metals

Review

Surface Engineering of Metals: Techniques, Characterizations and Applications

Maziar Ramezani [1,*], Zaidi Mohd Ripin [2], Tim Pasang [3] and Cho-Pei Jiang [4]

1 Department of Mechanical Engineering, Auckland University of Technology, Auckland 1010, New Zealand
2 School of Mechanical Engineering, Universiti Sains Malaysia, Nibong Tebal 14300, Malaysia
3 Department of Manufacturing and Mechanical Engineering Technology, Oregon Institute of Technology, Klamath Falls, OR 97601, USA
4 Department of Mechanical Engineering, National Taipei University of Technology, Taipei 10608, Taiwan
* Correspondence: maziar.ramezani@aut.ac.nz

Abstract: This paper presents a comprehensive review of recent advancements in surface engineering of metals, encompassing techniques, characterization methods and applications. The study emphasizes the significance of surface engineering in enhancing the performance and functionality of metallic materials in various industries. The paper discusses the different techniques employed in surface engineering, including physical techniques such as thermal spray coatings and chemical techniques such as electroplating. It also explores characterization methods used to assess the microstructural, topographical, and mechanical properties of engineered surfaces. Furthermore, the paper highlights recent advancements in the field, focusing on nanostructured coatings, surface modification for corrosion protection, biomedical applications, and energy-related surface functionalization. It discusses the improved mechanical and tribological properties of nanostructured coatings, as well as the development of corrosion-resistant coatings and bioactive surface treatments for medical implants. The applications of surface engineering in industries such as aerospace, automotive, electronics, and healthcare are presented, showcasing the use of surface engineering techniques to enhance components, provide wear resistance, and improve corrosion protection. The paper concludes by discussing the challenges and future directions in surface engineering, highlighting the need for further research and development to address limitations and exploit emerging trends. The findings of this review contribute to advancing the understanding of surface engineering and its applications in various sectors, paving the way for future innovations and advancements.

Keywords: corrosion protection; metals; coating; surface modification; tribological properties; wear resistance

Citation: Ramezani, M.; Mohd Ripin, Z.; Pasang, T.; Jiang, C.-P. Surface Engineering of Metals: Techniques, Characterizations and Applications. *Metals* **2023**, *13*, 1299. https://doi.org/10.3390/met13071299

Received: 18 June 2023
Revised: 16 July 2023
Accepted: 18 July 2023
Published: 20 July 2023

1. Introduction

Surface engineering plays a pivotal role in enhancing the performance and functionality of metallic materials across various industries. The ability to modify the surface properties of metals has opened up new avenues for improving their mechanical strength, wear resistance, corrosion protection, and biocompatibility [1,2]. Recent advancements in surface engineering techniques and characterization methods have further propelled the field, leading to innovative applications and transformative outcomes.

Surface engineering techniques can be broadly categorized into physical and chemical approaches. Physical techniques involve the application of heat or energy to modify the surface, such as thermal spray coatings, physical vapor deposition (PVD), chemical vapor deposition (CVD), and laser surface engineering. These techniques offer versatility in tailoring surface properties, including hardness, adhesion, and surface texture, to meet specific requirements. On the other hand, chemical techniques such as electroplating, electroless plating, sol–gel coatings, and chemical etching provide opportunities for controlled deposition and chemical modification of the surface, enabling improvements in corrosion resistance, biocompatibility, and functionalization [3–7].

To understand and evaluate the effectiveness of surface engineering processes, an array of characterization methods is employed. Microstructural characterization techniques, such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD), enable the examination of surface morphology, crystallographic structure, and phase composition. Surface topography analysis tools, such as atomic force microscopy (AFM), scanning tunneling microscopy (STM), and surface profilometry, allow for precise measurement and visualization of surface roughness, texture, and feature dimensions. Additionally, mechanical and tribological characterization methods, including hardness testing, wear and friction testing, and scratch and indentation testing, provide insights into the mechanical behavior and performance of the engineered surfaces [8,9].

Recent advancements in surface engineering have brought about remarkable improvements in the field. Nanostructured coatings [10–12] have emerged as a prominent area of research, with enhanced mechanical and tribological properties being achieved through precise control over the microstructure and composition at the nanoscale. These coatings exhibit exceptional hardness, wear resistance, and reduced friction, making them highly desirable for various industrial applications.

Furthermore, surface modification techniques have been developed to address the challenges of corrosion protection. Corrosion-resistant coatings [13,14] and surface passivation methods [15,16] offer improved durability and an extended lifespan for metallic components exposed to harsh environments. These advancements hold significant potential in industries such as automotive, aerospace, and marine, where corrosion-related failures can have severe consequences.

Surface engineering has also made significant contributions to the biomedical field. Bioactive coatings for implantable devices, such as orthopedic implants and dental prosthetics, promote osseointegration and reduce the risk of implant rejection [17,18]. Moreover, antimicrobial surface treatments have been developed to combat infections in healthcare settings, providing a crucial line of defense against microbial colonization on medical devices and surfaces [19].

The energy sector has also witnessed the impact of surface engineering advancements. Surface modifications have been employed to enhance the catalytic activity of materials for efficient energy-conversion processes. Additionally, coatings and surface functionalization have been explored to improve the performance and durability of energy storage devices, such as batteries [20] and fuel cells [21].

In the aerospace and defense sectors, surface engineering techniques are used to enhance the performance and longevity of critical components subjected to extreme conditions [22]. In the automotive sector, wear-resistant coatings and corrosion protection technologies are vital for ensuring the reliability and safety of engine components and automotive parts [23,24], while in the electronics and semiconductor industry, surface modifications enable the fabrication of high-performance devices [25].

Despite the significant advancements in surface engineering, several challenges remain. The complexity of the surface engineering processes, the need for precise control over deposition parameters, and the scalability of techniques for large-scale production are areas that require further investigation and development. Additionally, the integration of surface engineering with other manufacturing processes and the cost-effectiveness of these techniques are important considerations for practical implementation.

Looking towards the future, we see that the emerging trends and technologies in surface engineering hold great promise. The utilization of advanced computational modeling and simulation techniques can aid in the design and optimization of engineered surfaces with tailored properties. Furthermore, the exploration of novel materials, such as graphene and other two-dimensional materials, opens up possibilities for developing advanced coatings and functionalized surfaces with unique properties.

This paper aims to provide a comprehensive overview of recent advancements in the surface engineering of metals. By exploring the techniques, characterization methods and applications, this review highlights the significance of surface engineering in enhancing the performance and functionality of metallic materials across industries. The advancements in nanostructured coatings, corrosion protection, biomedical applications, and energy functionalization demonstrate the transformative potential of surface engineering. However, challenges and opportunities lie ahead, and future research and development efforts will further advance the field, leading to innovative solutions and novel applications that will shape the future of surface engineering.

2. Techniques for Surface Engineering of Metals

Surface engineering techniques play a crucial role in modifying the surface properties of metals to achieve desired characteristics and performance. This section discusses the primary physical and chemical techniques employed in the surface engineering of metals.

2.1. Physical Techniques

Thermal Spray Coatings: Thermal spray coatings involve the deposition of molten or semi-molten materials onto the metal surface, using a high-velocity thermal spray gun. Commonly used materials include ceramics, metals, and polymers. The molten particles adhere to the substrate, forming a coating that enhances properties such as wear resistance, corrosion protection, and thermal insulation. Various thermal spray techniques include plasma spraying [26], flame spraying [27], and high-velocity oxy-fuel (HVOF) spraying [28]. Figure 1 shows a schematic of the thermal spraying technique.

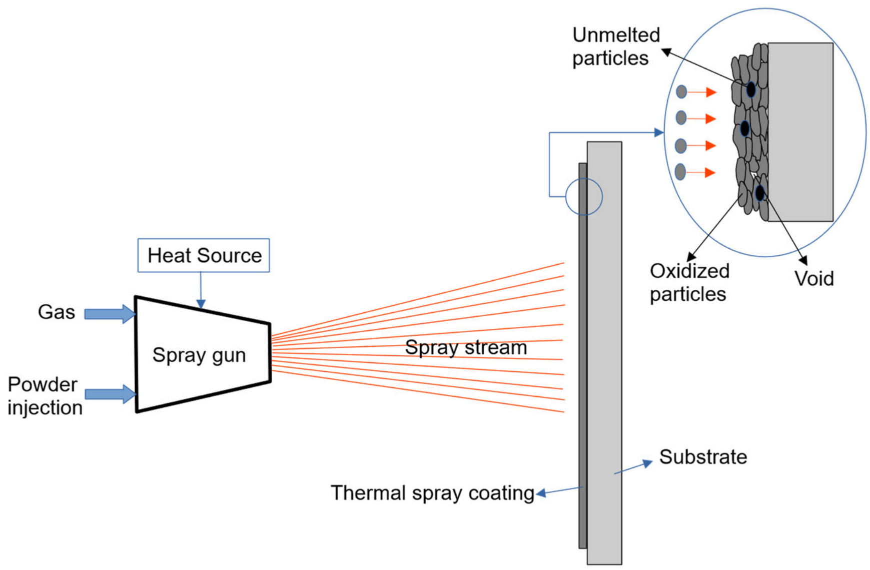

Figure 1. Schematic illustration of the thermal spray coating.

Arc plasma deposition is a cutting-edge thermal spray coating technique that utilizes an electric arc to generate a high-temperature plasma stream, which is directed towards a target material. This process offers advantages such as high deposition rates, strong bond strength, and precise control over coating thickness and composition. It finds applications in aerospace for thermal barrier coatings, in automotive for wear-resistant coatings on engine components, and in manufacturing cutting tools and electronic devices for enhanced performance and protection. The versatility and effectiveness of arc plasma deposition make it a preferred choice for a wide range of coating applications across industries [29,30].

Physical Vapor Deposition (PVD): PVD is a vacuum-based technique that involves the deposition of thin films onto metal surfaces. The process utilizes the physical vaporization and condensation of source materials, resulting in the formation of a thin coating layer. Techniques such as sputtering and evaporation are employed to deposit materials such as metals, ceramics, and alloys. PVD coatings offer excellent adhesion, hardness, and chemical stability, making them suitable for wear-resistant and decorative applications [31]. The PVD coating technique is depicted in Figure 2.

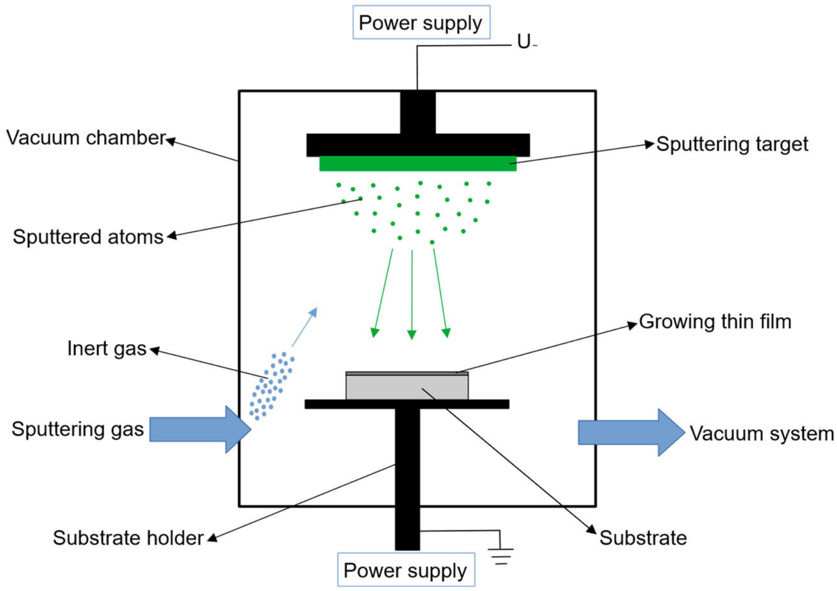

Figure 2. Physical vapor deposition coating technique.

Chemical Vapor Deposition (CVD): CVD is a chemical technique that enables the deposition of thin films onto metal surfaces by the reaction of vaporized precursor molecules. The precursor molecules decompose on the heated substrate, forming a solid coating. CVD coatings exhibit excellent adhesion, conformal coverage, and precise control over composition and thickness. Common applications include corrosion protection [32], optical coatings [33], and semiconductor manufacturing [34]. Figure 3 shows a schematic representation of the CVD coating process.

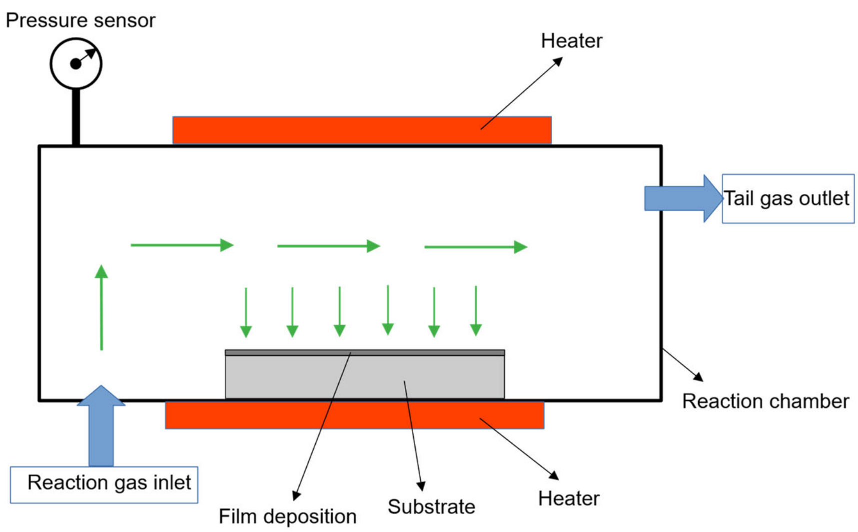

Figure 3. Chemical vapor deposition coating technique.

Laser Surface Engineering: Laser surface engineering techniques involve the use of lasers to modify the surface properties of metals. Laser surface treatment methods include laser cladding [35], laser alloying [36], laser hardening [37], and laser surface texturing [38]. These techniques offer localized treatment, enabling precise control over surface properties such as hardness, wear resistance, and thermal behavior. Laser surface engineering finds applications in areas such as tooling, automotive components, and aerospace structures. Figure 4 shows a sketch of the laser cladding process.

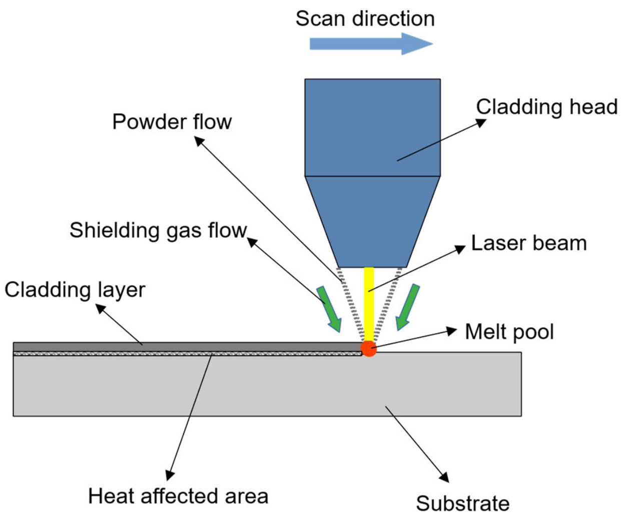

Figure 4. Schematic of laser cladding.

The advantages and limitations of the four physical surface engineering techniques presented in this section are summarized in Table 1.

2.2. Chemical Techniques

Electroplating: Electroplating is a widely used technique that involves the deposition of a metal coating onto a conductive substrate through an electrochemical process. As depicted in Figure 5, the substrate is immersed in an electrolyte solution containing metal ions, and an electric current is applied to initiate the electrodeposition of the desired metal. Electroplating enables the enhancement of surface properties such as corrosion resistance, aesthetics, and conductivity. It finds extensive applications in industries such as automotive, electronics, and jewelry manufacturing [39,40].

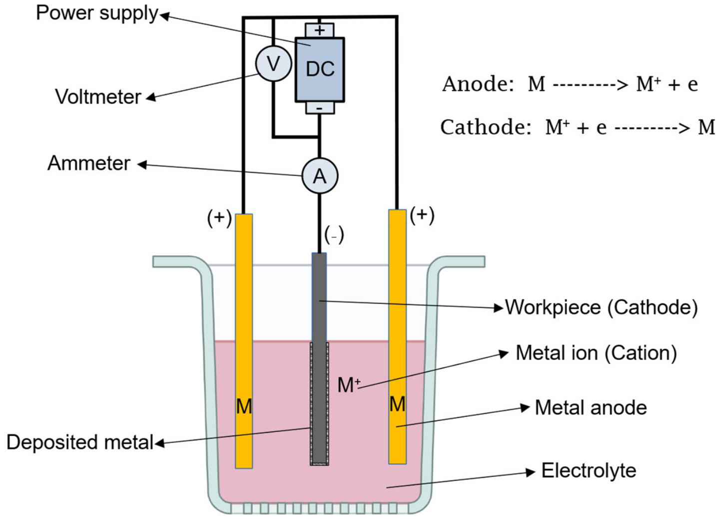

Figure 5. Schematic representation of electroplating.

Table 1. Comparison of physical surface engineering techniques.

Technique	Deposition Method	Advantages	Limitations
Thermal spray coatings	Spraying molten or powdered material onto a prepared surface	- Wide range of material options - Ability to apply thick coatings - Good wear and corrosion resistance - Suitable for large-area coatings	- Poor coating adhesion on some substrates - High process temperature may cause substrate distortion - Coating porosity can affect properties
Physical vapor deposition (PVD)	Evaporation or sputtering of material onto a substrate	- High-quality, dense, and adherent coatings - Control over coating thickness and composition - Good adhesion on various substrates - Low contamination and impurity levels	- Limited deposition rate - Limited coating thickness - Equipment and maintenance costs - Limited scalability for large-scale production
Chemical vapor deposition (CVD)	Chemical reaction to deposit solid material onto a substrate	- Precise control over coating composition - High-quality and conformal coatings - Uniform coating thickness and coverage - Excellent adhesion on various substrates - Good scalability for large-scale production	- High process temperature may restrict compatibility with certain substrates - Deposition rate can be slower compared to PVD - Equipment and maintenance costs - Environmental and safety concerns
Laser surface engineering	Laser beam melts or heats the surface of the material	- Precise control over treated area and depth - Minimal heat-affected zone and distortion - High flexibility for surface modification - Enhanced surface hardness and wear resistance	- Limited to localized treatment - Limited to certain materials and geometries - Limited to specific laser system availability - Limited deposition rate

Electroless Plating: Unlike electroplating, electroless plating (depicted in Figure 6) is a non-electrochemical process that involves the deposition of a metal coating onto a substrate without the need for an external power source. The coating is formed through a controlled chemical reduction reaction. Electroless plating offers advantages such as uniform coating thickness, excellent adhesion, and the ability to coat complex shapes and non-conductive materials. It is commonly used for applications such as printed circuit boards, automotive components, and corrosion protection [41,42].

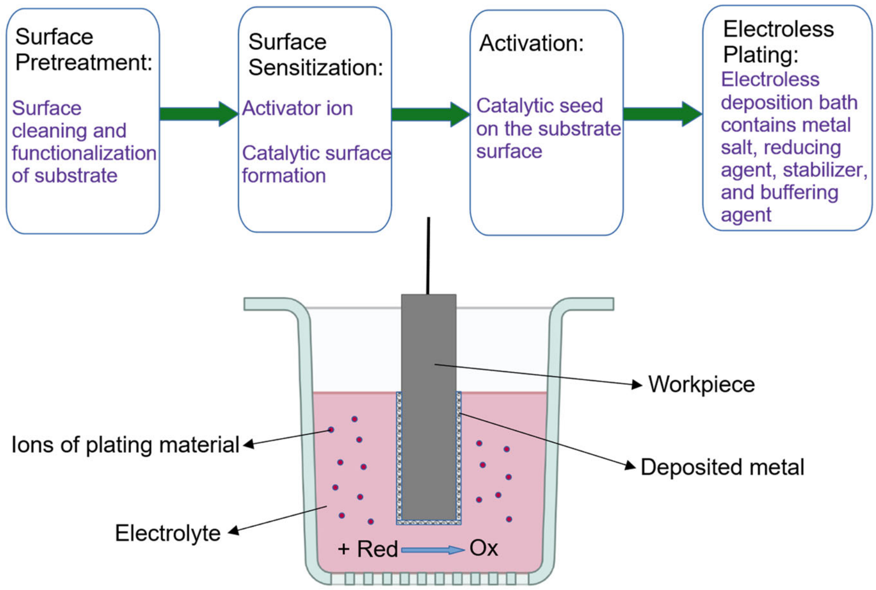

Figure 6. Schematic view of the electroless plating.

Sol–Gel Coatings: Sol–gel coatings are formed through the hydrolysis and condensation of metal alkoxides or metal salts to produce a colloidal suspension or "sol." The sol is applied to the metal surface, and subsequent drying and curing result in the formation of a thin film. Sol–gel coatings offer benefits, such as good adhesion, optical transparency, and chemical resistance. They find applications in areas such as optics, sensors, and protective coatings [43–45]. A sketch of the sol–gel coating process is shown in Figure 7.

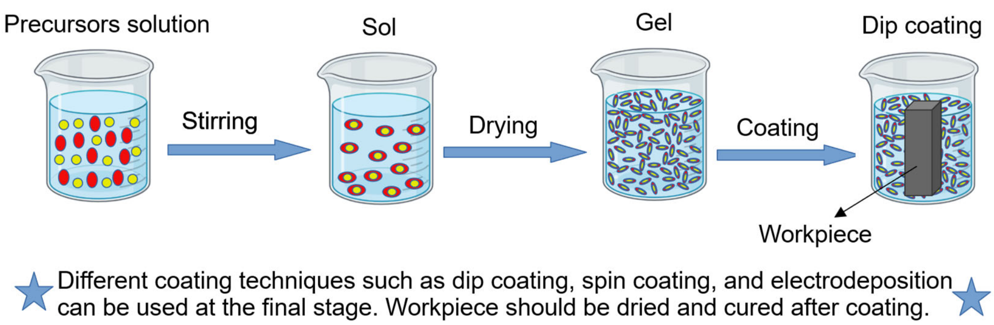

Figure 7. Schematic illustration of the sol–gel dip coating process.

Chemical Etching: Chemical etching, also known as chemical milling, involves the selective removal of material from the metal surface using chemical etchants. The etching process can be controlled to create specific patterns, textures, or designs on the surface. Chemical etching is often used for decorative purposes, precision machining, or the removal of surface defects. It offers advantages such as high precision, intricate detailing, and the ability to etch complex geometries [46]. Applications of chemical etching include jewelry, nameplates, microelectromechanical systems (MEMSs), and integrated circuits.

A comparison of the four types of chemical surface engineering techniques presented in this section is offered in Table 2. These physical and chemical techniques for the surface engineering of metals offer a wide range of possibilities for tailoring the surface properties according to specific requirements. Whether through the deposition of coatings, the controlled modification of the surface chemistry, or the creation of surface textures, these techniques enable the enhancement of mechanical strength, wear resistance, corrosion protection, and aesthetic appeal of metal surfaces.

Table 2. Comparison of chemical surface engineering techniques.

Technique	Coating Method	Coating Properties	Substrate Compatibility	Applications
Electroplating	Electrochemical deposition of metal coatings onto a conductive substrate	Controlled thickness and composition Good adhesion and surface finish	- Conductive substrates - Limited compatibility with non-conductive - substrates	- Decorative coatings - Corrosion protection - Wear resistance - Electronic components
Electroless plating	Auto-catalytic deposition of metal coatings onto a variety of substrates	Uniform and conformal coatings High corrosion and wear resistance Self-catalyzing and self-limiting	- Wide range of substrates - Complex geometries and internal surfaces	- Printed circuit boards - Automotive components - Chemical industry equipment
Sol–gel coatings	Chemical solution deposition and controlled gelation on substrates	Tailorable composition and properties Excellent adhesion and porosity Adjustable thickness and porosity	- Wide range of substrates - Versatile deposition methods - Potential for functionalization	- Optical coatings - Anti-reflective coatings - Protective coatings - Biomedical applications
Chemical etching	Chemical dissolution of material from surface to create desired patterns or structures	Precise control over etched features High aspect ratio and fine details Surface texturing and roughening	- Wide range of metallic and non-metallic substrates - Chemical selectivity for etching	- Microelectromechanical systems (MEMSs) - Semiconductor devices - Microfluidic devices - Surface texturing for adhesion control

It is important to note that the selection of a surface engineering technique depends on various factors, such as the desired properties, substrate material, cost considerations, and scalability. Each technique has its advantages and limitations, and the choice of technique should be based on a thorough understanding of the specific application and performance requirements.

In recent years, efforts have been focused on improving these techniques further. For example, advancements in thermal spray coatings have led to the development of nanostructured coatings with enhanced mechanical and tribological properties [47,48]. The refinement of PVD and CVD processes has enabled the deposition of thin films with precise control over composition, thickness, and microstructure [49–51]. Laser surface engineering techniques have benefited from advancements in laser technology, allowing for more precise and efficient surface modifications [38].

In the realm of chemical techniques, electroplating processes have been optimized to achieve higher deposition rates, an improved coating quality, and a reduced environmental impact [39]. Electroless plating techniques have seen advancements in the development of new plating solutions and strategies for selective plating on complex surfaces [52]. Sol–gel coatings have witnessed progress in the synthesis of novel materials and the exploration of hybrid organic–inorganic coatings for improved performance [53,54]. Chemical etching techniques have benefited from advancements in etchant formulation, masking techniques, and process control for achieving high precision and repeatability [55].

The continuous advancements in surface engineering techniques offer immense opportunities for diverse applications across industries. From aerospace and automotive components to electronics, medical devices, and consumer goods, the ability to tailor the surface properties of metals has a significant impact on product performance, durability, and functionality. The ongoing research and development efforts in this field are driving the exploration of new materials, innovative process optimizations, and the integration of surface engineering with other manufacturing processes.

3. Characterization Methods for Surface Engineering

Characterization plays a crucial role in evaluating the effectiveness and performance of surface engineering techniques. By examining the microstructural, topographical, and mechanical properties of engineered surfaces, researchers can gain insights into the structure–function relationship and make informed decisions for process optimization and material selection [8]. This section discusses the key characterization methods used in the surface engineering of metals.

3.1. Microstructural Characterization

Scanning Electron Microscopy (SEM): SEM is a widely used technique for microstructural analysis of surfaces. It provides high-resolution images of the surface morphology, revealing details such as grain structure, porosity, and coating thickness. SEM utilizes a focused electron beam to scan the surface, and the interaction of the beam with the sample generates signals that are used to construct an image. Energy-dispersive X-ray spectroscopy (EDS) can be coupled with SEM to analyze the elemental composition of the surface. The integration of SEM and EDS offers a powerful toolset for surface engineering research. SEM provides morphological information, aiding in evaluating surface treatment techniques and understanding the relationship between microstructure and material properties. EDS complements this by providing an elemental analysis, identifying impurities, assessing coating quality, and optimizing surface engineering processes. Together, SEM and EDS enable researchers to gain comprehensive insights into surface morphology, elemental composition, and overall characteristics, driving advancements in materials science and technology.

Transmission Electron Microscopy (TEM): TEM allows for a detailed examination of the microstructure at the nanoscale. A thin sample is illuminated with a beam of electrons, and the transmitted electrons are collected to form an image. TEM provides information on the crystal structure, grain boundaries, and defects within the material. It is particularly useful for characterizing thin films, nanoparticles, and interfaces. TEM provides invaluable insights into the atomic-level characteristics of materials, facilitating a deeper understanding of their properties and performance. It is particularly useful for analyzing thin films, enabling the precise examination of thickness, uniformity, and crystalline structure. Additionally, TEM plays a significant role in investigating nanoparticles and interfaces, offering high-resolution imaging for studying size, shape, and internal structure. Focused Ion Beam (FIB) technology complements TEM by enabling precise sample preparation, including cross-sectional imaging and in situ nanoscale modification. FIB allows for controlled milling, extraction of thin lamellae, and fabrication of nanostructures, enhancing the capabilities of TEM analysis. The integration of TEM and FIB techniques offers a powerful platform for materials' characterization and manipulation, enabling advancements in diverse fields of research and applications, such as materials science, nanotechnology, and device fabrication.

X-ray Diffraction (XRD): XRD is employed to analyze the crystallographic structure and phase composition of materials. When a polycrystalline sample is exposed to X-ray radiation, the diffraction pattern produced provides information about the crystal lattice and the arrangement of atoms. XRD can identify the phases present in coatings or surface-modified layers and assess their crystallinity. Through XRD analysis, researchers can determine the types of crystal structures present in a material, as well as their relative abundances. By comparing the obtained diffraction pattern with known crystallographic databases, the specific phases within the sample can be identified. Furthermore, XRD can provide insights into the quality of crystal growth and the presence of any structural defects or strain in the material. In the context of coatings or surface modification, XRD is highly useful for characterizing the crystalline phases formed during the process. It can help determine the degree of phase transformation and assess the overall crystallinity of the modified surface. This information is essential for understanding the structure–property relationships and optimizing the performance of engineered surfaces.

3.2. Surface Topography Analysis

Atomic Force Microscopy (AFM): AFM is a versatile technique that is used to analyze surface topography at the nanoscale. It utilizes a sharp probe that scans the surface and measures the forces between the probe tip and the sample. The tip's movement is tracked, generating a high-resolution topographic image of the surface. AFM can quantify parameters such as roughness, surface features, and texture. Additionally, advanced modes such as scanning Kelvin probe microscopy (SKPM) and magnetic force microscopy (MFM) can provide information about the surface potential and magnetic properties, respectively. The versatility of AFM makes it a valuable tool for surface characterization in various fields of research and industry. Its ability to visualize and measure surface features at the nanoscale provides crucial information for understanding material properties, assessing surface quality, and optimizing processes. With the integration of advanced modes such as SKPM and MFM, AFM expands its capabilities to investigate electrical and magnetic properties, broadening its application range.

Scanning Tunneling Microscopy (STM): STM is a technique that provides atomic-level imaging and analysis of surfaces. It involves scanning a sharp metallic probe tip over the sample surface while maintaining a small tunneling current between the tip and the sample. By monitoring the tip–sample distance, STM generates a three-dimensional image of the surface with atomic resolution. STM is particularly useful for studying the surface defects, atomic arrangements, and electronic properties of materials. The atomic-level imaging capabilities of STM have revolutionized the field of surface science. It has been instrumental in advancing our understanding of surface phenomena, such as surface reconstructions, surface diffusion, and surface reactions. Furthermore, STM has proven valuable in studying the behavior of molecules and nanoscale devices on surfaces, facilitating the development of molecular electronics and nanotechnology.

Surface Profilometry: Surface profilometry is a technique used to measure surface roughness and evaluate the height variations of a sample. It employs a stylus or optical methods to scan the surface and record the height profile. Surface profilometry provides quantitative data on parameters such as the average roughness (R_a), maximum height (R_{max}), and spatial wavelength features. The technique finds widespread applications in quality control, surface characterization, and process optimization within the field of surface engineering. By quantifying surface roughness, profilometry helps ensure the desired quality and consistency of manufactured surfaces. It aids in evaluating the effectiveness of surface treatments and coatings, enabling researchers and engineers to optimize processes and enhance material performance. Surface profilometry plays a crucial role in industries such as semiconductor manufacturing, automotive, aerospace, and microelectronics, where the precise control of surface properties is essential. A comparison of the different characterization methods discussed above is presented in Table 3.

Table 3. Comparison of characterization methods in surface engineering.

Characterization Method	Principle	Key Parameters Measured	Advantages
Scanning Electron Microscopy (SEM)	Scanning electron beam interaction with sample surface	- Surface morphology, topography, and composition - Elemental composition through energy-dispersive X-ray spectroscopy (EDS)	- High-resolution imaging, large field of view - Surface chemical mapping capabilities
Transmission Electron Microscopy (TEM)	Transmission of electron beam through sample	- Microstructure, crystallography, defects, and interfaces - Nanoparticle size and shape characterization	- High-resolution imaging, atomic-scale analysis - Elemental mapping and chemical analysis
X-ray Diffraction (XRD)	Diffraction of X-rays by crystal lattice planes	- Crystal structure, phase identification, and orientation - Lattice parameters and crystal defects	- Non-destructive analysis, quantitative phase analysis - Determination of residual stress and texture
Atomic Force Microscopy (AFM)	Sensing the forces between a probe and the sample surface	- Surface topography, roughness, and texture - Quantification of surface roughness parameters	- High-resolution imaging, measurement of surface forces - Capability to image and measure surfaces at the nanoscale
Scanning Tunneling Microscopy (STM)	Tunneling current between a sharp tip and sample surface	- Atomic-scale imaging of surface topography - Surface defects and electronic properties	- Atomic resolution, surface mapping of conductive and non-conductive materials - Capability to study surface electronic structures and properties
Surface Profilometry	Optical or mechanical measurement of surface profile	- Surface roughness, step height, and feature dimensions - Coating thickness determination	- Rapid and non-destructive measurement of surface topography - Profiling of surface features, suitable for larger surface areas

3.3. Mechanical and Tribological Characterization

Hardness Testing: Hardness testing measures the resistance of a material to indentation or penetration. Common hardness tests include the Rockwell hardness test, Vickers hardness test, and Brinell hardness test. These tests assess the material's mechanical properties, such as hardness, toughness, and elastic modulus, which are critical for evaluating the wear resistance and durability of surface-engineered materials. There are several common hardness tests employed in practice, including the Rockwell hardness test, Vickers hardness test, and Brinell hardness test. Each test utilizes specific indentation techniques and measurement parameters to determine the hardness of the material. By subjecting a material to a controlled indentation or penetration, hardness testing enables the assessment of its ability to withstand external forces and resist deformation. This information is particularly important in surface engineering, as it aids in selecting suitable materials and surface treatments to enhance the wear resistance and longevity of components subjected to mechanical stress. The results obtained from hardness testing can assist in optimizing material selection, evaluating the effectiveness of surface engineering processes, and ensuring compliance with industry standards and specifications.

Wear and Friction Testing: Wear and friction testing methods evaluate the tribological performance of surface-engineered materials. Techniques such as pin-on-disk, ball-on-disk, and reciprocating sliding tests are used to simulate real-world contact and sliding conditions. These tests measure parameters such as wear rate, coefficient of friction, and surface damage. They provide valuable information about the effectiveness of surface engineering techniques in reducing wear, improving lubrication, and enhancing the tribological properties of materials [56]. Through wear and friction testing, researchers can evaluate the performance and durability of surface-engineered materials under various operating conditions. These tests simulate the mechanical interactions and stresses that occur during sliding or rubbing contact, allowing for a realistic assessment of the material's resistance to wear and the efficiency of lubrication. The measurements obtained from these tests help in identifying the most suitable surface treatments, coatings, or lubricants to enhance the tribological performance of materials in practical applications. By quantifying wear rates, the coefficient of friction, and surface damage, wear and friction testing enables a comparative analysis of different materials and surface modifications. It aids in the optimization of material selection and surface engineering processes to achieve improved wear resistance, reduced friction, and extended service life.

Nanoscale friction measurement using friction force microscopy (FFM) is a powerful technique that allows for the investigation and characterization of frictional behavior at the nanoscale level. FFM employs a sharp probe tip, typically a cantilever with a sharp tip, which is scanned across the surface of the sample of interest. As the tip interacts with the sample, the lateral force or friction between the tip and the surface is measured [57]. By analyzing the lateral force signal, researchers can extract information about the frictional properties, such as the friction coefficient, adhesion, and surface interactions, at the nanoscale.

When comparing nanoscale friction measurement using FFM to macroscale friction measurement, it is important to recognize the fundamental differences in scale and contact mechanics. At the nanoscale, the surface interactions and forces governing friction behavior can differ significantly from those at the macroscale. Nanoscale friction is influenced by various factors, including atomic-level interactions, surface roughness, adhesion, and lubrication effects. In contrast, macroscale friction is primarily influenced by factors such as the normal force, surface roughness, and the nature of the sliding materials [56–58]. However, both nanoscale and macroscale friction measurements provide valuable insights into the fundamental understanding of friction and play a crucial role in the development of advanced materials, coatings, and lubricants for various applications. By studying friction behavior at both scales, researchers can gain a comprehensive understanding of frictional phenomena and develop strategies to optimize tribological performance in practical systems.

Scratch and Indentation Testing: Scratch and indentation tests are employed to assess the hardness, adhesion, and deformation behavior of surface-engineered coatings or modified layers. Techniques such as nanoindentation and microscratch testing involve applying controlled loads and measuring the resulting deformation or damage. These tests can determine critical properties such as the hardness, elastic modulus, adhesive strength, and resistance to deformation, providing insights into the mechanical integrity and performance of the engineered surfaces. Through scratch and indentation testing, researchers can assess the response of surface-engineered coatings or modified layers to external forces. By subjecting the material to controlled scratching or indenting, these tests provide quantitative data on hardness, measuring the material's resistance to deformation. Additionally, they evaluate the adhesive strength of coatings or modified layers by assessing their ability to withstand applied loads without delamination or failure. These tests play a crucial role in characterizing the mechanical properties of surface-engineered materials. They aid in optimizing coating processes, selecting suitable materials, and assessing the durability of engineered surfaces under different operating conditions. The measurements obtained from scratch and indentation testing help in determining the material's ability to resist wear, withstand mechanical stresses, and maintain its functional properties.

By employing these characterization methods, researchers can gain a comprehensive understanding of the structural, topographical, and mechanical properties of surface-engineered metals. These insights aid in the evaluation, optimization, and quality control of surface engineering processes. Furthermore, the characterization data obtained from these techniques help establish correlations between processing parameters, microstructure, and functional properties, facilitating the development of improved surface engineering strategies and materials.

The selection of characterization techniques depends on the specific objectives and requirements of the surface engineering study. Each technique has its strengths and limitations, and a combination of complementary techniques is often employed to obtain a holistic characterization of the engineered surfaces.

4. Applications of Surface Engineering in Industry

Surface engineering plays a crucial role in various industrial sectors, enabling the enhancement of material performance, protection against environmental degradation, and the development of advanced functionalities. This section focuses on the applications of surface engineering in key industries, including aerospace and defense, automotive, electronics and semiconductor, biomedical and healthcare, and energy sectors. It discusses the specific applications, challenges, and benefits of surface engineering techniques in each industry.

4.1. Aerospace and Defense

Coatings for Aircraft Components: Surface engineering techniques play a crucial role in the aerospace industry, constantly striving to enhance the performance and durability of aircraft components. Recent research and developments in this field have led to significant advancements in coating technologies, allowing for improved resistance to high-temperature environments, wear, and corrosion.

One notable area of research is the development of advanced thermal barrier coatings (TBCs). TBCs are applied to engine components and turbine blades to provide thermal insulation, thus reducing heat transfer and protecting the underlying materials from thermal degradation. Recent studies have focused on enhancing the durability and thermal stability of TBCs by exploring novel materials and deposition techniques [59–61]. For example, researchers have investigated the use of ceramic matrix composites as TBCs, which exhibit superior thermal properties compared to conventional materials [61]. These advancements in TBCs have resulted in increased component lifespan, improved engine efficiency, and reduced maintenance costs.

Wear-resistant coatings are another critical area of research. Aircraft components experience significant wear due to friction, especially in high-stress areas such as landing gears and engine parts. Recent studies have focused on developing innovative wear-resistant coatings with improved hardness, low friction coefficients, and resistance to abrasive wear [62–64]. For instance, the application of diamond-like carbon (DLC) coatings has shown promising results in reducing wear and extending the service life of critical aircraft components [63]. DLC coatings exhibit excellent hardness and low friction, making them ideal for applications where wear resistance is essential.

Corrosion-resistant coatings also play a vital role in protecting aircraft components from environmental factors and corrosive agents [65]. Ongoing research efforts have focused on developing environmentally friendly corrosion-resistant coatings with enhanced performance and longevity. For instance, researchers have explored the use of self-healing coatings that can autonomously repair damage caused by corrosion, thereby increasing the durability of aircraft structures [66,67]. These coatings incorporate corrosion inhibitors or microcapsules containing healing agents that are released when the coating is damaged, effectively repairing the protective layer and preventing further corrosion.

Surface Treatments for Military Equipment: The defense sector heavily relies on surface engineering techniques to ensure the performance, durability, and protection of military equipment, particularly in harsh environments and combat situations. Recent research and developments have led to significant advancements in surface treatments, catering to the specific needs of military applications.

Hardening techniques have been a focal point of research in military equipment surface treatments [68]. The goal is to enhance the hardness and strength of materials, such as firearms and armored vehicles, to withstand extreme conditions and resist deformation or damage. Advanced heat treatment methods, such as induction hardening [69] and laser surface hardening [70], have been investigated to achieve precise and localized hardening, optimizing the mechanical properties of critical components. These techniques help enhance the wear resistance and longevity of military equipment, ensuring reliable performance during demanding operations [71].

Protective coatings have also been extensively studied to enhance the corrosion resistance of military equipment. In harsh environments, such as marine or desert environments, military equipment is exposed to corrosive agents that can degrade its performance and compromise safety. Recent research has focused on developing multifunctional coatings that provide corrosion protection [13,72], while offering additional benefits, such as camouflage or reduced radar signature. Nanostructured coatings, for example, can result in providing both corrosion resistance and stealth capabilities, thereby improving the operational effectiveness of military equipment.

Specialized finishes have gained attention in surface engineering for military equipment to meet specific operational requirements. These finishes include coatings with low reflectivity, reduced infrared signatures, and improved adhesion for camouflage purposes [73,74]. Recent advancements in materials and application techniques have allowed for the development of coatings that provide enhanced stealth capabilities by reducing the equipment's visibility in different bands of the electromagnetic spectrum. This can significantly improve the survivability and effectiveness of military assets in combat scenarios.

4.2. Automotive Sector

Wear-Resistant Coatings for Engine Components: In the automotive sector, surface engineering plays a crucial role in improving the performance and lifespan of engine components. Recent research and developments have focused on enhancing wear-resistant coatings to minimize friction, reduce wear, and optimize fuel efficiency [75,76].

DLC coatings have emerged as a prominent solution for wear resistance in engine components. DLC coatings exhibit a unique combination of properties, including high hardness, low friction coefficients, and excellent adhesion to substrates. Recent studies have explored different variants of DLC coatings, such as amorphous hydrogenated DLC [77,78] and tetrahedral amorphous carbon [79], to enhance their tribological performance. These coatings have demonstrated remarkable resistance to abrasive wear, reducing friction losses and improving the efficiency of internal combustion engines.

Additionally, research has focused on improving the adhesion and cohesion of wear-resistant coatings to ensure their durability under high-stress conditions [80,81]. Techniques such as surface pretreatments, interlayer materials, and optimized deposition processes have been investigated to enhance the bonding strength between the coating and the substrate [82–84]. For example, the use of intermediate layers such as titanium nitride (TiN) or chromium nitride (CrN) has shown improved adhesion, leading to enhanced wear resistance and an extended component lifespan [85–87].

Furthermore, the application of single crystal coatings has gained attention in recent years [83]. Single crystal coatings offer superior mechanical properties compared to their polycrystalline counterparts, thanks to their high crystalline order and absence of grain boundaries. They exhibit enhanced resistance to wear, improved adhesion, and reduced friction, making them attractive for wear-resistant applications. The precise control of crystallographic orientation in single crystal coatings allows researchers to tailor their properties to specific applications and optimize their performance under demanding operating conditions.

Corrosion Protection for Automotive Parts: Corrosion is a significant concern in the automotive industry, impacting the longevity and aesthetics of vehicles. Surface engineering techniques have been instrumental in providing effective corrosion protection to automotive parts, ensuring their durability in diverse environments.

Zinc–nickel alloy coatings have gained attention as a corrosion-resistant solution for automotive components [88]. Recent research has focused on optimizing the composition and deposition parameters of these coatings to enhance their corrosion resistance and adhesion. Zinc–nickel coatings offer superior protection against corrosion, even in harsh conditions such as exposure to road salts or acidic environments [89,90]. Furthermore, advancements in electrodeposition techniques, such as pulse plating [91,92] or electrodeposition from ionic liquids [93], have contributed to the development of high-performance zinc–nickel alloy coatings with improved uniformity and enhanced corrosion resistance.

Electroplated coatings have also been extensively studied for corrosion protection in automotive parts. For instance, researchers have investigated the application of an electroplating bath containing trivalent chromium ions for chromium coatings. This particular bath, utilizing trivalent chromium ions, offers an eco-friendly alternative to the traditional hexavalent chromium bath [94,95]. Trivalent chromium coatings provide excellent corrosion resistance, adhesion, and aesthetic appeal, while reducing the environmental impact associated with traditional chromium plating processes. Additionally, nanocomposite coatings, incorporating nanoparticles or organic inhibitors, have been investigated to enhance the corrosion protection of automotive parts further [96,97].

4.3. Electronics and Semiconductor Industry

Surface Modifications for Electronic Devices: Surface engineering techniques are crucial for optimizing the performance and reliability of electronic devices, as well as enabling their miniaturization. Recent research and developments in this field have focused on various surface modifications to enhance the electrical properties, adhesion, and moisture resistance of electronic components [98].

Plasma treatments have gained significant attention in surface engineering for electronic devices [99]. Plasma etching and deposition techniques allow for the precise control of surface characteristics, such as surface roughness, wettability, and chemical composition. Plasma treatment can be used to remove contaminants, activate surfaces for better adhesion, or modify surface energy to improve the wetting behavior of coatings or adhesives [100]. Recent studies have investigated plasma treatments using different gas compositions and process parameters to tailor the surface properties of electronic components for specific applications. For example, plasma surface modification has been employed to enhance the adhesion of wire bonding and soldering materials to electronic substrates, improving the reliability of interconnections [100–102].

Chemical treatments are another important aspect of surface engineering for electronic devices. Chemical processes, such as etching, cleaning, and passivation, are utilized to remove impurities, improve surface uniformity, and enhance the chemical stability of components. Recent research has focused on developing environmentally friendly chemical treatments that minimize the use of hazardous substances while achieving high-performance surface modifications. For instance, innovative solutions based on water-based chemistries or environmentally benign etchants have been explored to replace traditional chemical treatments involving toxic chemicals. These advancements contribute to the sustainable manufacturing of electronic devices [103–105].

Surface passivation is a critical surface modification technique to protect electronic components from moisture and environmental factors [105]. Passivation layers—typically thin films or coatings—are applied to electronic devices to prevent the degradation of their electrical performance due to moisture absorption or corrosion. Recent developments have focused on the development of passivation materials with improved barrier properties, such as organosilanes or conformal atomic layer deposition coatings [106,107]. These materials provide an effective moisture barrier, preventing the penetration of water vapor into sensitive electronic components and ensuring their long-term reliability.

Thin Film Coatings for Microelectromechanical Systems (MEMSs): Surface engineering plays a vital role in the fabrication of the microelectromechanical systems (MEMSs) used in electronic and sensor applications. Thin film coatings are deposited onto MEMS devices to provide insulation, protection against environmental factors, and mechanical stability, thereby enabling the development of highly sensitive and reliable MEMS devices [108].

Silicon dioxide (SiO_2) and silicon nitride (SiN_x) are commonly used as thin film coatings in MEMS. SiO_2 films offer excellent electrical insulation, high-temperature stability, and chemical resistance, making them suitable for applications requiring electrical isolation or protection against harsh environments. SiN_x coatings provide mechanical stability, low stress, and enhanced barrier properties, ensuring the protection of MEMS structures from moisture, chemical attack, and particle contamination. Recent research has focused on optimizing the deposition processes, film properties, and interface engineering techniques to enhance the performance and reliability of SiO_2 and SiN_x coatings for MEMS applications [109,110].

Metal films have also been extensively studied as thin film coatings for MEMS devices. Metals such as aluminum, gold, and titanium are deposited onto MEMS structures to provide electrical conductivity, bonding pads, or optical reflectivity. Recent advancements have focused on improving the adhesion, uniformity, and reliability of metal films through innovative deposition techniques, such as sputtering, evaporation, or electroplating [111–113]. Moreover, research efforts have been directed towards the development of biocompatible metal coatings for MEMS devices used in biomedical applications, facilitating their integration with biological systems [114,115].

Recent research has also explored the integration of functional materials and surface modifications in electronic devices. For example, the development of self-cleaning or antifouling coatings on electronic surfaces has gained attention to improve the performance and longevity of devices in demanding environments. By incorporating hydrophobic or oleophobic properties into the surface coatings, researchers aim to prevent the accumulation of dust, oils, or contaminants, reducing the need for frequent cleaning and maintenance [116].

Moreover, surface modifications have been explored to enable novel functionalities in electronic devices. For instance, surface patterning techniques, such as nanoimprint lithography or self-assembly of nanoparticles, have been utilized to create micro- or nanostructures with specific optical, electrical, or mechanical properties. These patterned surfaces can be employed in applications such as light-emitting diodes (LEDs), optical filters, or microfluidic devices, where precise control over surface properties is essential for device performance [117,118].

Nanoimprint lithography enables the replication of nanoscale patterns by imprinting a resist material onto a substrate by using a master template. This technique allows the creation of nanostructures with precise dimensions, shapes, and arrangements, offering opportunities to tailor the optical and electrical properties of surfaces [117]. By controlling the size, shape, and spacing of nanostructures, nanoimprint lithography enables the manipulation of light at the nanoscale, leading to enhanced light extraction efficiency in LEDs, improved light–matter interactions in sensors, and optimized optical filters with tailored spectral characteristics.

The self-assembly of nanoparticles is another approach to fabricate nanostructured coatings. By exploiting the intrinsic properties of nanoparticles, such as their size, shape, and surface chemistry, researchers can engineer surfaces with desired functionalities [118]. The self-assembly process allows nanoparticles to organize into well-defined patterns or structures, creating surfaces with unique optical, electrical, or mechanical properties. These nanostructured coatings have been used in various applications, including plasmonic devices, energy harvesting systems, and biosensors, where surface properties at the nanoscale play a crucial role in achieving desired functionality.

The precise control and manipulation of surface properties through surface patterning techniques in nanostructured coatings have opened up new avenues for innovation and advancement in electronic devices. By tailoring the optical, electrical, and mechanical properties of surfaces at the nanoscale, researchers can create functional coatings that offer improved device performance, enhanced efficiency, and new possibilities for emerging technologies.

4.4. Biomedical and Healthcare Sector

Surface Engineering for Medical Implants: Surface engineering techniques have significantly advanced the field of medical implants, addressing the critical need for biocompatibility and successful integration within the human body. Recent research and developments have focused on enhancing the surface properties of implants to promote osseointegration, reduce the risk of rejection, and improve patient outcomes [119,120].

Bioactive coatings have been at the forefront of surface engineering for medical implants. Hydroxyapatite (HA), a biocompatible material that closely resembles the mineral component of natural bone, has been widely used as a coating to promote bone integration. HA coatings provide a favorable surface for the attachment and proliferation of bone cells, facilitating the formation of a strong bond between the implant and the surrounding bone tissue [119]. Recent studies have explored the use of novel methods, such as electrochemical deposition or biomimetic approaches, to improve the adherence, uniformity, and bioactivity of HA coatings on implant surfaces [121,122].

In addition to HA, biocompatible polymers have also been utilized as coatings for medical implants. These polymers, such as polyethylene glycol and polycaprolactone, can be applied to implant surfaces to reduce inflammation, minimize the foreign body response, and enhance tissue integration. Researchers have focused on optimizing the surface chemistry and topography of these polymer coatings to facilitate cellular adhesion, improve biocompatibility, and promote tissue regeneration around the implant [119,123].

Surface modifications beyond coatings have also been explored in recent years. Nanostructured surfaces, created through techniques such as nanoimprinting or nanotexturing, have shown promising results in promoting cell adhesion, proliferation, and differentiation. Nanostructures mimic the natural extracellular matrix, providing cues that guide cellular behavior and tissue formation. Furthermore, functional groups' immobilization, such as the introduction of peptide sequences or growth factors onto implant surfaces, can modulate cellular responses and facilitate specific tissue integration [119,124].

Antimicrobial Coatings for Healthcare Settings: Surface engineering has played a critical role in enhancing hygiene and reducing the spread of infections in healthcare settings. Antimicrobial coatings have been developed and applied to medical devices, equipment, and high-touch surfaces to inhibit the growth and proliferation of bacteria, viruses, and fungi.

Silver-based coatings have been extensively studied and utilized for their potent antimicrobial properties. Silver ions released from these coatings disrupt microbial cell membranes and inhibit their growth. Recent research has focused on developing silver-based coatings with controlled release mechanisms to ensure long-lasting antimicrobial activity while minimizing the potential toxicity to human cells [125,126]. Additionally, researchers have explored the incorporation of other antimicrobial metals, such as copper alloys, which also exhibit broad-spectrum antimicrobial activity and have shown promise in reducing bacterial contamination on surfaces [127].

Antimicrobial polymers have also been developed as coatings for healthcare surfaces. These polymers, such as quaternary ammonium compounds or polymeric nanoparticles with antimicrobial agents, provide durable and effective antimicrobial properties. These coatings can be applied to medical devices, touch surfaces, or even textiles, contributing to the reduction of healthcare-associated infections and promoting a safer environment for patients and healthcare professionals [119].

Furthermore, advancements in surface engineering techniques have facilitated the development of self-cleaning surfaces in healthcare settings. These surfaces utilize innovative approaches, such as photocatalytic coatings or superhydrophobic materials, to repel water, prevent the adhesion of contaminants, and enable easy cleaning. By minimizing the attachment of microorganisms and organic matter, these self-cleaning surfaces contribute to improved hygiene and reduce the risk of cross-contamination in healthcare settings [119,128].

Recent research has focused on the development of multifunctional coatings that not only possess antimicrobial properties but also provide additional functionalities. For example, coatings with photocatalytic properties have been investigated, utilizing materials such as titanium dioxide (TiO_2), which can generate reactive oxygen species upon exposure to light [129,130]. These coatings have shown promise in effectively degrading organic pollutants and eliminating bacteria on surfaces when activated by UV light. Similarly, researchers have explored the incorporation of antifouling properties into antimicrobial coatings, reducing the attachment of proteins, biofilms, and other contaminants on surfaces [131].

To ensure the efficacy and durability of antimicrobial coatings in healthcare settings, recent studies have focused on optimizing coating deposition methods, surface roughness, and release kinetics of antimicrobial agents. Techniques such as plasma-enhanced chemical vapor deposition, electrochemical deposition, or layer-by-layer assembly have been employed to achieve uniform and conformal coatings with controlled antimicrobial properties. Furthermore, strategies for sustained release of antimicrobial agents from coatings have been investigated, including encapsulation within nanoparticles or incorporating them into biodegradable polymers [132,133].

The application of antimicrobial coatings in healthcare settings extends beyond medical devices and equipment. High-touch surfaces in hospitals, such as door handles, handrails, or bed rails, are also targeted to minimize the transmission of pathogens. Recent developments have explored the use of durable antimicrobial coatings that withstand frequent cleaning and disinfection protocols, maintaining their antimicrobial efficacy over extended periods [119].

4.5. Energy Applications

Surface Modifications for Enhanced Catalytic Activity: Surface engineering techniques have significantly contributed to improving the catalytic activity of metal surfaces, enabling advancements in various energy-related applications. Recent research has focused on tailoring the surface properties of catalysts to enhance their catalytic performance and selectivity [134].

One approach involves controlling the surface roughness of catalysts. The manipulation of surface morphology at the nanoscale or through the introduction of hierarchical structures can significantly impact catalytic activity. Increased surface roughness provides a larger active surface area, improves reactant adsorption, and facilitates the diffusion of reactant molecules, resulting in enhanced catalytic efficiency. Additionally, surface functionalization through the introduction of specific chemical groups or functional ligands can alter the electronic structure of the catalyst surface, influencing its catalytic activity and selectivity [135,136].

Another important aspect of surface engineering in catalysis involves the creation of bimetallic or alloyed structures. By combining two or more metals with different catalytic properties, researchers can tune the surface composition and electronic structure to enhance catalytic performance. Bimetallic catalysts often exhibit synergistic effects, where the interaction between the two metals leads to improved catalytic activity, selectivity, and stability. These catalysts have been extensively explored in processes such as hydrogen production [137], carbon dioxide conversion [138], and selective oxidation reactions [139].

Recent developments in surface engineering for catalysis have also focused on the design of catalyst supports and the introduction of surface modifiers. Catalyst supports with high surface areas and tailored pore structures can enhance mass transport and improve the accessibility of reactants to active sites. Surface modifiers, such as oxides or molecular coatings, can provide additional functionalities, such as improved stability, selectivity, or resistance to catalyst deactivation [140].

These surface modifications and advancements in catalysis have significant implications for the development of sustainable energy technologies. For instance, in the field of hydrogen production, efficient catalysts are essential for processes such as water splitting or steam reforming. By optimizing the surface properties of catalysts, researchers aim to enhance the efficiency, reduce energy consumption, and improve the overall sustainability of hydrogen production methods [141].

Coatings for Improved Energy Storage and Conversion: Surface engineering techniques have played a critical role in improving the performance of materials used in energy storage and conversion devices, enabling advancements in areas such as batteries [142] and solar cells [143].

In the field of lithium-ion batteries, surface coatings on electrode materials have been extensively studied to enhance battery performance. These coatings serve multiple purposes, including improving the stability of electrode materials during cycling, inhibiting undesired side reactions, and enhancing ion and electron transport within the battery. For example, coating electrode materials with protective layers, such as oxides or polymers, can prevent direct contact between the electrode and electrolyte, reducing side reactions and enhancing the stability of the battery. Furthermore, surface modifications can enhance the interfacial compatibility between different components of the battery, improving charge transfer and cyclability [142,144].

Similarly, in solar cell technologies, surface engineering has been utilized to optimize light absorption, charge transport, and device efficiency. Surface texturing techniques, such as nanostructuring or surface patterning, can effectively trap and scatter light within the solar cell, increasing the path length of photons and enhancing absorption [145]. Additionally, surface modifications with anti-reflection coatings can reduce light reflection at the cell surface, improving light absorption and overall device performance [146]. Surface passivation techniques have also been employed to reduce surface recombination losses, enhancing charge extraction and maximizing the efficiency of solar cells [147].

Furthermore, surface engineering techniques are being explored to address challenges in emerging energy storage and conversion technologies. For instance, in the field of electrochemical energy storage, such as supercapacitors [148] and metal–air batteries [149], surface modifications are being investigated to enhance the surface area, ion transport kinetics, and stability of electrode materials. The use of advanced surface coatings, nanoscale architectures, and tailored surface functionalities can improve electrochemical performance and enable higher energy and power densities in these systems.

5. Challenges and Future Directions

Surface engineering has made significant strides in enhancing the performance and functionality of metals in various applications. However, there are still challenges to be addressed and opportunities for future advancements in the field. This section discusses the limitations of current surface engineering techniques, emerging trends and technologies, and potential areas for future research and development.

5.1. Limitations of Current Surface Engineering Techniques

Process Complexity and Cost: Many surface engineering techniques involve complex processes, specialized equipment, and skilled operators, resulting in high production costs. The implementation of these techniques in industrial settings may be challenging due to the need for specialized facilities and expertise. There is a need to develop cost-effective and scalable surface engineering processes that can be readily adopted by industries.

Durability and Longevity: While surface coatings and modifications can enhance the performance of metals, their durability and longevity can still be a concern. Coatings may degrade over time, leading to reduced protection against wear, corrosion, or other environmental factors. Improving the longevity of surface-engineered materials is crucial to ensure long-term performance and cost-effectiveness.

Compatibility and Adhesion: Achieving good adhesion between the coating and the substrate is essential for the effectiveness of surface engineering techniques. However, certain combinations of materials may pose challenges to achieving strong and durable adhesion. Developing strategies to improve the compatibility and adhesion between coatings and substrates is crucial for reliable and long-lasting surface engineering solutions.

Complex Geometries: Surface engineering techniques may face limitations when it comes to treating complex geometries or intricate structures. Coating uniformity and coverage can be difficult to achieve in such cases, leading to variations in performance across the surface. Finding effective solutions for the surface engineering of complex shapes and structures is necessary to meet the demands of diverse industries and applications.

Environmental Impact: Some surface engineering processes involve the use of hazardous chemicals or high-energy inputs or generate waste products, which can have negative environmental implications. Minimizing the environmental footprint of surface engineering techniques is crucial to ensure sustainable and responsible manufacturing practices. Developing eco-friendly alternatives and optimizing process efficiency are important considerations.

Limited Material Selection: Certain surface engineering techniques may have limitations in terms of the materials they can be applied to. For example, some coatings may not adhere well to certain types of metals or non-metallic materials. Expanding the range of materials that can benefit from surface engineering techniques is essential to cater to a broader range of applications and industries.

Process Control and Reproducibility: Achieving consistent and reproducible results in surface engineering can be challenging, particularly when it comes to large-scale production. Variations in process parameters, environmental conditions, or material properties can affect the quality and performance of surface-engineered products. Enhancing process control and developing robust quality-assurance protocols are necessary to ensure reliability and reproducibility in surface engineering.

Integration with Existing Manufacturing Processes: Incorporating surface engineering techniques into existing manufacturing workflows can be complex and may require modifications to production lines or equipment. The seamless integration of surface engineering processes with existing manufacturing systems is crucial to facilitate their widespread adoption and enable efficient production.

Addressing these limitations will require ongoing research and development efforts in the field of surface engineering. Collaborations between researchers, engineers, and industry professionals are essential to overcome these challenges and drive the advancement of surface engineering techniques towards greater efficiency, affordability, durability, and sustainability. A list of challenges and future directions in surface engineering of metals is presented in Table 4.

Table 4. Challenges and future directions in surface engineering of metals.

Challenges	Future Directions
Process Complexity and Cost	- Develop cost-effective and scalable surface engineering processes - Simplify process steps and equipment requirements - Improve process efficiency and productivity
Durability and Longevity	- Enhance coating durability and longevity - Develop self-healing or protective coatings - Optimize coating performance under various environmental conditions
Compatibility and Adhesion	- Improve compatibility between coatings and substrates - Develop advanced surface preparation techniques for better adhesion - Enhance interfacial bonding and mechanical properties
Complex Geometries	- Develop specialized surface engineering techniques for complex shapes and structures - Explore additive manufacturing for surface engineering of complex geometries - Optimize coating deposition methods for uniform coverage
Environmental Impact	- Minimize the use of hazardous chemicals and reduce energy inputs - Develop eco-friendly alternatives and sustainable manufacturing processes - Implement waste reduction and recycling methods for surface-engineered materials
Limited Material Selection	- Expand the range of materials suitable for surface engineering - Develop coatings compatible with non-metallic materials - Explore surface engineering techniques for polymers and composites
Process Control and Reproducibility	- Enhance process control and optimization - Develop quality-assurance protocols and standards - Implement real-time monitoring and feedback systems
Integration with Existing Manufacturing Processes	- Facilitate seamless integration of surface engineering into existing production workflows - Modify production lines or equipment to accommodate surface engineering processes - Develop standardized protocols for integrating surface engineering techniques

5.2. Emerging Trends and Technologies in the Field

Multifunctional Coatings: There is a growing interest in the development of multifunctional coatings that offer a combination of properties, such as self-healing, self-cleaning, anti-icing, or antifouling capabilities. These coatings can provide enhanced performance and reduce the need for additional treatments or maintenance. The integration of different functionalities into a single coating represents an emerging trend in surface engineering [13].

Nanotechnology and Nanomaterials: Nanotechnology has revolutionized surface engineering by enabling precise control over surface structures and properties at the nanoscale. The use of nanomaterials, such as nanoparticles [20,125], nanocomposites [24,96], and nanolayers [144], has shown promise in improving the performance of surface-engineered materials. The incorporation of nanotechnology into surface engineering opens up new opportunities for tailoring properties, enhancing functionality, and developing advanced applications.

Biomimetic Surfaces: Inspired by nature, biomimetic surfaces aim to replicate the unique properties and functionalities found in natural systems. The development of surfaces that mimic the self-cleaning properties of lotus leaves, the adhesive properties of gecko feet, or the drag-reduction properties of shark skin represents an exciting direction in surface engineering. Biomimetic surfaces have the potential to provide innovative solutions in fields such as aerospace, automotive, and healthcare [116].

Additive Manufacturing for Surface Engineering: Additive manufacturing, or 3D printing, is being increasingly explored as a tool for surface engineering. This technology allows for the precise deposition of materials layer by layer, enabling the creation of complex surface structures and coatings with tailored properties. Additive manufacturing techniques can be used to fabricate surfaces with graded compositions, roughness profiles, or even embedded functionalities, offering new possibilities for customized surface engineering solutions [150].

Smart Surfaces: The development of smart surfaces is an emerging trend in surface engineering. These surfaces have the ability to actively respond and adapt to changes in their environment. For example, smart surfaces can change their wettability, adhesion, or optical properties in response to external stimuli such as temperature, light, or pH. Such surfaces hold promise for applications in fields such as adaptive optics, microfluidics, and sensors, where dynamic control over surface properties is crucial [151].

Machine Learning and Artificial Intelligence in Surface Engineering: The integration of machine learning and artificial intelligence (AI) techniques into surface engineering is gaining attention. These technologies can assist in the design and optimization of surface structures, coatings, and modifications by predicting their properties and performance based on large datasets and computational modeling. Machine-learning algorithms can also aid in the development of new materials with tailored surface properties, enabling faster and more efficient surface engineering processes [152].

In Situ Characterization and Monitoring: Real-time characterization and monitoring of surface properties and performance are becoming increasingly important in surface engineering. In situ techniques such as spectroscopy, microscopy, and sensing methods allow for the assessment of surface modifications and coatings during operation or in simulated environments. This information can guide the optimization of surface engineering processes, ensure the quality and reliability of surface treatments, and enable proactive maintenance strategies [153].

Table 5 lists the abovementioned emerging trends and technologies in the surface engineering of metals and their potential benefits and applications.

5.3. Potential Areas for Future Research and Development

Sustainable Surface Engineering: With the increasing focus on sustainability, there is a need for surface engineering techniques that minimize the environmental impact. Research efforts should be directed towards the development of environmentally friendly coatings, the reduction of hazardous materials, and the use of sustainable manufacturing processes. Exploring bio-based coatings, eco-friendly surface treatments, and recycling methods for surface-engineered materials can contribute to a more sustainable approach.

Advanced Characterization Techniques: Advancements in surface characterization techniques are crucial for understanding the structure–property relationships of surface-engineered materials. Further development and refinement of characterization techniques, such as in situ and real-time monitoring methods, high-resolution imaging techniques, and advanced spectroscopic methods, will provide valuable insights into the behavior and performance of surface-engineered materials.

Surface Engineering for Extreme Environments: Exploring surface engineering solutions for extreme environments, such as high-temperature, corrosive, or abrasive conditions, is an area of great importance. Developing coatings and surface modifications that can withstand extreme conditions, maintain their functionality, and provide long-term protection is crucial for industries such as aerospace, energy, and manufacturing. Research efforts should focus on materials with high-temperature stability, superior corrosion resistance, and enhanced mechanical properties.

Table 5. Emerging trends and technologies in surface engineering of metals.

Emerging Trend/Technology	Potential Benefits	Potential Applications
Multifunctional Coatings	- Enhanced performance and functionality - Reduced need for additional treatments - or maintenance	- Automotive coatings - Aerospace coatings - Antifouling marine coatings
Nanotechnology and Nanomaterials	- Improved surface properties - Tailored functionalities - Enhanced material performance	- Wear-resistant coatings - Corrosion-resistant coatings - Biomedical implants - Electronics
Biomimetic Surfaces	- Self-cleaning properties - Adhesive properties - Drag reduction properties	- Aerospace surfaces - Automotive surfaces - Marine antifouling surfaces
Additive Manufacturing for Surface Engineering	- Tailored surface structures - Graded compositions - Embedded functionalities	- Customized surface engineering - Aerospace components - Biomedical implants
Smart Surfaces	- Adaptive response to external stimuli - Dynamic control over surface properties	- Adaptive optics - Microfluidics - Sensors
Machine Learning and Artificial Intelligence	- Design optimization - Predictive modeling - Faster and more efficient processes	- Coating development - Surface modification - Material discovery
In Situ Characterization and Monitoring	- Real-time assessment - Quality assurance - Proactive maintenance strategies	- Coating performance monitoring - Surface modification evaluation - Wear and corrosion monitoring

Biocompatible and Bioactive Surfaces: In the biomedical field, there is a need for advanced surface engineering techniques that can enhance the biocompatibility and bioactivity of materials. Developing novel coatings and surface modifications that promote cell adhesion, tissue integration, and controlled drug release is critical for applications such as implantable devices, tissue engineering, and regenerative medicine. Additionally, exploring surface engineering approaches to combat bacterial infections, such as developing antimicrobial surfaces and biofilm-resistant coatings, is of utmost importance.

Scale-Up and Industrial Implementation: For surface engineering techniques to have a significant impact in various industries, there is a need for scalable and easily implementable processes. Efforts should be directed towards developing surface engineering techniques that can be readily adopted by industrial manufacturers. This involves addressing challenges such as process scalability, cost-effectiveness, ease of integration into existing manufacturing processes, and robust quality-control measures.

Dynamic and Reconfigurable Surfaces: The development of surfaces that can dynamically change their properties in response to external stimuli represents an exciting area for future research. This includes surfaces that can switch between different states of wettability, adhesion, or optical properties, enabling new functionalities and applications. Exploring materials with stimuli-responsive properties and developing surface engineering techniques to control their dynamic behavior will be crucial in this field.

Bio-Inspired Surface Engineering: Nature provides a wealth of inspiration for surface engineering. Future research should focus on understanding and replicating the unique properties and functionalities found in natural systems, such as self-cleaning, anti-fogging, or anti-reflective surfaces. By mimicking nature, researchers can develop innovative surface engineering solutions that offer improved performance, durability, and sustainability.

Multiscale Surface Engineering: Many applications require surface engineering at multiple length scales, from the nanoscale to the macroscale. Research efforts should aim to develop techniques that can precisely control surface structures and properties across different length scales. This includes strategies for hierarchical surface engineering, where surface modifications are applied at different scales to achieve synergistic effects and optimized performance.

Integration of Surface Engineering with 3D Printing: As additive manufacturing continues to advance, there is an opportunity to integrate surface engineering techniques directly into the 3D-printing process. This includes in situ surface modifications during printing or the development of novel printing materials with inherent surface functionalities. The combination of 3D printing and surface engineering can lead to the fabrication of complex components with tailored surface properties and functionalities.

Overall, the future of surface engineering lies in addressing current limitations, exploring new application areas, and integrating emerging technologies. By focusing on sustainability, advanced characterization, artificial intelligence, extreme environments, biomedical applications, scalability, flexible electronics, dynamic surfaces, bio-inspired approaches, multiscale engineering, and 3D-printing integration, researchers can drive the field forward and unlock new possibilities for surface engineering in diverse industries and applications.

6. Conclusions

The surface engineering of metals has witnessed remarkable advancements in recent years, driven by the need for enhanced material performance, protection, and functionality across various industries. This paper provided a comprehensive review of the techniques, characterization methods, applications, challenges, and future directions in the field of surface engineering of metals.

The techniques for the surface engineering of metals encompass a range of physical and chemical processes. Physical techniques such as thermal spray coatings, physical vapor deposition (PVD), chemical vapor deposition (CVD), and laser surface engineering offer versatile means to modify surface properties. Chemical techniques such as electroplating, electroless plating, sol–gel coatings, and chemical etching provide effective methods for depositing coatings and modifying surface chemistries. These techniques enable the tailoring of surface characteristics such as wear resistance, corrosion resistance, biocompatibility, and electrical properties to meet specific application requirements.

Characterization methods play a crucial role in assessing the effectiveness and quality of surface-engineered materials. Microstructural characterization techniques, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD), provide insights into the surface morphology, crystal structure, and phase composition. Surface topography analysis techniques such as atomic force microscopy (AFM) and scanning tunneling microscopy (STM) enable the precise measurement and imaging of surface features at the nanoscale. Mechanical and tribological characterization techniques, including hardness testing, wear and friction testing, and scratch and indentation testing, assess the mechanical properties and performance of surface-engineered materials.

Recent advancements in the surface engineering of metals have focused on several key areas. Nanostructured coatings have gained attention due to their unique properties and improved mechanical and tribological performance. Advances in nanocoating deposition techniques have allowed precise control over coating structures, resulting in enhanced functionality. Surface modification for corrosion protection has seen the development of corrosion-resistant coatings and surface passivation techniques to mitigate the effects of corrosion on metal components. Surface engineering for biomedical applications has led to the development of bioactive coatings for implantable devices and antimicrobial surface treatments to prevent infections. Surface functionalization for energy applications has focused on surface modifications to enhance catalytic activity and develop coatings for improved energy storage and conversion.

The applications of surface engineering in industry have demonstrated their significant impact on various sectors. In the aerospace and defense industry, coatings and surface treatments play a vital role in enhancing aircraft components and protecting military equipment. The automotive sector benefits from wear-resistant coatings and corrosion protection for engine components and automotive parts. The electronics and semiconductor industry relies on surface modifications and thin film coatings for electronic devices and microelectromechanical systems.

However, several challenges and future directions need to be addressed to further advance the surface engineering of metals. The limitations of current surface engineering techniques, including process complexity, durability, and adhesion issues, require attention to develop cost-effective and reliable processes. Emerging trends such as multifunctional coatings, nanotechnology, and biomimetic surfaces offer exciting prospects for future developments. Sustainable surface engineering, advanced characterization techniques, integration of artificial intelligence and machine learning, surface engineering for extreme environments, biocompatible surfaces, and facilitating industrial implementation are potential areas for future research and development.

In conclusion, the surface engineering of metals continues to evolve and revolutionize various industries by enhancing material performance, protection, and functionality. The advancements in techniques, characterization methods and applications discussed in this paper provide a comprehensive overview of the field. By addressing the challenges and exploring the future directions highlighted, surface engineering will continue to play a pivotal role in meeting the evolving needs of industries, leading to improved material performance, extended component lifespans, reduced maintenance costs, and enhanced overall system efficiency.

Author Contributions: Writing—original draft preparation, M.R.; writing—review and editing, M.R., Z.M.R., T.P. and C.-P.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ramezani, M.; Pasang, T.; Chen, Z.; Neitzert, T.; Au, D. Evaluation of carbon diffusion in heat treatment of H13 tool steel under different atmospheric conditions. *J. Mater. Res. Technol.* **2015**, *4*, 114–125. [CrossRef]
2. Li, H.; Ramezani, M.; Chen, Z.; Singamneni, S. Effects of Process Parameters on Temperature and Stress Distributions During Selective Laser Melting of Ti–6Al–4V. *Trans. Indian Inst. Met.* **2019**, *72*, 3201–3214. [CrossRef]
3. Awang, M.; Khalili, A.A.; Pedapati, S.R. A review: Thin protective coating for wear protection in high-temperature application. *Metals* **2020**, *10*, 42. [CrossRef]
4. Riquelme, A.; Rodrigo, P. An introduction on the laser cladding coatings on magnesium alloys. *Metals* **2021**, *11*, 1993. [CrossRef]
5. Fotovvati, B.; Namdari, N.; Dehghanghadikolaei, A. On coating techniques for surface protection: A review. *J. Manuf. Mater. Process.* **2019**, *3*, 28. [CrossRef]
6. Butt, M.A. Thin-Film Coating Methods: A Successful Marriage of High-Quality and Cost-Effectiveness—A Brief Exploration. *Coatings* **2022**, *12*, 1115. [CrossRef]
7. Schalk, N.; Tkadletz, M.; Mitterer, C. Hard coatings for cutting applications: Physical vs. chemical vapor deposition and future challenges for the coatings community. *Surf. Coat. Technol.* **2022**, *429*, 127949. [CrossRef]
8. Panwar, A.S.; Singh, A.; Sehgal, S. Material characterization techniques in engineering applications: A review. *Mater. Today Proc.* **2020**, *28*, 1932–1937. [CrossRef]
9. Li, H.; Ramezani, M.; Chen, Z.W. Dry sliding wear performance and behaviour of powder bed fusion processed Ti–6Al–4V alloy. *Wear* **2019**, *440–441*, 203103. [CrossRef]
10. Ghezzi, D.; Boi, M.; Sassoni, E.; Valle, F.; Giusto, E.; Boanini, E.; Baldini, N.; Cappelletti, M.; Graziani, G. Customized biofilm device for antibiofilm and antibacterial screening of newly developed nanostructured silver and zinc coatings. *J. Biol. Eng.* **2023**, *17*, 18. [CrossRef]
11. Leitans, A.; Jansons, E.; Lungevics, J.; Kundzins, K.; Boiko, I.; Kanders, U.; Kovalenko, V.; Linins, O. Tribological and Micromechanical Properties of the Nanostructured Carbonitride/Nitride Coatings of Transition Metals Alloyed by Hf and Nb. *Coatings* **2023**, *13*, 552. [CrossRef]

12. Grigoriev, S.; Vereschaka, A.; Milovich, F.; Sitnikov, N.; Bublikov, J.; Seleznev, A.; Sotova, C.; Rykunov, A. Investigation of the Properties of Multilayer Nanostructured Coating Based on the (Ti,Y,Al)N System with High Content of Yttrium. *Coatings* **2023**, *13*, 335. [CrossRef]
13. Huang, N.; Wang, Y.; Zhang, Y.; Liu, L.; Yuan, N.; Ding, J. Multifunctional coating on magnesium alloy: Superhydrophobic, self-healing, anti-corrosion and wear-resistant. *Surf. Coat. Technol.* **2023**, *463*, 129539. [CrossRef]
14. Nazarzade, K.; Naderi, R.; Mahdavian, M. Fabrication of corrosion-resistant conversion coating based on ZIF-8 on electro-galvanized steel utilizing pulse electrodeposition technique. *Surf. Coat. Technol.* **2023**, *457*, 129292. [CrossRef]
15. Mo, Y.; Ma, X.; Wang, S.; Zhong, H.; Yang, J.; Cao, Z. In-situ constructing and EDTA-enhancing of meta-aluminate passivation films on electroplated zinc surfaces. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *657*, 130573. [CrossRef]
16. Kozaderov, O.; Światowska, J.; Dragoe, D.; Burliaev, D.; Volovitch, P. Effect of Cr(III) passivation layer on surface modifications of zinc-nickel coatings in chloride solutions. *J. Solid State Electrochem.* **2021**, *25*, 1161–1173. [CrossRef]
17. Katić, J.; Krivačić, S.; Petrović, Ž.; Mikić, D.; Marciuš, M. Titanium Implant Alloy Modified by Electrochemically Deposited Functional Bioactive Calcium Phosphate Coatings. *Coatings* **2023**, *13*, 640. [CrossRef]
18. Nikolova, M.P.; Apostolova, M.D. Advances in Multifunctional Bioactive Coatings for Metallic Bone Implants. *Materials* **2023**, *16*, 183. [CrossRef]
19. Costa, R.C.; Nagay, B.E.; Dini, C.; Borges, M.H.; Miranda, L.F.; Cordeiro, J.M.; Souza, J.G.; Sukotjo, C.; Cruz, N.C.; Barão, V.A. The race for the optimal antimicrobial surface: Perspectives and challenges related to plasma electrolytic oxidation coating for titanium-based implants. *Adv. Colloid Interface Sci.* **2023**, *311*, 102805. [CrossRef]
20. Wang, C.; Jiu, H.; Zhang, L.; Xu, R.; Che, S.; Guo, Z.; Han, Y.; Ma, J.; Li, H.; Guo, F. Carbon coating hollow NiS nanoparticles anchored on Ti_3C_2 nanosheet as high-performance anode for lithium-ion batteries. *J. Alloys Compd.* **2023**, *956*, 170332. [CrossRef]
21. Su, Y.L.; Kao, W.H.; Chang, G.Y. Tribological, Anti-corrosion, and Electrical Conductivity Properties of CrCx Coatings Deposited on Stainless Steel 316L and Used as Metal Bipolar Plates for Fuel Cells. *J. Mater. Eng. Perform.* **2023**, *32*, 3739–3754. [CrossRef]
22. Bonu, V.; Barshilia, H.C. High-Temperature Solid Particle Erosion of Aerospace Components: Its Mitigation Using Advanced Nanostructured Coating Technologies. *Coatings* **2022**, *12*, 1979. [CrossRef]
23. Zhang, S.N.; Chen, Z.; Arfaei, B. Graphene Coating as a Corrosion Protection Barrier for Metallic Terminals in Automotive Environments. *SAE Int. J. Adv. Curr. Pract. Mobil.* **2021**, *3*, 3176–3183. [CrossRef]
24. Wasekar, N.P.; Bathini, L.; Ramakrishna, L.; Rao, D.S.; Padmanabham, G. Pulsed electrodeposition, mechanical properties and wear mechanism in Ni-W/SiC nanocomposite coatings used for automotive applications. *Appl. Surf. Sci.* **2020**, *527*, 146896. [CrossRef]
25. Wang, J.; Wang, L.; Su, X.; Xiao, R.; Cheng, H. Polarization Maintaining Fiber Temperature and Stress Gradient Sensitization Sensor Based on Semiconductor-Metal–Polymer Three-Layer Film Coating. *ACS Appl. Mater. Interfaces* **2022**, *14*, 20053–20061. [CrossRef]
26. Li, C.-J.; Luo, X.-T.; Dong, X.-Y.; Zhang, L.; Li, C.-X. Recent Research Advances in Plasma Spraying of Bulk-Like Dense Metal Coatings with Metallurgically Bonded Lamellae. *J. Therm. Spray Technol.* **2022**, *31*, 5–27. [CrossRef]
27. Yao, H.-L.; Xia, J.; Yi, D.-L.; Yang, C.; Zhang, M.-X.; Bai, X.-B.; Chen, Q.-Y.; Wang, H.-T.; Li, S.-B. Microstructure and Corrosion Properties of Biodegradable Mg/MgO Composite Coating on Mg Alloy Prepared by High Velocity Suspension Flame Spraying. *J. Therm. Spray Technol.* **2021**, *30*, 1544–1556. [CrossRef]
28. Liu, B.; Xiao, F.; Zhu, H.; Tang, M. Promising WC-30WB-10Co Cemented Carbide Coating with Improved Density and Hardness Deposited by High Velocity Oxy-Fuel Spraying: Microstructure and Mechanical Properties. *J. Mater. Eng. Perform.* **2023**, *32*, 6405–6411. [CrossRef]
29. Lee, H.-S.; Singh, J.K. Deposition and corrosion studies of plasma arc thermal sprayed Zn and 85Zn–15Al films on steel surface. *J. Mater. Sci.* **2022**, *57*, 19650–19665. [CrossRef]
30. Leonov, A.A.; Denisova, Y.A.; Denisov, V.V.; Syrtanov, M.S.; Shmakov, A.N.; Savostikov, V.M.; Teresov, A.D. Structure and Properties of CrN/TiN Multi-Layer Coatings Obtained by Vacuum-Arc Plasma-Assisted Deposition Method. *Coatings* **2023**, *13*, 351. [CrossRef]
31. Li, H.; Chen, Z.W.; Ramezani, M. Wear behaviours of PVD-TiN coating onTi-6Al-4V alloy processed by laser powder bed fusion or conventionally processed. *Int. J. Adv. Manuf. Technol.* **2021**, *113*, 1389–1399. [CrossRef]
32. Zhang, M.; Zhou, T.; Li, H.; Liu, Q. UV-durable superhydrophobic ZnO/SiO_2 nanorod arrays on an aluminum substrate using catalyst-free chemical vapor deposition and their corrosion performance. *Appl. Surf. Sci.* **2023**, *623*, 157085. [CrossRef]
33. Cheng, Y.; Wang, K.; Qi, Y.; Liu, Z. Chemical Vapor Deposition Method for Graphene Fiber Materials. *Wuli Huaxue Xuebao/Acta Phys.-Chim. Sin.* **2020**, *38*, 2006046. [CrossRef]
34. Seo, J.; Kim, J.; Lee, J.; Koo, D.; Jeong, G.; Choi, Y.; bin Son, E.; Park, H. Intergranular Diffusion-Assisted Liquid-Phase Chemical Vapor Deposition for Wafer-Scale Synthesis of Patternable 2D Semiconductors. *Adv. Funct. Mater.* **2022**, *32*, 2205695. [CrossRef]
35. Su, W.; Cui, X.; Jin, G.; Liu, C.; Liu, E.; Zhao, H.; Cao, B. Effects of different Y compounds on the microstructure and properties of laser cladding NiTi coatings in a semi-open environment. *Intermetallics* **2023**, *160*, 107936. [CrossRef]
36. Brover, G.I.; Shcherbakova, E.E. Aspects of Structure Formation in Surface Layers of Steel after Laser Alloying from Various Coatings. *Metallurgist* **2022**, *66*, 672–680. [CrossRef]
37. Kanazawa, T.; Hayakawa, M.; Vinas, D.; Tahara, Y.; Hata, N.; Yoshimoto, M. Sustainable technology for remanufacturing of carburized steels by laser hardening. *J. Mater. Res. Technol.* **2023**, *24*, 39–48. [CrossRef]

38. Dashtbozorg, B.; Penchev, P.; Romano, J.-M.; Li, X.; Sammons, R.L.; Dimov, S.; Dong, H. Development of surfaces with antibacterial durability through combined S phase plasma hardening and athermal femtosecond laser texturing. *Appl. Surf. Sci.* **2021**, *565*, 150594. [CrossRef]
39. Comparini, A.; Del Pace, I.; Giurlani, W.; Emanuele, R.; Verrucchi, M.; Bonechi, M.; Innocenti, M. Electroplating on Al6082 Aluminium: A New Green and Sustainable Approach. *Coatings* **2022**, *13*, 13. [CrossRef]
40. Zhang, Z.; Kitada, A.; Fukami, K.; Murase, K. Aluminum Electroplating on AZ31 Magnesium Alloy with Acetic Anhydride Pretreatment. *Acta Met. Sin. Engl. Lett.* **2022**, *35*, 1996–2006. [CrossRef]
41. Tian, M.; Jian, Z.; Hai, R.; Chang, F. Non-isothermal crystallization kinetics of amorphous electroless nickel-phosphorus alloy plating. *J. Therm. Anal. Calorim.* **2023**, *148*, 1959–1970. [CrossRef]
42. Dai, G.; Wu, S.; Huang, X.; Wang, M.; Wu, R. Research on the coating formation of Al-induced electroless plating on metallic surfaces. *J. Mater. Sci.* **2023**, *58*, 3768–3789. [CrossRef]
43. Koli, P.B.; Kapadnis, K.H.; Deshpande, U.G.; Tupe, U.J.; Shinde, S.G.; Ingale, R.S. Fabrication of thin film sensors by spin coating using sol-gel $LaCrO_3$ Perovskite material modified with transition metals for sensing environmental pollutants, greenhouse gases and relative humidity. *Environ. Chall.* **2021**, *3*, 100043. [CrossRef]
44. Gautam, A.; Raju, K.R.C.S.; Gobi, K.V.; Subasri, R. Effect of Transition Metal and Different Rare-Earth Inhibitors-Based Sol–gel Coatings on Corrosion Protection of Mild Steel. *Met. Mater. Int.* **2023**. [CrossRef]
45. Pratima, B.; Subrahmanyam, A. Protective coatings on copper using as-deposited sol-gel TiO_2—SiO_2 films. *Mater. Today Proc.* **2023**, *80*, 1061–1065. [CrossRef]
46. Lidsky, D.; Cain, J.M.; Hutchins-Delgado, T.; Lu, T.M. Inverse metal-assisted chemical etching of germanium with gold and hydrogen peroxide. *Nanotechnology* **2023**, *34*, 065302. [CrossRef] [PubMed]
47. Rengarajan, S.; Ramaraj, B.K.; Paramashivan, S.S.; Velusamy, S. Oxidation behavior of near nanostructured coating developed by the HVOF process. *Mater. Corros.* **2023**, *74*, 482–492. [CrossRef]
48. Chen, J.; An, Y.; Liu, G.; Chen, G.; Zhao, X.; Jia, L. Tribological Performance and Thermal Stability of a Novel Cold Sprayed Nanostructured Ni-based Lubrication Coating. *J. Therm. Spray Technol.* **2022**, *31*, 1702–1711. [CrossRef]
49. Mahana, D.; Mauraya, A.K.; Singh, P.; Muthusamy, S.K. Evolution of CuO thin films through thermal oxidation of Cu films prepared by physical vapour deposition techniques. *Solid State Commun.* **2023**, *366–367*, 115152. [CrossRef]
50. Monti, J.M.; Stewart, J.A.; Custer, J.O.; Adams, D.P.; Depla, D.; Dingreville, R. Linking simulated polycrystalline thin film microstructures to physical vapor deposition conditions. *Acta Mater.* **2023**, *245*, 118581. [CrossRef]
51. Uno, K.; Ohta, M. Control of Al composition of mist chemical vapor deposition grown α-$(AlGa)_2O_3$ alloy thin films by acetylacetonation of Al ion. *Jpn. J. Appl. Phys.* **2023**, *62*, SF1026. [CrossRef]
52. Zhao, Q.; Hu, G.; Huang, R.; Qiang, L.; Zhang, X. Iodide-induced galvanic replacement of nickel film on copper as activator for electroless nickel-phosphorus plating. *Mater. Lett.* **2022**, *314*, 131833. [CrossRef]
53. El Hadad, A.; García-Galván, F.; Mezour, M.; Hickman, G.; Soliman, I.; Jiménez-Morales, A.; Barranco, V.; Galván, J.; Perry, C. Organic-inorganic hybrid coatings containing phosphorus precursors prepared by sol–gel on Ti6Al4V alloy: Electrochemical and in-vitro biocompatibility evaluation. *Prog. Org. Coat.* **2020**, *148*, 105834. [CrossRef]
54. Perrin, F.; Ziarelli, F.; Dupuis, A. Relation between the corrosion resistance and the chemical structure of hybrid sol-gel coatings with interlinked inorganic-organic network. *Prog. Org. Coat.* **2020**, *141*, 105532. [CrossRef]
55. Samanta, S.; Jin, S.; Lee, C.-H.; Lee, S.-S.; Struyf, H.; Kim, T.-G.; Park, J.-G. Effect of ammonium halide salts on wet chemical nanoscale etching and polishing of InGaAs surfaces for advanced CMOS devices. *Mater. Sci. Semicond. Process.* **2023**, *161*, 107469. [CrossRef]
56. Li, H.; Chen, Z.W.; Fiedler, H.; Ramezani, M. Wear behaviour of n ion implanted Ti-6Al-4V alloy processed by selective laser melting. *Metals* **2021**, *11*, 1639. [CrossRef]
57. Watanabe, Y.; Capaz, R.B.; Simao, R.A. Surface characterization using Friction Force Microscopy and the Jarzynski equality. *Appl. Surf. Sci.* **2023**, *607*, 155070. [CrossRef]
58. Kuznetsova, T.; Lapitskaya, V.; Warcholinski, B.; Gilewicz, A.; Chizhik, S. Friction and Wear of ZrN Coatings under Conditions of Microcontact Using Atomic-Force Microscopy. *J. Frict. Wear* **2020**, *41*, 287–294. [CrossRef]
59. Mehta, A.; Vasudev, H.; Singh, S. Sustainable manufacturing approach with novel thermal barrier coatings in lowering CO_2 emissions: Performance analysis with probable solutions. *Int. J. Interact. Des. Manuf. (IJIDeM)* **2023**. [CrossRef]
60. Mehta, A.; Vasudev, H.; Singh, S.; Prakash, C.; Saxena, K.K.; Linul, E.; Buddhi, D.; Xu, J. Processing and Advancements in the Development of Thermal Barrier Coatings: A Review. *Coatings* **2022**, *12*, 1318. [CrossRef]
61. Park, S.M.; Nahm, S.; Oh, Y.S. Thermal durability of ytterbium silicate environmental barrier coating prepared by suspension plasma spray. *J. Korean Ceram. Soc.* **2021**, *58*, 192–200. [CrossRef]
62. Molak, R.; Topolski, K.; Spychalski, M.; Dulińska-Molak, I.; Morończyk, B.; Pakieła, Z.; Nieużyła, L.; Mazurkiewicz, M.; Wojucki, M.; Gebeshuber, A.; et al. Functional properties of the novel hybrid coatings combined of the oxide and DLC layer as a protective coating for AZ91E magnesium alloy. *Surf. Coat. Technol.* **2019**, *380*, 125040. [CrossRef]
63. Marin, E.; Lanzutti, A.; Nakamura, M.; Zanocco, M.; Zhu, W.; Pezzotti, G.; Andreatta, F. Corrosion and scratch resistance of DLC coatings applied on chromium molybdenum steel. *Surf. Coat. Technol.* **2019**, *378*, 124944. [CrossRef]
64. Kai-Hui, D.; Ying-Wei, S.; En-Hou, H. Research progress on the preparation of wear-resistant micro-arc oxidation coatings on titanium alloys. *Surf. Technol.* **2021**, *50*, 57–65. [CrossRef]

65. Yang, C.; Zhu, J.; Cui, S.; Chen, P.; Wu, Z.; Ma, Z.; Fu, R.K.; Tian, X.; Chu, P.K.; Wu, Z. Wear and corrosion resistant coatings prepared on LY12 aluminum alloy by plasma electrolytic oxidation. *Surf. Coat. Technol.* **2021**, *409*, 126885. [CrossRef]
66. Peñas-Caballero, M.; Martín-Cordón, J.; Barranco, V.; Galván, J.C.; Santana, M.H.; Lopez-Manchado, M.A.; Verdejo, R. Corrosion control by autonomous self-healing epoxy coatings based on superabsorbent healing agents. *Prog. Org. Coat.* **2023**, *182*, 107600. [CrossRef]
67. Huangfu, H.; Guo, X.; Li, N.; Xiong, Y.; Huang, Y.; Zhang, J.; Wang, L. A smart composite coating with self-reporting and self-healing functions to enhance corrosion protection for magnesium alloys. *Prog. Org. Coat.* **2023**, *181*, 107598. [CrossRef]
68. Prochazka, J.; Studeny, Z.; Nguyen, C.H. Wear resistance enhancement of case-hardening steels by utilizing plasma nitriding in military applications. In Proceedings of the (2021) METAL 2021—30th Anniversary International Conference on Metallurgy and Materials, Brno, Czech Republic, 26–28 May 2021; pp. 612–620. [CrossRef]
69. Garois, S.; Daoud, M.; Chinesta, F. Data-Driven Inverse Problem for Optimizing the Induction Hardening Process of C45 Spur-Gear. *Metals* **2023**, *13*, 997. [CrossRef]
70. Aprilia, A.; Maharjan, N.; Zhou, W. Decarburization in Laser Surface Hardening of AISI 420 Martensitic Stainless Steel. *Materials* **2023**, *16*, 939. [CrossRef]
71. Zhang, H.; Wu, S.; Ao, N.; Zhou, L.; Wang, L.; Liu, D. The effect of gradient order on impact toughness of carbon S38C axle steels with induction hardening. *Eng. Fail. Anal.* **2023**, *149*, 107254. [CrossRef]
72. Pei, L.; Lin, D.; Yuan, S.; Lu, R.; Bai, Z.; Sun, Y.; Zhu, Y.; Jiang, Y.; Zhu, J.; Wang, H. A multifunctional and long-term waterborne anti-corrosion coating with excellent 'hexagonal warrior' properties. *Chem. Eng. J.* **2023**, *457*, 141158. [CrossRef]
73. Zhang, Y.; Wu, H.; Guo, S. Sandwich-Structured Surface Coating of a Silver-Decorated Electrospun Thermoplastic Polyurethane Fibrous Film for Excellent Electromagnetic Interference Shielding with Low Reflectivity and Favorable Durability. *ACS Appl. Mater. Interfaces* **2022**, *14*, 40351–40360. [CrossRef] [PubMed]
74. Hernán, D.M.V.; Aida, M.E.; Gilberto, B.G. Detailed study of the electrochemical behavior of low-reflectivity TiAlN coatings. *Surf. Innov.* **2020**, *9*, 293–307. [CrossRef]
75. Picas, J.; Menargues, S.; Martin, E.; Baile, M. Cobalt free metallic binders for HVOF thermal sprayed wear resistant coatings. *Surf. Coat. Technol.* **2023**, *456*, 129243. [CrossRef]
76. Ganvir, A.; Jahagirdar, A.R.; Mulone, A.; Örnfeldt, L.; Björklund, S.; Klement, U.; Joshi, S. Novel utilization of liquid feedstock in high velocity air fuel (HVAF) spraying to deposit solid lubricant reinforced wear resistant coatings. *J. Mater. Process. Technol.* **2021**, *295*, 117203. [CrossRef]
77. Bouabibsa, I.; Lamri, S.; Sanchette, F. Structure, mechanical and tribological properties of Me-doped diamond-like carbon (DLC) (Me = Al, Ti, or Nb) hydrogenated amorphous carbon coatings. *Coatings* **2018**, *8*, 370. [CrossRef]
78. Anderson, N.; Zhang, B.; Meng, A.; Zhang, X.; Lijesh, K.; Khonsari, M.; Meng, W. Cr-containing diamond-like carbon coatings deposited on 316 stainless steel substrates: Characterization and interfacial fracture toughness measurements. *Surf. Coat. Technol.* **2023**, *462*, 129462. [CrossRef]
79. Peng, J.; Liao, J.; Zhang, G.; Huang, J.; Qiu, X. Microstructure evolution and mechanical performance of tetrahedral amorphous carbon coatings with dense droplets during annealing. *Mater. Chem. Phys.* **2023**, *301*, 127697. [CrossRef]
80. Kiryukhantsev-Korneev, P.V.; Sheveiko, A.N.; Petrzhik, M.I. Approaches to Increasing the Adhesion Strength of Hard Wear-Resistant Nanostructured Coatings Based on the Ti–B–(Cr, Si, C)–N System. *Prot. Met. Phys. Chem. Surfaces* **2019**, *55*, 502–510. [CrossRef]
81. Vereschaka, A.; Tabakov, V.; Grigoriev, S.; Aksenenko, A.; Sitnikov, N.; Oganyan, G.; Seleznev, A.; Shevchenko, S. Effect of adhesion and the wear-resistant layer thickness ratio on mechanical and performance properties of ZrN—(Zr,Al,Si)N coatings. *Surf. Coat. Technol.* **2019**, *357*, 218–234. [CrossRef]
82. Rashid, M.-U.; Tomkowski, R.; Archenti, A. Effect of Surface Pre-Treatment on the Adhesion between HiPIMS Thick Cu:$CuCN_x$ Coating and WC-Co Shim. *Coatings* **2022**, *12*, 1484. [CrossRef]
83. Liu, D.; Li, J.; Jin, X.; Mu, R.; Yang, W. Effect of Coating Pre-Treatment on Surface Recrystallization of DD6 Single Crystal. *Materials* **2022**, *15*, 7004. [CrossRef] [PubMed]
84. Kim, H.-K.; Kim, S.-M.; Lee, S.-Y. Influence of Interlayer Materials on the Mechanical Properties and Thermal Stability of a CrAlN Coating on a Tungsten Carbide Substrate. *Coatings* **2022**, *12*, 1134. [CrossRef]
85. Sizova, O.V.; Teryukalova, N.V.; Leonov, A.A.; Denisova, Y.A.; Novitskaya, O.S.; Kolubaev, A.V. Influence of the Intermediate Layer on the Adhesion and Friction of Titanium-Based Nitrided Coatings on a Copper Substrate. *Russ. Phys. J.* **2022**, *65*, 1123–1129. [CrossRef]
86. Ben Hassine, M.; Andrén, H.-O.; Iyer, A.H.; Lotsari, A.; Bäcke, O.; Stiens, D.; Janssen, W.; Manns, T.; Kümmel, J.; Halvarsson, M. Growth model for high-Al containing CVD TiAlN coatings on cemented carbides using intermediate layers of TiN. *Surf. Coat. Technol.* **2021**, *421*, 127361. [CrossRef]
87. Avcı, B.; Kazmanlı, K.; Evren, B.; Ürgen, M. Contribution of galvanic coupling with TiN, TiAlN, and CrN to the corrosion of steel in neutral and acidic chloride solutions. *Mater. Corros.* **2023**. [CrossRef]
88. Burliaev, D.V.; Kozaderov, O.A.; Volovitch, P. Zinc-nickel alloy coatings: Electrodeposition kinetics, corrosion, and selective dissolution. A review. *Kondens. Sredy Mezhfaznye Granitsy* **2021**, *23*, 3–15. [CrossRef]
89. Shekhanov, R.F.; Gridchin, S.N.; Balmasov, A.V. Electroplating and Physicochemical Properties of Zinc–Nickel Alloy Coatings from Ammonium Oxalate Electrolytes. *Surf. Eng. Appl. Electrochem.* **2020**, *56*, 427–431. [CrossRef]

90. Pinto, J.; Quiroz, D.; Delvasto, P.; Blanco, S. Characterization of a zinc-nickel alloy coating obtained from an electrolytic bath produced with spent batteries as raw materials. *J. Phys. Conf. Ser.* **2018**, *1119*, 012005. [CrossRef]
91. Lei, C.; Skouby, H.; Kellner, R.; Goosey, E.; Goosey, M.; Sellars, J.; Elliott, D.; Ryder, K.S. Barrel electroplating of Zn-Ni alloy coatings from a modified deep eutectic solvent. *Trans. IMF* **2022**, *100*, 63–71. [CrossRef]
92. Lei, C.; Alesary, H.F.; Khan, F.; Abbott, A.P.; Ryder, K.S. Gamma-phase Zn-Ni alloy deposition by pulse-electroplating from a modified deep eutectic solution. *Surf. Coat. Technol.* **2020**, *403*, 126434. [CrossRef]
93. Fashu, S.; Khan, R. Recent work on electrochemical deposition of Zn-Ni (-X) alloys for corrosion protection of steel. *Anti-Corros. Methods Mater.* **2019**, *66*, 45–60. [CrossRef]
94. Xu, L.; Pi, L.; Dou, Y.; Cui, Y.; Mao, X.; Lin, A.; Fernandez, C.; Peng, C. Electroplating of Thick Hard Chromium Coating from a Trivalent Chromium Bath Containing a Ternary Complexing Agent: A Methodological and Mechanistic Study. *ACS Sustain. Chem. Eng.* **2020**, *8*, 15540–15549. [CrossRef]
95. Ramelan, A.; Fauzi, A.; Rachmantyo, R.; Sasmita, F.; Lidya, L.; Eko, A.Z.; Nugroho, A.S. Effect of PEG addition and temperature on hard chromium coating using eco-friendly trivalent chromium. *AIP Conf. Proc.* **2020**, *2262*, 040019. [CrossRef]
96. Zhang, Z.; Yan, D.; Liu, X.; Li, W.; Wang, Z.; Wang, Y.; Song, D.; Zhang, T.; Liu, J.; Wang, J. Self-healing nanocomposite coatings containing organic-inorganic inhibitors functionalized dendritic silica nanocontainers for synergistic corrosion protection of carbon steel. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *656*, 130430. [CrossRef]
97. Lin, X.-Y.; Yu, Y.-H.; Tse, M.-M.; Cheng, S.-H.; Liu, Y.-H.; Lu, K.-L. Semiconductive (Cu–S)n metal–organic framework incorporated polyimide nanocomposite coatings forming an oxide barrier for durable anticorrosion effects. *Prog. Org. Coat.* **2023**, *180*, 107562. [CrossRef]
98. Ramesh, C.; Tyagi, P.; Kaswan, J.; Yadav, B.S.; Shukla, A.K.; Senthil Kumar, M.; Kushvaha, S.S. Effect of surface modification and laser repetition rate on growth, structural, electronic and optical properties of GaN nanorods on flexible Ti metal foil. *RSC Adv.* **2020**, *10*, 2113–2122. [CrossRef] [PubMed]
99. Deng, K.; Wang, X.; Huang, S.; Li, P.; Jiang, Q.; Yin, H.; Fan, J.; Wei, K.; Zheng, Y.; Shi, J.; et al. Effective Suppression of Amorphous Ga_2O and Related Deep Levels on the GaN Surface by High-Temperature Remote Plasma Pretreatments in GaN-Based Metal–Insulator–Semiconductor Electronic Devices. *ACS Appl. Mater. Interfaces* **2023**, *15*, 25058–25065. [CrossRef]
100. Zhang, S.; Huang, M.; Wu, Y.; Yang, M.; Lin, T.; He, P.; Paik, K.-W. A study on the oxygen plasma treatment on the peel adhesion strength and solder wettability of SnBi58 based anisotropic conductive films. In Proceedings of the 2019 Electronic Components and Technology Conference, Las Vegas, NV, USA, 28–31 May 2019; pp. 2022–2028. [CrossRef]
101. Dong, M.; Li, M.; Hang, T. Application of Ultrathin Organic Insulating Films for Electronic Package. In Proceedings of the 2019 IEEE International Conference on Integrated Circuits, Technologies and Applications (ICTA), Chengdu, China, 13–15 November 2019. [CrossRef]
102. Kencana, S.D.; Kuo, Y.-L.; Yen, Y.-W.; Schellkes, E.; Chuang, W. Improving the solder wettability via atmospheric plasma technology. In Proceedings of the 2019 IEEE 69th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 28–31 May 2019; pp. 2067–2071. [CrossRef]
103. Yan, C.; Byrne, D.; Ondry, J.C.; Kahnt, A.; Moreno-Hernandez, I.A.; Kamat, G.A.; Liu, Z.-J.; Laube, C.; Crook, M.F.; Zhang, Y.; et al. Facet-selective etching trajectories of individual semiconductor nanocrystals. *Sci. Adv.* **2022**, *8*, eabq1700. [CrossRef]
104. Yang, C.; Zhang, B.; Xie, X.; Li, C.; Xu, Y.; Wang, H.; Wang, L. Three-dimensional independent CoZnAl-LDH nanosheets via asymmetric etching of Zn/Al dual ions for high-performance supercapacitors. *J. Alloys Compd.* **2021**, *861*, 157933. [CrossRef]
105. Arora, H.; Jung, Y.; Venanzi, T.; Watanabe, K.; Taniguchi, T.; Hübner, R.; Schneider, H.; Helm, M.; Hone, J.C.; Erbe, A. Effective Hexagonal Boron Nitride Passivation of Few-Layered InSe and GaSe to Enhance Their Electronic and Optical Properties. *ACS Appl. Mater. Interfaces* **2019**, *11*, 43480–43487. [CrossRef] [PubMed]
106. Kavinkumar, T.; Sivagurunathan, A.T.; Kim, D.-H. Construction of highly transparent, flexible, and robust solid-state symmetric supercapacitors using NiO electrodes roughened by conformal atomic layer deposition. *Appl. Surf. Sci.* **2023**, *616*, 156453. [CrossRef]
107. Cheng, L.; Adinolfi, V.; Weeks, S.L.; Barabash, S.V.; Littau, K.A. Conformal deposition of GeTe films with tunable Te composition by atomic layer deposition. *J. Vac. Sci. Technol. A* **2019**, *37*, 020907. [CrossRef]
108. Ma, Y.; Song, J.; Wang, X.; Liu, Y.; Zhou, J. Synthesis, microstructure and properties of magnetron sputtered lead zirconate titanate (Pzt) thin film coatings. *Coatings* **2021**, *11*, 944. [CrossRef]
109. Shamma, K.; Albrithen, H.; Alodhayb, A. Thickness dependence of the response of metal-dioxide-based micromechanical sensors for sensitive gamma-ray detection. *Appl. Radiat. Isot.* **2022**, *186*, 110225. [CrossRef]
110. Beaucejour, R.; D'agati, M.; Kalyan, K.; Olsson, R.H. Compensation of the Stress Gradient in Physical Vapor Deposited $Al_{1-x}Sc_xN$ Films for Microelectromechanical Systems with Low Out-of-Plane Bending. *Micromachines* **2022**, *13*, 1169. [CrossRef]
111. Chou, C.-H.; Nagarjuna, Y.; Yang, Z.-C.; Hsiao, Y.-J.; Wang, S.-C. Catalytic effect of Ag embedded with ZnO prepared by Co-sputtering on H_2S gas sensing MEMS device. *Vacuum* **2022**, *202*, 111210. [CrossRef]
112. Hsueh, T.-J.; Li, P.-S.; Fang, S.-Y.; Hsu, C.-L. A vertical CuO-NWS/MEMS NO2 gas sensor that is produced by sputtering. *Sens. Actuators B Chem.* **2022**, *355*, 131260. [CrossRef]
113. Salehi, M.; Heidari, P.; Ruhani, B.; Kheradmand, A.; Purcar, V.; Căprărescu, S. Theoretical and experimental analysis of surface roughness and adhesion forces of MEMS surfaces using a novel method for making a compound sputtering target. *Coatings* **2021**, *11*, 1551. [CrossRef]

114. Auciello, O. Review of materials science and technological applications of transformational integrated multifunctional oxide/ultrananocrystalline diamond (UNCD) films/crystalline diamond for new generation of high-tech and biomedical devices. *J. Mater. Res.* **2023**, *38*, 571–585. [CrossRef]
115. You, Z.-W.; Wei, L.; Zhang, M.-L.; Yang, F.-H.; Wang, X.-D. Design of a novel MEMS implantable blood pressure sensor and stress distribution of parylene-based coatings. In Proceedings of the 2022 IEEE 16th International Conference on Solid-State & Integrated Circuit Technology (ICSICT), Nanjing, China, 25–28 October 2022; pp. 1–3. [CrossRef]
116. Sun, D.; Böhringer, K.F. Self-Cleaning: From bio-inspired surface modification to MEMS/microfluidics system integration. *Micromachines* **2019**, *10*, 101. [CrossRef] [PubMed]
117. Jiang, S.; Feng, Y.; Chen, Z.; Zhang, L.; Jiang, X.; Jiao, Q.; Li, J.; Chen, Y.; Li, D.; Liu, L.; et al. Study on Light Extraction from GaN-based Green Light-Emitting Diodes Using Anodic Aluminum Oxide Pattern and Nanoimprint Lithography. *Sci. Rep.* **2016**, *6*, 21573. [CrossRef] [PubMed]
118. Sun, J.; Shi, Z.; Li, M.; Chen, S.; Zhong, M.; Liu, X.; Sha, J.; Jia, S. Theoretical investigation of the microfluidic and magnetic field-assisted self-assembly of colloidal magnetic-plasmonic nanoparticles. *J. Phys. D Appl. Phys.* **2021**, *54*, 325004. [CrossRef]
119. Ramezani, M.; Ripin, Z.M. An Overview of Enhancing the Performance of Medical Implants with Nanocomposites. *J. Compos. Sci.* **2023**, *7*, 199. [CrossRef]
120. Ding, Y.; Tao, B.; Ma, R.; Zhao, X.; Liu, P.; Cai, K. Surface modification of titanium implant for repairing/improving microenvironment of bone injury and promoting osseointegration. *J. Mater. Sci. Technol.* **2023**, *143*, 1–11. [CrossRef]
121. Geng, Z.; Li, X.; Ji, L.; Li, Z.; Zhu, S.; Cui, Z.; Wang, J.; Cui, J.; Yang, X.; Liu, C. A novel snail-inspired bionic design of titanium with strontium-substituted hydroxyapatite coating for promoting osseointegration. *J. Mater. Sci. Technol.* **2021**, *79*, 35–45. [CrossRef]
122. Lu, M.; Chen, H.; Yuan, B.; Zhou, Y.; Min, L.; Xiao, Z.; Zhu, X.; Tu, C.; Zhang, X. Electrochemical deposition of nanostructured hydroxyapatite coating on titanium with enhanced early stage osteogenic activity and osseointegration. *Int. J. Nanomed.* **2020**, *15*, 6605–6618. [CrossRef]
123. Ziemba, A.M.; Woodson, M.C.C.; Funnell, J.L.; Wich, D.; Balouch, B.; Rende, D.; Amato, D.N.; Bao, J.; Oprea, I.; Cao, D.; et al. Development of a Slow-Degrading Polymerized Curcumin Coating for Intracortical Microelectrodes. *ACS Appl. Bio Mater.* **2023**, *6*, 806–818. [CrossRef]
124. Cherian, A.M.; Joseph, J.; Nair, M.B.; Nair, S.V.; Vijayakumar, M.; Menon, D. Coupled benefits of nanotopography and titania surface chemistry in fostering endothelialization and reducing in-stent restenosis in coronary stents. *Biomater. Adv.* **2022**, *142*, 213149. [CrossRef]
125. Alcudia, A.; Begines, B.; Rodriguez-Lejarraga, P.; Greyer, V.; Godinho, V.C.F.; Pajuelo, E.; Torres, Y. Development of porous silver nanoparticle/polycaprolactone/polyvinyl alcohol coatings for prophylaxis in titanium interconnected samples for dental implants. *Colloid Interface Sci. Commun.* **2022**, *48*, 100621. [CrossRef]
126. Tran, H.A.; Tran, P.A. In Situ Coatings of Silver Nanoparticles for Biofilm Treatment in Implant-Retention Surgeries: Antimicrobial Activities in Monoculture and Coculture. *ACS Appl. Mater. Interfaces* **2021**, *13*, 41435–41444. [CrossRef] [PubMed]
127. Cordeiro, J.M.; Nagay, B.E.; Dini, C.; Souza, J.G.; Rangel, E.C.; da Cruz, N.C.; Yang, F.; van den Beucken, J.J.; Barão, V.A. Copper source determines chemistry and topography of implant coatings to optimally couple cellular responses and antibacterial activity. *Biomater. Adv.* **2021**, *134*, 112550. [CrossRef] [PubMed]
128. Wu, H.; Xie, L.; He, M.; Zhang, R.; Tian, Y.; Liu, S.; Gong, T.; Huo, F.; Yang, T.; Zhang, Q.; et al. A wear-resistant TiO_2 nanoceramic coating on titanium implants for visible-light photocatalytic removal of organic residues. *Acta Biomater.* **2019**, *97*, 597–607. [CrossRef] [PubMed]
129. Ali, A.; Chowdhury, S.; Janorkar, A.V.; Marquart, M.; Griggs, J.A.; Bumgardner, J.D.; Roach, M.D. A novel single-step anodization approach for pani-doping oxide surfaces to improve the photocatalytic activity of titanium implants. *Biomed. Mater.* **2023**, *18*, 015010. [CrossRef]
130. Qi, L.; Guo, B.; Lu, Q.; Gong, H.; Wang, M.; He, J.; Jia, B.; Ren, J.; Zheng, S.; Lu, Y. Preparation and Photocatalytic and Antibacterial Activities of Micro/Nanostructured TiO_2-Based Photocatalysts for Application in Orthopedic Implants. *Front. Mater.* **2022**, *9*, 914905. [CrossRef]
131. Parfenova, L.V.; Galimshina, Z.R.; Gil'Fanova, G.U.; Alibaeva, E.I.; Danilko, K.V.; Pashkova, T.M.; Kartashova, O.L.; Farrakhov, R.G.; Mukaeva, V.R.; Parfenov, E.V.; et al. Hyaluronic acid bisphosphonates as antifouling antimicrobial coatings for PEO-modified titanium implants. *Surf. Interfaces* **2022**, *28*, 101678. [CrossRef]
132. Akshaya, S.; Rowlo, P.K.; Dukle, A.; Nathanael, A.J. Antibacterial Coatings for Titanium Implants: Recent Trends and Future Perspectives. *Antibiotics* **2022**, *11*, 1719. [CrossRef]
133. Simon, N.; Schmid, M.; Blendinger, F.; Bucher, V. Long Term Evaluation of the Barrier Properties of Polymer/Metal Oxide Hybrid Layers for Use in Medical Implants. *Curr. Dir. Biomed. Eng.* **2022**, *8*, 435–438. [CrossRef]
134. Visser, N.L.; Verschoor, J.C.; Smulders, L.C.; Mattarozzi, F.; Morgan, D.J.; Meeldijk, J.D.; van der Hoeven, J.E.; Stewart, J.A.; Vandegehuchte, B.D.; de Jongh, P.E. Influence of carbon support surface modification on the performance of nickel catalysts in carbon dioxide hydrogenation. *Catal. Today* **2023**, *418*, 114071. [CrossRef]
135. Kübler, M.; Wagner, S.; Jurzinsky, T.; Paul, S.; Weidler, N.; Villa, E.D.G.; Cremers, C.; Kramm, U.I. Impact of Surface Functionalization on the Intrinsic Properties of the Resulting Fe–N–C Catalysts for Fuel Cell Applications. *Energy Technol.* **2020**, *8*, 2000433. [CrossRef]

136. Binding, S.C.; Pernik, I.; Gonçales, V.; Wong, C.M.; Webster, R.; Cheong, S.; Tilley, R.D.; Garcia-Bennett, A.; Gooding, J.J.; Messerle, B.A. Simultaneous Functionalization of Carbon Surfaces with Rhodium and Iridium Organometallic Complexes: Hybrid Bimetallic Catalysts for Hydroamination. *Organometallics* **2019**, *38*, 780–787. [CrossRef]
137. Bai, J.; Zhang, J.; Eiler, K.; Yang, Z.; Fan, L.; Yang, D.; Zhang, M.; Hou, Y.; Guan, R.; Sort, J.; et al. Electrochemically fabricated surface-mesostructured cuni bimetallic catalysts for hydrogen production in alkaline media. *Nanomaterials* **2022**, *12*, 118. [CrossRef] [PubMed]
138. Sun, X.; Shao, X.; Yi, J.; Zhang, J.; Liu, Y. High-efficient carbon dioxide-to-formic acid conversion on bimetallic PbIn alloy catalysts with tuned composition and morphology. *Chemosphere* **2022**, *293*, 133595. [CrossRef]
139. Kottarathil, S.; Narayanaru, S.; Unni, S.M.; Tamaki, T.; Kuroki, H.; Hareesh, U.N.S.; Anilkumar, G.M.; Yamaguchi, T. Selective Borohydride Oxidation Reactions of Zeolitic Imidazolate Framework-Derived Bimetallic Carbon Alloy Electrocatalysts for Alkaline Fuel Cell Applications. *ACS Appl. Energy Mater.* **2022**, *5*, 12571–12582. [CrossRef]
140. Mncwabe, Z.; Farahani, M.D.; Friedrich, H.B. Switching Between Oxidation Types Using Molybdenum Phosphate Catalysts for Paraffin Activation Using Doped Fe as Surface Acidity Modifier and MoO_x as an Oxygen Insertion Tool. *Catal. Lett.* **2020**, *150*, 728–737. [CrossRef]
141. Gao, X.; Wen, Y.; Tan, R.; Huang, H.; Kawi, S. A review of catalyst modifications for a highly active and stable hydrogen production from methane. *Int. J. Hydrogen Energy* **2023**, *48*, 6204–6232. [CrossRef]
142. Zhang, Y.; Zhao, Y.; Hu, W.; Wang, X.; Yang, R. Microstructure and surface engineering through indium modification on Ni-rich layered cathode materials for enhanced electrochemical performance of lithium-ion batteries. *J. Alloys Compd.* **2023**, *934*, 167862. [CrossRef]
143. Hamidian, K.; Rahimi, R.; Hosseini-Kharat, M.; Alavi, M. Development of the molecular engineering of disazo dye sensitizers and TiO_2 semiconductor surface to improve the power conversion efficiency of dye-sensitized solar cells. *J. Photochem. Photobiol. A Chem.* **2021**, *418*, 113408. [CrossRef]
144. Sun, X.; Jing, M.; Dong, H.; Xie, W.; Luo, F. CuO-ZnO submicroflakes with nanolayered Al_2O_3 coatings as high performance anode materials in lithium-ion batteries. *J. Alloys Compd.* **2023**, *953*, 170137. [CrossRef]
145. Wang, C.; Gann, E.; Chesman, A.S.R.; McNeill, C.R. Residual solvent additive enables the nanostructuring of PTB7-Th:PC71BM solar cells via soft lithography. *AIP Adv.* **2019**, *9*, 065024. [CrossRef]
146. Huang, J.Y.; Fei, G.T.; Xu, S.H.; Wang, B. ZnO–SiO_2 composite coating with anti-reflection and photoluminescence properties for improving the solar cell efficiency. *Compos. Part B Eng.* **2023**, *251*, 110486. [CrossRef]
147. Guo, C.; Jia, R.; Li, X.; Tian, X.; Chen, J.; Ge, H.; Huang, H.; Yuan, L.; Xu, C. Influence of backside surface morphology on passivation and contact characteristics of TOPCON solar cells. *Sol. Energy* **2023**, *258*, 278–288. [CrossRef]
148. Singh, N.; Malik, A.; Nohwar, S.; Jana, R.; Mondal, P.C. Covalent surface modification of nickel ferrite nanoparticles for electrochemical supercapacitor performance. *N. J. Chem.* **2023**, *47*, 5308–5315. [CrossRef]
149. Zhang, Y.; Gao, S.; Zhao, T.; Chen, D.; Wang, R.; Yu, Y. Ge modified by metal–organic segments as anodes for Ge-air batteries with an alkaline gel polymer electrolyte. *Arab. J. Chem.* **2023**, *16*, 105021. [CrossRef]
150. Ramezani, M.; Ripin, Z.M. 4D printing in biomedical engineering: Advancements, challenges, and future directions. *J. Funct. Biomater.* **2023**, *14*, 347. [CrossRef]
151. Mutharani, B.; Ranganathan, P.; Chen, T.-W.; Chen, S.-M.; Vinoth Kumar, J. Thermoreversible Switchlike Electrocatalytic Reduction of Tizanidine Based on a Graphene Oxide Tethered Stimuli-Responsive Smart Surface Supported Pd Catalyst. *Anal. Chem.* **2020**, *92*, 8965–8973. [CrossRef]
152. Li, H.; Ai, Z.; Yang, L.; Zhang, W.; Yang, Z.; Peng, H.; Leng, L. Machine learning assisted predicting and engineering specific surface area and total pore volume of biochar. *Bioresour. Technol.* **2023**, *369*, 128417. [CrossRef]
153. Aghazadeh, M.; Ganjali, M.R.; Morad, M.M.; Gharailou, D. Saccharide-capped superparamagnetic copper cations-doped magnetite nanoparticles for biomedical applications: A novel and simple synthesis procedure, in-situ surface engineering and characterization. *Curr. Nanosci.* **2020**, *16*, 770–778. [CrossRef]