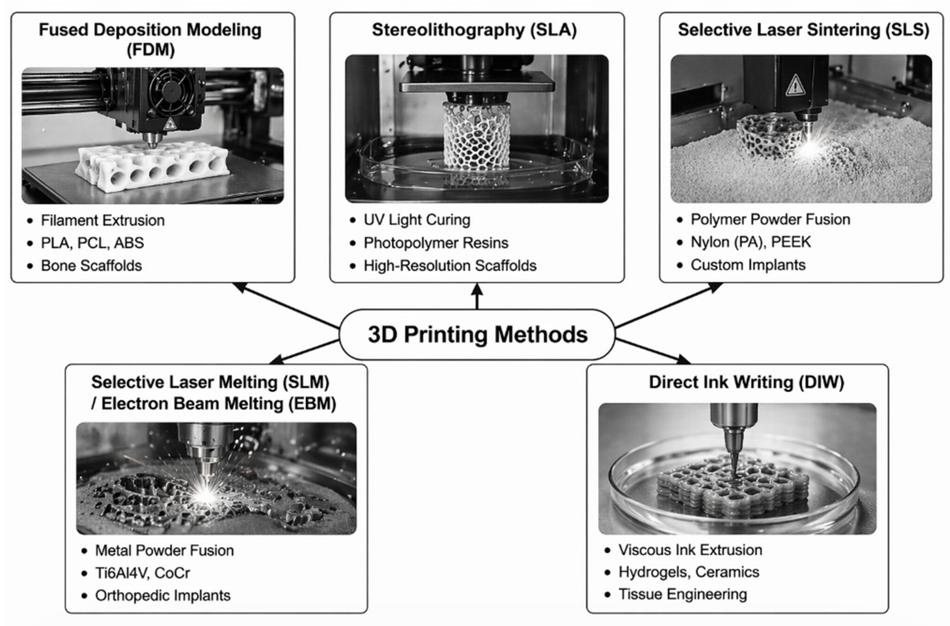

Figure 1. Main 3D printing techniques used for biomedical scaffolds: FDM, SLA, SLS, SLM/EBM, and DIW. The figure is an original schematic created by the author based on information compiled from the literature.

Each additive manufacturing technique presents distinct advantages and limitations in terms of resolution, material compatibility, and mechanical performance. For instance, powder-bed fusion methods are particularly suitable for load-bearing metallic implants, whereas extrusion and photopolymerization-based processes are widely used for polymeric scaffolds [21–23]. However, the benefits of additive manufacturing come with significant

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challenges. Rapid thermal cycles in processes such as selective laser melting can introduce residual stresses and microstructural heterogeneities, which may compromise the structural integrity of the final component [24,25]. Also, concerns regarding the biological response to certain alloying elements (e.g., vanadium and aluminum in Ti-6Al-4V) underscore the need for improved surface control [26,27]. Similar issues arise in photopolymer-based systems, where incomplete curing and residual photoinitiators may affect cytocompatibility [28].

To address these limitations, increasing attention has been directed toward surface modification strategies that enhance both mechanical and biological performance. Among the available options, diamond-like carbon (DLC) coatings have emerged as particularly promising. DLC materials are characterized by a complex mixture of sp^2 and sp^3 carbon bonding [29,30]. DLC materials can be tuned to achieve a wide range of properties, including high hardness, low friction, chemical inertness, and resistance to wear and corrosion [31–33]. As summarized in Figure 2, the use of different deposition techniques (such as magnetron sputtering, plasma-enhanced chemical vapor deposition (PECVD), filter cathodic vacuum arc (FCVA), pulsed laser deposition (PLD), and ion beam deposition) allows for positioning of DLC coatings within the sp^2–sp^3–H compositional space, thus enabling precise control over their structure and performance. Also, Figure 2 distinguishes between gas-phase and solid-target deposition routes, which differ mainly in the energy of the species involved during film growth. This has practical implications, as more energetic techniques are typically better suited for metallic or robust substrates, while lower-energy, gas-based processes are often preferred for temperature-sensitive or polymeric biomedical materials.

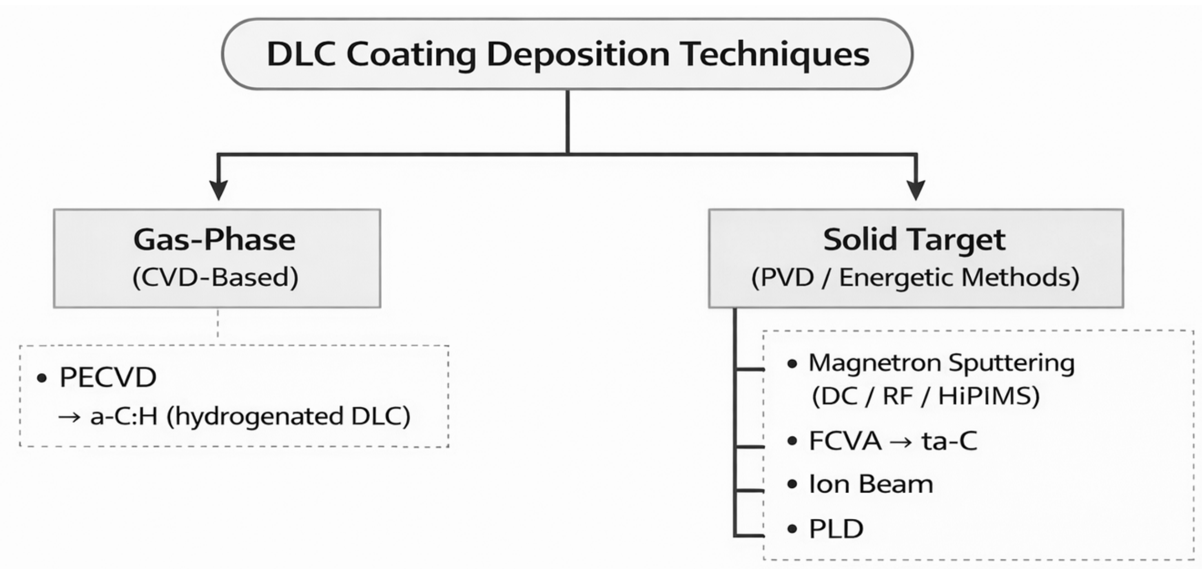

Figure 2. Diagram showing the key deposition methods used for the fabrication of DLC coatings.

Beyond their mechanical advantages, DLC coatings also offer significant potential for tailoring biological interactions. Through controlled doping and surface functionalization, it is possible to influence protein adsorption, cell adhesion, and even antibacterial behavior [34,35]. In practice, small changes at the surface can lead to noticeably different biological responses. These capabilities are important in the context of biomedical implants and scaffolds, where surface properties often determine clinical outcomes.

More recently, the integration of DLC coatings with additively manufactured components has attracted growing interest. This combined approach allows decoupling bulk structural design from surface functionality, which can enable independent optimization of mechanical properties and biological responses. However, applying coatings to complex, highly porous geometries remains a non-trivial challenge. Achieving uniform coverage within interconnected pore networks and ensuring long-term adhesion under physiological conditions requires careful optimization of deposition parameters and coating architecture. Addressing these challenges is essential for unlocking the full potential of DLC-coated additively manufactured devices and forms a central focus of the present review. A literature search was conducted in the Web of Science database, focusing primarily on publications from 2000 to 2025, as well as previous well-known works in DLC. The selection was guided by relevance to DLC coatings in biomedical and additive manufacturing contexts, combining well-established references with recent contributions. Papers outside this scope were not considered.

2. DLC Coatings for Prosthetic Implants

Diamond-like carbon (DLC) coatings have been extensively investigated as a means of improving the surface performance of prosthetic implants, particularly in applications where both mechanical durability and chemical stability are critical. Their combination of low friction, high hardness, and corrosion resistance makes them especially attractive for load-bearing systems, where surface degradation can directly influence implant lifetime [31–33,36]. In recent years, attention has increasingly shifted toward their application on additively manufactured implants, where complex geometries and engineered porosity introduce additional considerations for surface modification [37].

A broad overview of the evolution of DLC coatings in biomedical implants is presented in Table 1, which summarizes representative coating types, substrate materials, and targeted applications. As highlighted in this table, the versatility of DLC coatings comes not only from their intrinsic properties but also from the wide range of compositional modifications that can be introduced depending on the deposition technology used to be able to tailor their performance for specific clinical scenarios.

Table 1. Examples of studies on DLC coatings in conventional prosthetic implants.

DLC Material/Modification	Implant Type/Application	Reference
Hydrogenated DLC (a-C:H)	Hip joint prosthesis (wear reduction)	Grill, 1999 [32]
DLC on Ti6Al4V	Orthopedic implants (corrosion resistance)	Hauert, 2004 [34]
Nitrogen-doped DLC (a-C:N)	Cardiovascular stents	Robertson, 2002 [31]
Fluorinated DLC (F-DLC)	Blood-contacting implants	Roy & Lee, 2007 [38]
DLC on CoCr alloys	Hip/knee implants (tribology)	Donnet & Erdemir, 2004 [36]
DLC coatings (PECVD)	Dental implants	Narayan, 2005 [39]
Silver-doped DLC (Ag-DLC)	Orthopedic implants (antibacterial)	Endrino et al., 2010 [40]
DLC on stainless steel	Surgical implants	Bewilogua & Hofmann, 2014 [33]
DLC multilayer coatings	Joint prostheses (wear + fatigue)	Grill, 1999 [32]
Tungsten-doped DLC (W-DLC)	Load-bearing implants	Voevodin et al., 1999 [41]
DLC on Ti alloys	Bone implants (biocompatibility)	Uzumaki, 2006 [42]
DLC coatings (PVD)	Artificial joints	Erdemir, 2001 [43]
DLC on NiTi alloys	Orthodontic archwires	Kobayashi et al. [44]
DLC coatings on CoCrMo	Knee prostheses	Roy & Lee, 2007 [38]
DLC coatings for load-bearing prostheses	Hip implants	Hauert, 2004 [34]
DLC on medical-grade alloys	General prosthetics	Bewilogua et al., 2014 [33]

2.1. DLC Coatings on Conventionally Manufactured Implants

The use of DLC coatings on conventionally manufactured implants has been explored for several decades, particularly in orthopedic, dental, and cardiovascular applications. These coatings have been successfully applied to commonly used biomaterials such as Ti6Al4V, CoCr alloys, and stainless steel, primarily to mitigate wear and corrosion-related degradation [31,32,36,45]. As detailed in Table 1, early implementations focused on improving tribological performance in joint prostheses, while more recent developments have incorporated additional functionalities such as antibacterial behavior and enhanced biocompatibility.

One of the key motivations for employing DLC coatings in joint prostheses lies in their excellent tribological behavior, proven in multiple mechanical applications [46,47]. In articulating systems, including hip and knee replacements, surface wear can generate debris that may trigger inflammatory responses and ultimately contribute to implant failure. Hydrogenated DLC coatings have been shown to significantly reduce friction coefficients and wear rates, thereby improving long-term performance under cyclic loading conditions [41,43]. These improvements become significant in high-load environments, where even small reductions in wear can translate into substantial increases in implant lifetime and reduced osteolysis.

Due to their tribological advantages, DLC and DLC–metal coatings serve as effective corrosion barriers and can exhibit improved tribological performance [48,49]. This can be important for metallic implants exposed to physiological environments, where ion release can trigger adverse biological reactions. By providing a chemically stable interface, DLC coatings help to limit metal ion diffusion and enhance overall biocompatibility [50]. The importance of this function is underscored by the range of substrate materials listed in Table 1, which highlights the broad applicability of DLC coatings across different implant types.

More importantly, the properties of DLC coatings can be tailored through compositional modification. The incorporation of elements such as nitrogen or silicon allows for adjustment of surface energy and wettability, which in turn influence protein adsorption and subsequent cell behavior [34,35]. Similarly, fluorinated DLC has been explored for blood-contacting applications due to its reduced interaction with biological fluids [38]. The addition of antibacterial agents, such as silver, further extends the function of DLC coatings by inhibiting bacterial adhesion and reducing the risk of infection [40,51]. These compositional strategies, also reflected in Table 1, illustrate how DLC coatings can be engineered to address multiple performance requirements simultaneously.

As shown in Figure 2, DLC coatings are most commonly deposited using chemical vapor deposition (CVD) and physical vapor deposition (PVD) techniques, which provide considerable flexibility in controlling film structure and thickness [33,52]. For instance, plasma immersion techniques have been successfully employed to produce DLC coatings for orthopedic applications, demonstrating good adhesion and biocompatibility [42]. While DLC deposition methods are well established for relatively simple geometries, ensuring robust adhesion under repeated mechanical loading remains a critical challenge, particularly in high-stress applications [34].

2.2. DLC Coatings on 3D-Printed Prosthetic Implants

The adoption of additive manufacturing in the production of prosthetic implants has enabled the fabrication of components with complex, patient-specific geometries and controlled porosity. These features can improve mechanical compatibility and promote tissue integration; however, they also introduce surface characteristics such as increased roughness and internal porosity [37].

Within this context, DLC coatings have emerged as a valuable post-processing strategy. Their application to additively manufactured metallic implants, including Ti6Al4V and CoCr systems, has been shown to enhance wear resistance, corrosion protection, and biocompatibility [53,54]. Similar trends have been reported for additively manufactured titanium scaffolds incorporating carbon-based coatings, where improvements in both mechanical performance and biological response have been observed [55]. A comparative

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overview of these developments is provided in Table 2, which associates different coating approaches with specific implant types and performance outcomes. As shown in this table, plasma-based techniques such as PECVD play a dominant role due to their ability to deposit conformal coatings on complex geometries [53].

Table 2. Examples of studies in DLC Coatings on 3D-printed prosthetic implants.

DLC Material/Modification	Implant Type/Application	Reference
DLC on AM Ti6Al4V	Orthopedic implants (osseointegration)	Li et al., 2018 [56]
DLC coatings via PECVD	3D-printed metallic implants	Bociaga et al., 2016 [53]
DLC-coated AM porous Ti	Bone implants	Yick et al., 2023 [55]
Silver-doped DLC on AM implants	Antibacterial implants	Endrino et al., 2010 [40]
DLC on 3D-printed CoCr	Joint prostheses	Yilmaz et al., 2024 [57]
Nanostructured DLC on AM implants	Cell adhesion improvement	Rifai et al., 2018 [54]
DLC coatings on AM stainless steel	Surgical implants	Nouri et al. [58]
DLC-coated lattice structures	Lightweight implants	Tsubone et al., 2007 [37]
Plasma DLC on AM implants	Surface functionalization	Lantada, 2012 [59]
DLC coatings on 3D-printed parts	3D Polymers	V-Nino et al. [60]

An important advantage of combining additive manufacturing with DLC coatings is the ability to decouple structural and surface design. The bulk architecture of an implant can be optimized for mechanical performance and osseointegration, while the DLC coating provides an independent protective and functional interface. This separation of roles could be beneficial in orthopedic applications, where both mechanical and biological factors must be carefully balanced [56]. The examples summarized in Table 2 further illustrate how this approach can be adapted to different implant geometries and clinical requirements.

Nevertheless, coating additively manufactured implants presents several challenges. The irregular surface topography and interconnected pore networks characteristic of these structures can make uniform coating deposition difficult, particularly in internal regions. This limitation is further supported by recent work on metamaterial-inspired 3D-printed substrates, where DLC deposition highlighted the sensitivity of coating uniformity to architecture complexity and internal accessibility [60]. Incomplete coverage or poor adhesion may compromise performance under cyclic loading conditions, emphasizing the need for careful optimization of deposition parameters, including plasma conditions and exposure time [61]. DLC coatings can also be engineered to provide antibacterial functionality. The incorporation of elements such as silver and fluor has been shown to reduce bacterial adhesion, which is especially important given the increased surface area and complexity of additively manufactured implants [45,51]. Also, surface modification strategies for additively manufactured metallic biomaterials increasingly aim to integrate antipathogenic functionality alongside mechanical enhancement, highlighting the growing importance of multifunctional coatings in this field [58].

2.3. Structure–Coating–Performance Relationships in Implants

The performance of DLC-coated implants depends strongly on how the coating interacts with the underlying substrate and on the operating conditions. For conventionally manufactured implants, relatively smooth, well-defined surfaces generally enable uniform coating deposition and predictable mechanical behavior. In contrast, additively manufactured implants introduce greater complexity. Surface roughness, partially melted particles, and interconnected porosity can all influence coating adhesion and lead to local variations in performance, particularly under cyclic loading conditions [60,62].

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Coating composition plays a central role in these applications. Parameters such as the sp^2/sp^3 bonding ratio, hydrogen content, and dopant incorporation determine key properties, including hardness, friction coefficient, and chemical stability [31,35,63,64]. Increasing the sp^3 fraction, for example, typically enhances hardness and wear resistance, but this may also increase internal stresses and reduce adhesion if not properly managed. Similarly, doping strategies (with Ag, F, or Si) introduce antibacterial functionality or modify surface energy, although these changes may come at the expense of mechanical robustness [30].

Achieving reliable performance requires balancing these competing effects. A coating optimized only for hardness or antibacterial activity may not perform well if adhesion is insufficient or if the coating fails under repeated loading. In additively manufactured implants, this is critical, as local stress concentrations and geometric complexity amplify these issues. The examples summarized in Tables 1 and 2 illustrate that successful implementations are typically those in which coating design, deposition parameters, and substrate characteristics are considered together rather than independently.

Not all DLC coatings behave the same, and a big part of that comes down to both composition and how they are deposited. For example, hydrogenated films (a-C:H) tend to show slightly softer behavior and, in some cases, a more gradual biological response, while hydrogen-free coatings (a-C) are typically harder and can even support stronger initial cell attachment [30]. At the same time, the deposition route matters just as much: ion-based techniques such as cathodic arc or plasma immersion processes tend to produce denser films with higher sp^3 content, whereas gas-based processes like PECVD introduce hydrogen and lead to different bonding environments. These differences also affect how additional elements, like silver, are incorporated (either as well-dispersed phases or as clusters), which influences both antibacterial behavior and mechanical stability [30,40]. In practice, this means that coating performance is not defined by a single parameter but by a combination of structure, chemistry, and the effectiveness with which the film can be formed across the actual surface.

3. DLC Coatings for Tissue Engineering

DLC coatings have been increasingly explored in the context of tissue engineering, where the ability to control both structural and surface properties is essential for promoting positive cellular behavior and culture growth. In contrast to traditional bioactive coatings, which rely primarily on ionic interactions, DLC provides a chemically stable yet tunable interface that can influence protein adsorption, cell adhesion, and even antibacterial response [31,34,38]. An overview of these applications is presented in Table 3, which highlights the relationship between coating composition and cellular response.

Table 3. Overview of studies related to DLC use in tissue engineering applications.

DLC Material/Modification	Application/Cells	Reference
Hydrogenated DLC (a-C:H)	Osteoblast adhesion and proliferation	Grill, 1999 [32]
Nitrogen-doped DLC (a-C:N)	Endothelial cell growth	Robertson, 2002 [31]
Fluorinated DLC (F-DLC)	Blood compatibility	Hauert, 2004 [34]
PECVD DLC coatings	Osteoblast response	Roy & Lee, 2007 [38]
Silver-doped DLC (Ag-DLC)	Antibacterial + osteoblast	Endrino et al., 2008 [30]
DLC on metallic foams	Bone scaffolds	Dorner-Reisel et al., 2005 [65]
DLC on Ti substrates	Osteoblast proliferation	Narayan, 2005 [39]

3.1. DLC-Coated Conventional Scaffolds

The application of DLC coatings to conventional scaffold materials such as biodegradable polymers like polycaprolactone (PCL), polylactic acid (PLA), and porous metallic substrates has been widely investigated. Early studies demonstrated that hydrogenated DLC coatings can enhance osteoblast adhesion and proliferation while preserving the mechanical integrity of the scaffold [32,38]. As shown in Table 3, these effects are strongly dependent on both coating composition and processing conditions.

The biological response to DLC-coated scaffolds is strongly influenced by surface chemistry. Modifications such as nitrogen incorporation or fluorination enable tuning of surface energy and wettability, which directly affect protein adsorption and subsequent cell attachment [34,35]. Oxygen-functionalized DLC surfaces have also been shown to promote osteogenic activity, underscoring the importance of surface functional groups in regulating cell–material interactions [50].

Doping strategies further expand the functionality of DLC coatings. Silver-doped DLC, for example, introduces antibacterial properties through controlled ion release while maintaining acceptable cytocompatibility [30,51]. This multifunctionality can become critical in tissue engineering since both tissue integration and infection prevention are critical. Moreover, DLC coatings applied to porous metallic scaffolds have been reported to improve corrosion resistance and wear behavior, contributing to long-term stability in biological environments [39]. In line with this, improved electrochemical stability observed in carbon-coated nitrocarburized systems reinforces the role of DLC as a protective interface in physiologically relevant environments [66]. From a practical point of view, plasma-based techniques such as PECVD and PVD, which enable relatively low-temperature processing and strong adhesion to a variety of substrates, are preferred deposition techniques [33,52].

3.2. DLC-Coated 3D-Printed Scaffolds

Recent studies on additively manufactured and porous scaffold systems have highlighted the strong influence of surface properties and architecture on cell adhesion, proliferation, and overall tissue response [67,68]. The combination of additive manufacturing with DLC coatings offers a powerful approach for designing scaffolds with both controlled architecture and enhanced surface functionality. Additive manufacturing enables precise control over pore size, porosity, and interconnectivity, while DLC coatings modify surface properties at the micro- and nanoscale to promote favorable biological responses [53,56].

A summary of these developments is shown in Table 4, which summarizes representative examples of DLC-coated additively manufactured scaffolds and their corresponding biological outcomes. For example, in vivo studies on Ti-6Al-7Nb scaffolds with a 3D honeycomb architecture coated with DLC have demonstrated enhanced bone formation following implantation in animal models [69]. These in vivo findings provide important validation that the combined effect of scaffold architecture and DLC surface modification can translate into measurable biological outcomes beyond in vitro observations [69]. This table highlights the growing interest in combining structural design with surface engineering to achieve improved cell adhesion, proliferation, and bioactivity.

The workflow associated with the general proposed approach (1. scaffold fabrication, 2. surface modification, and 3. subsequent biological interaction) is illustrated schematically in Figure 3. As shown in this figure, integrating additive manufacturing with plasma-based DLC deposition enables a sequential, interconnected process in which structural design and surface functionalization can be achieved successfully [59,68].

Table 4. Examples of studies of DLC coatings on 3D-printed substrates for tissue engineering.

DLC Material/Modification	Application/Cells	Reference
DLC on rapid prototyping scaffolds	Cell adhesion	Lantada et al., 2012 [59]
DLC on 3D-printed polymers	Osteoblast proliferation	Moroni et al., 2008 [61]
Plasma DLC on AM scaffolds	Bioactivity enhancement	Bociaga et al., 2016 [53]
DLC nanofilms on icaritin (ICT)/β-tricalcium phosphate (β-TCP) scaffolds (I/BS)	Bone tissue in joints	Liu et al., 2025 [70]
Ti-6Al-7Nb scaffolds consisting of 3D honey-comb with DLC	Bone formation	Kawaguchi, 2021 [69]
DLC on AM Ti scaffolds	Bone ingrowth	Li et al., 2018 [56]
Nanostructured DLC on 3D scaffolds	Stem cell adhesion	Rifai et al., 2018 [54]

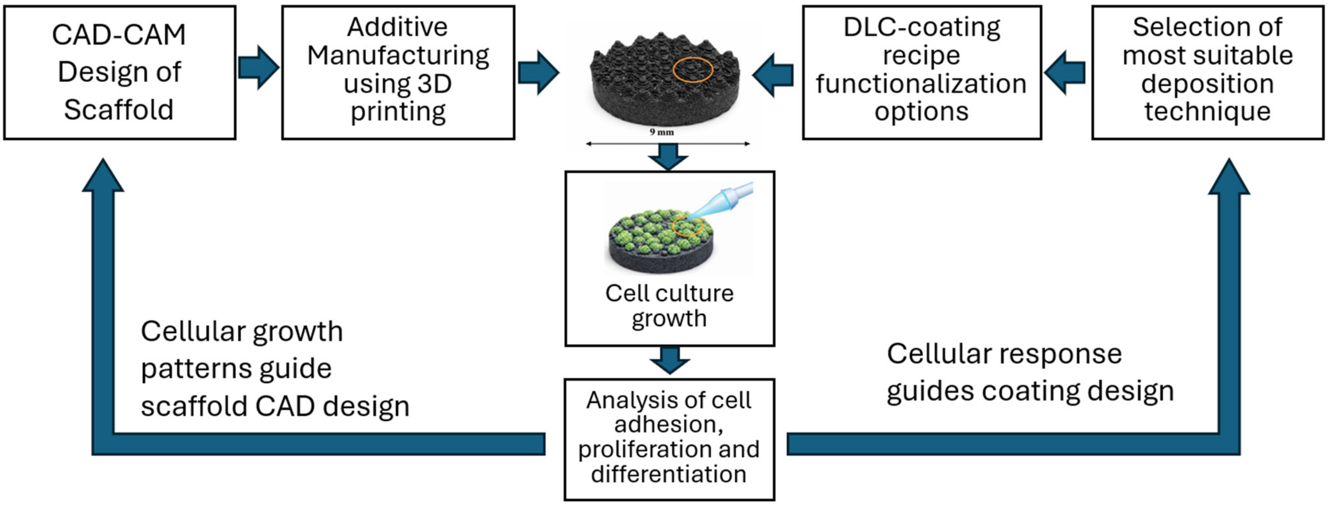

Figure 3. Schematic diagram showing the design for manufacturing strategy used in various tissue engineering applications (bone regeneration, cartilage repair, and nerve and blood vessel fabrication), supported by three pillars: 3D manufacturing of scaffolds, DLC surface modification, and cell culture growth.

This integrated view can be useful for understanding how surface modifications influence cellular response without altering the underlying architecture. The DLC layer acts as a functional interface that mediates interactions between the scaffold and the biological environment, thereby promoting conditions favorable for tissue formation. At the same time, Figure 3 emphasizes that coating deposition is not merely a finishing step but an integral component of the overall scaffold design strategy.

However, the high porosity and complex internal geometry of additively manufactured scaffolds can pose significant challenges for coating deposition. Achieving uniform coverage throughout the scaffold volume requires careful optimization of process parameters, particularly when using plasma-based techniques [53,59,61,71]. As shown in the schematic representation in Figure 3, ensuring effective coating penetration into internal regions remains a key technical limitation that must be addressed for reliable performance.

Despite these challenges, DLC-coated 3D-printed scaffolds have demonstrated improved biological performance, including enhanced osteoblast activity and stem cell adhesion as well as modulation of soft tissue responses at implant interfaces, as reported in percutaneous orthopedic systems [40,72]. More recently, DLC nanofilms have been shown to mimic cartilage-like behavior when applied to β-TCP-based scaffolds, enabling the repair of combined bone and cartilage defects and expanding the functional scope of these coatings [70]. A similar trend has been reported for DLC-coated titanium surfaces, which can simultaneously inhibit bacterial growth while promoting favorable bone cell responses [71]. In addition, incorporating antibacterial elements, such as silver and fluor, mitigates infection risks, which are often exacerbated by the high surface area of porous scaffolds [40,51,73–76].

3.3. Structure–Coating–Cell Interactions

The biological performance of DLC-coated scaffolds is closely linked to how surface characteristics influence early-stage interactions with proteins and cells. Surface roughness, chemistry, and nanoscale features all play a role in determining protein adsorption, which in turn affects cell adhesion, proliferation, and differentiation. DLC coatings provide a stable platform where these parameters can be adjusted without altering the overall scaffold architecture [50].

One of the main challenges in designing these systems is balancing antibacterial functionality with cytocompatibility. While doped DLC coatings (in particular those incorporating silver) can effectively reduce bacterial adhesion, excessive ion release may negatively impact surrounding cells. Achieving a controlled response, therefore, requires careful tuning of coating composition and release kinetics, rather than simply maximizing antibacterial activity [51].

Long-term behavior is another critical factor. Although short-term in vitro studies often show promising results, sustained performance under physiological conditions is not always guaranteed. However, available in vivo studies indicate that DLC-coated titanium systems can maintain favorable tissue responses over extended periods, supporting their potential for long-term biomedical use [77].

Overall, the results discussed in this section and summarized in Tables 3 and 4 suggest that DLC coatings can significantly improve scaffold performance when properly designed. Their integration with additive manufacturing enables tailoring both structure and surface properties simultaneously, but success ultimately depends on a careful balance among biological, mechanical, and chemical requirements, which can be achieved with the appropriate CVD or PVD deposition technique.

4. Conclusions

Diamond-like carbon coatings have clearly established themselves as a useful option for improving the surface performance of biomedical implants and tissue engineering scaffolds. One of their main strengths is that they allow surface properties (mainly chemical stability and bioresponse) to be adjusted without changing the bulk material. This becomes extremely important in additive manufacturing, where complex geometries and porous architectures make it advantageous to separate structural design from surface function. Although this work is based on a selective literature survey and may not capture all emerging directions in the field, it is evident that DLC coatings can enhance wear resistance, corrosion behavior, and, in many cases, the biological performance of 3D-printed devices. These benefits are not always straightforward to achieve. In practice, achieving uniform coating coverage in highly porous or intricate structures remains difficult, and adhesion under physiological conditions often requires careful tuning of the coating process rather than a standard solution.

In practice, the choice of deposition method becomes particularly important when dealing with complex or porous structures. PVD-based approaches tend to produce dense coatings with good mechanical properties and relatively low hydrogen content, which is often beneficial for wear and stability. However, because they rely on a primarily line-of-sight process, it can be difficult to coat internal surfaces or highly interconnected porosity uniformly. PECVD, on the other hand, generally provides better coverage in these situations, as reactive species can reach more hidden areas, leading to a more conformal coating. That said, this comes with its own trade-offs. The higher hydrogen content typically found in PECVD films can affect hardness, thermal stability, and long-term behavior. For this reason, the choice between PVD and PECVD is rarely straightforward and usually depends on what matters most in the application, whether that is coating quality, conformity, or long-term performance under physiological conditions.

In the future, improvements will likely come from better control of deposition processes, particularly for coating complex geometries where internal surfaces are difficult to access. At the same time, there is still a need for more consistent in vivo data, as short-term results do not always translate directly into long-term performance. DLC coatings are no longer just an additional surface treatment. They are increasingly part of how these systems are designed from the outset, especially when combined with additive manufacturing.

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References

1. Ratner, B.D.; Hoffman, A.S.; Schoen, F.J.; Lemons, J.E. *Biomaterials Science: An Introduction to Materials in Medicine*; Elsevier: Amsterdam, The Netherlands, 2013.
2. Williams, D.F. On the Mechanisms of Biocompatibility. *Biomaterials* **2008**, *29*, 2941–2953. [CrossRef]
3. Black, J.; Hastings, G. *Handbook of Biomaterial Properties*; Springer: New York, NY, USA, 2013.
4. Chen, Q.; Thouas, G.A. Metallic Implant Biomaterials. *Mater. Sci. Eng. R Rep.* **2015**, *87*, 1–57. [CrossRef]
5. Navarro, M.; Michiardi, A.; Castaño, O.; Planell, J.A. Biomaterials in Orthopaedics. *J. R. Soc. Interface* **2008**, *5*, 1137–1158. [CrossRef] [PubMed]
6. Geetha, M.; Singh, A.K.; Asokamani, R.; Gogia, A.K. Ti Based Biomaterials. *Prog. Mater. Sci.* **2009**, *54*, 397–425. [CrossRef]
7. United Nations. *World Population Ageing 2019 Highlights*; United Nations: New York, NY, USA, 2019.
8. Bose, S.; Roy, M.; Bandyopadhyay, A. Recent Advances in Bone Tissue Engineering Scaffolds. *Trends Biotechnol.* **2012**, *30*, 546–554. [CrossRef] [PubMed]
9. O'Brien, F.J. Biomaterials & Scaffolds for Tissue Engineering. *Mater. Today* **2011**, *14*, 88–95. [CrossRef]
10. Place, E.S.; George, J.H.; Williams, C.K.; Stevens, M.M. Synthetic Polymer Scaffolds. *Chem. Soc. Rev.* **2009**, *38*, 1139–1151. [CrossRef]
11. Stevens, M.M. Biomaterials for Bone Tissue Engineering. *Mater. Today* **2008**, *11*, 18–25. [CrossRef]
12. Gibson, I.; Rosen, D.W.; Stucker, B. *Additive Manufacturing Technologies*; Springer: New York, NY, USA, 2015.
13. Murr, L. Metallurgy of Additive Manufacturing: Examples from Electron Beam Melting. *Addit. Manuf.* **2015**, *5*, 40–53. [CrossRef]
14. Murphy, S.V.; Atala, A. 3D Bioprinting of Tissues and Organs. *Nat. Biotechnol.* **2014**, *32*, 773–785. [CrossRef]
15. Bose, S.; Vahabzadeh, S.; Bandyopadhyay, A. Bone Tissue Engineering Using 3D Printing. *Mater. Today* **2013**, *16*, 496–504. [CrossRef]
16. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive Manufacturing: A Review of Materials, Methods, Applications and Challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [CrossRef]
17. Paul, G.M.; Rezaienia, A.; Wen, P.; Condoor, S.; Parkar, N.; King, W.; Korakianitis, T. Medical Applications for 3D Printing: Recent Developments. *Mo. Med.* **2018**, *115*, 75–81. [PubMed]
18. Melchels, F.P.W.; Feijen, J.; Grijpma, D.W. A Review on Stereolithography and Its Applications in Biomedical Engineering. *Biomaterials* **2010**, *31*, 6121–6130. [CrossRef]
19. Derby, B. Printing and Prototyping of Tissues and Scaffolds. *Science* **2012**, *338*, 921–926. [CrossRef]
20. Hutmacher, D.W. Scaffolds in Tissue Engineering Bone and Cartilage. *Biomaterials* **2000**, *21*, 2529–2543. [CrossRef] [PubMed]

https://doi.org/10.3390/coatings16050536

21. Murr, L.E.; Gaytan, S.M.; Ramirez, D.A.; Martinez, E.; Hernandez, J.; Amato, K.N.; Shindo, P.W.; Medina, F.; Wicker, R.B. Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies. *J. Mater. Sci. Technol.* **2012**, *28*, 1–14. [CrossRef]
22. Chia, H.N.; Wu, B.M. Recent Advances in 3D Printing of Biomaterials. *J. Biol. Eng.* **2015**, *9*, 4. [CrossRef] [PubMed]
23. Jammalamadaka, U.; Tappa, K. Recent Advances in Biomaterials for 3D Printing and Tissue Engineering. *J. Funct. Biomater.* **2018**, *9*, 22. [CrossRef]
24. Mercelis, P.; Kruth, J.-P. Residual Stresses in Selective Laser Sintering and Selective Laser Melting. *Rapid Prototyp. J.* **2006**, *12*, 254–265. [CrossRef]
25. Fang, Z.C.; Wu, Z.L.; Huang, C.G.; Wu, C.W. Review on Residual Stress in Selective Laser Melting Additive Manufacturing of Alloy Parts. *Opt. Laser Technol.* **2020**, *129*, 106283. [CrossRef]
26. Costa, B.C.; Tokuhara, C.K.; Rocha, L.A.; Oliveira, R.C.; Lisboa-Filho, P.N.; Costa Pessoa, J. Vanadium Ionic Species from Degradation of Ti-6Al-4V Metallic Implants: In Vitro Cytotoxicity and Speciation Evaluation. *Mater. Sci. Eng. C* **2019**, *96*, 730–739. [CrossRef]
27. Marin, E.; Lanzutti, A. Biomedical Applications of Titanium Alloys: A Comprehensive Review. *Materials* **2024**, *17*, 114. [CrossRef] [PubMed]
28. Kim, G.T.; Jang, Y.S.; Kim, H.J.; Lee, S.; Kim, H.S.; Kim, J.E. Cytotoxicity, Colour Stability and Dimensional Accuracy of 3D Printing Resin with Three Different Photoinitiators. *Polymers* **2022**, *14*, 979. [CrossRef]
29. Gago, R.; Vinnichenko, M.; Jäger, H.U.; Belov, A.Y.; Jiménez, I.; Huang, N.; Sun, H.; Maitz, M.F. Evolution of Sp2 Networks with Substrate Temperature in Amorphous Carbon Films: Experiment and Theory. *Phys. Rev. B* **2005**, *72*, 014120. [CrossRef]
30. Endrino, J.L.; Galindo, R.E.; Zhang, H.-S.; Allen, M.; Gago, R.; Espinosa, A.; Anders, A. Structure and Properties of Silver-Containing a-C(H) Films Deposited by Plasma Immersion Ion Implantation. *Surf. Coat. Technol.* **2008**, *202*, 3675–3682. [CrossRef]
31. Robertson, J. Diamond-like Amorphous Carbon. *Mater. Sci. Eng. R Rep.* **2002**, *37*, 129–281. [CrossRef]
32. Grill, A. Diamond-like Carbon: State of the Art. *Diam. Relat. Mater.* **1999**, *8*, 428–434. [CrossRef]
33. Bewilogua, K.; Hofmann, D. History of Diamond-like Carbon Films. *Surf. Coat. Technol.* **2014**, *242*, 214–225. [CrossRef]
34. Hauert, R. Modified DLC Coatings for Biological Applications. *Tribol. Int.* **2004**, *37*, 991–1003. [CrossRef]
35. Ferrari, A.C.; Robertson, J. Interpretation of Raman Spectra of Disordered and Amorphous Carbon. *Phys. Rev. B* **2000**, *61*, 14095–14107. [CrossRef]
36. Donnet, C.; Erdemir, A. Historical Developments and New Trends in Tribological and Solid Lubricant Coatings. *Surf. Coat. Technol.* **2004**, *180–181*, 76–84. [CrossRef]
37. Tsubone, D.; Hasebe, T.; Kamijo, A.; Hotta, A. Fracture Mechanics of Diamond-like Carbon (DLC) Films Coated on Flexible Polymer Substrates. *Surf. Coat. Technol.* **2007**, *201*, 6423–6430. [CrossRef]
38. Roy, R.K.; Lee, K.R. Biomedical Applications of Diamond-like Carbon Coatings: A Review. *J. Biomed. Mater. Res. Part B Appl. Biomater.* **2007**, *83B*, 72–84. [CrossRef] [PubMed]
39. Narayan, R. Nanostructured Diamondlike Carbon Thin Films for Medical Applications. *Mater. Sci. Eng. C-Biomim. Supramol. Syst.* **2005**, *25*, 405–416. [CrossRef]
40. Endrino, J.L.; Sánchez-López, J.C.; Escobar Galindo, R.; Horwat, D.; Anders, A. Beneficial Silver: Antibacterial Nanocomposite Ag-DLC Coating to Reduce Osteolysis of Orthopaedic Implants. *J. Phys. Conf. Ser.* **2010**, *252*, 012005. [CrossRef]
41. Voevodin, A.A.; Zabinski, J.S. Nanocomposite and Nanostructured Tribological Materials for Space Applications. *Compos. Sci. Technol.* **2005**, *65*, 741–748. [CrossRef]
42. Uzumaki, E.; Lambert, C.; Belangero, W.; Freire, C.; Zavaglia, C. Evaluation of Diamond-like Carbon Coatings Produced by Plasma Immersion for Orthopaedic Applications. *Diam. Relat. Mater.* **2006**, *15*, 982–988. [CrossRef]
43. Erdemir, A. The Role of Hydrogen in Tribological Properties of Diamond-like Carbon Films. *Surf. Coat. Technol.* **2001**, *146–147*, 292–297. [CrossRef]
44. Kobayashi, S.; Ohgoe, Y.; Ozeki, K.; Sato, K.; Sumiya, T.; Hirakuri, K.; Aoki, H. Diamond-like Carbon Coatings on Orthodontic Archwires. *Diam. Relat. Mater.* **2005**, *14*, 1094–1097. [CrossRef]
45. Endrino, J.; Marco, J.; Allen, M.; Poolcharuansin, P.; Phani, A.; Albella, J.; Anders, A. Functionalization of Hydrogen-Free Diamond-like Carbon Films Using Open-Air Dielectric Barrier Discharge Atmospheric Plasma Treatments. *Appl. Surf. Sci.* **2008**, *254*, 5323–5328. [CrossRef]
46. Zhang, H.; Endrino, J.; Anders, A. Modification of Surface and Tribological Properties of Dlc Films by Adding Silver Content. In *International Joint Tribology Conference*; ASME: New York, NY, USA, 2009; pp. 537–539.
47. Brzezinka, T.; Rao, J.; Paiva, J.; Kohlscheen, J.; Fox-Rabinovich, G.; Veldhuis, S.; Endrino, J. DLC and DLC-WS2 Coatings for Machining of Aluminium Alloys. *Coatings* **2019**, *9*, 192. [CrossRef]
48. Pardo, A.; Buijnsters, J.G.; Endrino, J.L.; Gomez-Aleixandre, C.; Abrasonis, G.; Bonet, R.; Caro, J. Effect of the Metal Concentration on the Structural, Mechanical and Tribological Properties of Self-Organized a-C:Cu Hard Nanocomposite Coatings. *Appl. Surf. Sci.* **2013**, *280*, 791–798. [CrossRef]

49. Zhang, H.-S.; Endrino, J.L.; Anders, A. Comparative Surface and Nano-Tribological Characteristics of Nanocomposite Diamond-like Carbon Thin Films Doped by Silver. *Appl. Surf. Sci.* **2008**, *255*, 2551–2556. [CrossRef]
50. Yang, W.; Auciello, O.; Butler, J.E. Biocompatibility of Diamond-like Carbon Coatings. *Biomaterials* **2002**, *23*, 277–286.
51. Pérez-Tanoira, R.; Pérez-Jorge, C.; Endrino, J.L.; Gómez-Barrena, E.; Horwat, D.; Pierson, J.F.; Esteban, J. Bacterial Adhesion on Biomedical Surfaces Covered by Micrometric Silver Islands. *J. Biomed. Mater. Res. Part A* **2012**, *100A*, 1521–1528. [CrossRef]
52. Anders, A.; Pasaja, N.; Sansongsiri, S. Filtered Cathodic Arc Deposition with Ion-Species-Selective Bias. *Rev. Sci. Instrum.* **2007**, *78*, 063901. [CrossRef] [PubMed]
53. Bociaga, D.; Sobczyk-Guzenda, A.; Szymanski, W. Plasma-Assisted Deposition of Carbon Coatings on Additively Manufactured Substrates. *Surf. Coat. Technol.* **2016**, *303*, 193–200. [CrossRef]
54. Rifai, A.; Tran, N.; Lau, D.W.; Elbourne, A.; Zhan, H.; Stacey, A.D.; Mayes, E.L.H.; Sarker, A.; Ivanova, E.P.; Crawford, R.J.; et al. Polycrystalline Diamond Coating of Additively Manufactured Titanium for Biomedical Applications. *Acs Appl. Mater. Interfaces* **2018**, *10*, 8474–8484. [CrossRef]
55. Yick, S.; Reneman, J.; Martin, P.J.; Evans, M.D.M.; Bean, P.A.; Sohnel, T.; Tse, N.M.K.; Bendavid, A. Enhancing the Biocompatibility of Additively Manufactured Ti-6al-4 V Eli with Diamond-Like Carbon Coating. *Adv. Mater. Interfaces* **2023**, *10*, 2300225. [CrossRef]
56. Li, X.; Wang, C.; Zhang, W.; Li, Y. Additively Manufactured Ti Scaffolds with Carbon-Based Coatings for Biomedical Applications. *Mater. Sci. Eng. C.* **2018**, *91*, 474–482. [CrossRef]
57. Yilmaz, B.; Ayyildiz, S.; Kalyoncuoglu, U.T.; Tahmasebifar, A.; Baran, E.T. Surface Characteristics of Additively Manufactured CoCr and Ti6Al4V Dental Alloys: The Effects of Carbon and Gold Thin Film Coatings, and Alkali-Heat Treatment. *Microsc. Res. Tech.* **2024**, *87*, 1222–1240. [CrossRef]
58. Nouri, A.; Shirvan, A.R.; Li, Y.; Wen, C. Surface Modification of Additively Manufactured Metallic Biomaterials with Active Antipathogenic Properties. *Smart Mater. Manuf.* **2023**, *1*, 100001. [CrossRef]
59. Lantada, A.D.; Luis Endrino, J.; Sanchez Vaquero, V.; Mosquera, A.; Lafont, P.; Predestinacion Garcia-Ruiz, J. Tissue Engineering Using Novel Rapid Prototyped Diamond-Like Carbon Coated Scaffolds. *Plasma Process. Polym.* **2012**, *9*, 98–107. [CrossRef]
60. V-Nino, E.D.; Endrino, J.L.; Lantada, A.D.; Martinez, I.F.; Duran, H.A.E.; Goel, S. Fabrication and Characterisation of Ti and DLC Coatings on Metamaterial-Architecture-Inspired 3D-Printed Polymer Substrates. *Int. J. Adv. Manuf. Technol.* **2026**, *142*, 6379–6391. [CrossRef]
61. Moroni, L.; de Wijn, J.R.; van Blitterswijk, C.A. Integrating Novel Technologies to Fabricate Smart Scaffolds. *J. Biomed. Mater. Res. Part A* **2008**, *19*, 543–572.
62. Beakea, B.D.; Isern, L.; Harris, A.J.; Endrino, J.L. Probe Geometry and Surface Roughness Effects in Microscale Impact Testing of WC-Co. *Mater. Manuf. Process.* **2020**, *35*, 836–844. [CrossRef]
63. Robertson, J. Mechanisms of Sp^3 Bond Formation in Diamond-like Carbon. *Diam. Relat. Mater.* **2005**, *14*, 942–948. [CrossRef]
64. Luis Endrino, J.; Horwat, D.; Anders, A.; Andersson, J.; Gago, R. Impact of Annealing on the Conductivity of Amorphous Carbon Films Incorporating Copper and Gold Nanoparticles Deposited by Pulsed Dual Cathodic Arc. *Plasma Process. Polym.* **2009**, *6*, S438–S443. [CrossRef]
65. Dorner-Reisel, A.; Irmer, G.; Schürer, C.; Nestler, B.; Müller, E. Diamond-like Carbon Coatings on Metallic Foams for Biomedical Applications. *Diam. Relat. Mater.* **2005**, *14*, 2213–2217. [CrossRef]
66. Derakhshandeh, S.; Hadavi, S.; Eshraghi, M.; Javaheri, M.; Mozafari, M. Improved Electrochemical Performance of Nitrocarburised Stainless Steel by Hydrogenated Amorphous Carbon Thin Films for Bone Tissue Engineering. *IET Nanobiotechnology* **2017**, *11*, 656–660. [CrossRef]
67. Lantada, A.D. Systematic Development Strategy for Smart Devices Based on Shape-Memory Polymers. *Polymers* **2017**, *9*, 496. [CrossRef]
68. Lantada, A.D.; Endrino, J.L. Nanomanufacturing Technologies for Biomedical Microsystems Interacting at a Molecular Scale. In *Microsystems for Enhanced Control of Cell Behavior: Fundamentals, Design and Manufacturing Strategies, Applications and Challenges*; Lantada, A.D., Ed.; Springer: Berlin/Heidelberg, Germany, 2016; Volume 18, pp. 147–162.
69. Kawaguchi, M.; Segawa, A.; Shintani, K.; Nakamura, Y.; Ishigaki, Y.; Yonezawa, K.; Sasamoto, T.; Kaneuji, A.; Kawahara, N. Bone Formation at Ti-6Al-7Nb Scaffolds Consisting of 3D Honeycomb Frame and Diamond-like Carbon Coating Implanted into the Femur of Beagles. *J. Biomed. Mater. Res. Part B-Appl. Biomater.* **2021**, *109*, 1283–1291. [CrossRef] [PubMed]
70. Liu, X.; Song, Z.; Xue, P.; Xi, H.; Chen, H.; Huang, Y.; Peng, C.; Sun, G.; Jiang, X.; Du, B. DLC Nanofilm Mimics the Function of Cartilage and Modifying the β-TCP/ICT Scaffold for the Repair of the Combined Injury of Bone and Cartilage. *Diam. Relat. Mater.* **2025**, *155*, 112278. [CrossRef]
71. Jongwannasiri, C.; Krasaesin, A.; Pinijsuwan, S.; Udomsom, S.; Boonprakong, L.; Eawsakul, K.; Osathanon, T.; Manaspon, C. Diamond-like Carbon (DLC)-Coated Titanium Surface Inhibits Bacterial Growth and Modulates Human Alveolar Bone Cell Responses in Vitro. *Diam. Relat. Mater.* **2023**, *136*, 110022. [CrossRef]
72. Smith, T.; Galm, A.; Chatterjee, S.; Wells, R.; Pedersen, S.; Parizi, A.; Goodship, A.; Blunn, G. Modulation of the Soft Tissue Reactions to Percutaneous Orthopaedic Implants. *J. Orthop. Res.* **2006**, *24*, 1377–1383. [CrossRef]

73. Onodera, S.; Fujii, S.; Moriguchi, H.; Tsujioka, M.; Hirakuri, K. Antibacterial Property of F Doped DLC Film with Plasma Treatment. *Diam. Relat. Mater.* **2020**, *107*, 107835. [CrossRef]
74. Marciano, F.R.; Lima-Oliveira, D.A.; Da-Silva, N.S.; Corat, E.J.; Trava-Airoldi, V.J. Antibacterial Activity of Fluorinated Diamond-like Carbon Films Produced by PECVD. *Surf. Coat. Technol.* **2010**, *204*, 2986–2990. [CrossRef]
75. Marciano, F.R.; Bonetti, L.F.; Santos, L.V.; Da-Silva, N.S.; Corat, E.J.; Trava-Airoldi, V.J. Antibacterial Activity of DLC and Ag-DLC Films Produced by PECVD Technique. *Diam. Relat. Mater.* **2009**, *18*, 1010–1014. [CrossRef]
76. Marciano, F.R.; Bonetti, L.F.; Da-Silva, N.S.; Corat, E.J.; Trava-Airoldi, V.J. Wettability and Antibacterial Activity of Modified Diamond-like Carbon Films. *Appl. Surf. Sci.* **2009**, *255*, 8377–8382. [CrossRef]
77. Mohanty, M.; Anilkumar, T.; Mohanan, P.; Muraleedharan, C.; Bhuvaneshwar, G.; Derangere, F.; Sampeur, Y.; Suryanarayanan, R. Long Term Tissue Response to Titanium Coated with Diamond like Carbon. *Biomol. Eng.* **2002**, *19*, 125–128. [CrossRef]

https://doi.org/10.3390/coatings16050536