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MINI REVIEW

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Exploring coating technologies: A mini-review on traditional types and the revolutionary role of graphene

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ABSTRACT

This mini-review provides an in-depth exploration of various coating technologies, including physical vapor deposition (PVD), chemical vapor deposition (CVD), micro-arc oxidation (MAO), sol-gel, and thermal spray coating. The working principle and advantages of these techniques are examined to highlight their roles in enhancing material properties and performance across multiple industries. The review then shifts to the revolutionary potential of graphene as a coating material. The unique combination of exceptional mechanical strength, electrical, thermal conductivity, and chemical stability makes graphene a superior coating material. By establishing coating technologies with the innovative applications of graphene, this mini-review highlights the transformative impact of graphene on anti-corrosion and anti-microbial coating applications.

KEYWORDS

Sewerage; By-product; Cost calculation; System dynamics

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Introduction

Recently, coating technology has attracted significant interest in materials science and engineering because of its wide range of applications in industries and medical scetors [1-3]. A coating refers to a material layer that envelops the surface of a larger material to attain particular characteristics.

Through the application of a material layer on the surface of a product, coatings are utilized to safeguard, enhance, and optimize the functionality of the substrates [4,5]. The primary objective of coating technology is to protect the surface and the bulk from corrosion, fouling, mechanical wear, microorganisms, and environmental hazards [6,7]. Functional coatings have been designed not only for protective applications but also to adsorb chemical contaminants and hazardous gases [8].

Coating materials exhibit different deposition mechanisms, such as physical vapor deposition (PVD), chemical vapor deposition (CVD), micro-arc oxidation (MAO), sol-gel, and thermal spray coatings. They provide unique deposition techniques, materials, secondary phases, thicknesses, and densities, thereby requiring careful consideration of mechanical stability, corrosion resistance, biocompatibility, and overall enhancement of material properties [5,9].

Recent progress in nanotechnology and materials science has introduced innovative coating materials, with graphene emerging as a particularly promising option [10,11]. Renowned for its outstanding mechanical strength, chemical resistance, gas impermeability, high adsorption capacity, antibacterial properties, thermal stability, thermal conductivity, and electrical properties, graphene has turned the eyeballs of researchers for various coating applications. Consequently, it emerges as an optimal choice for a diverse array of applications, encompassing anti-corrosion and anti-microbial coatings, as well as advanced electronics for a wide range of industrial and commercial applications [12].

This mini-review aims to explore the various types of coating technologies, emphasizing their principles and applications. Further, special emphasis has been placed on the revolutionary influence of graphene on the advancement of coating technologies, especially for anti-corrosion and anti-microbial coating applications.

Overview of traditional coating types

Conventional methods of coating like PVD, CVD, MAO, sol-gel, and thermal spray coatings provide a diverse array of advantages customized for particular uses in different sectors. These coating techniques find wide applications in various industries, from aerospace and automotive to electronics and healthcare.

Physical vapor deposition (PVD)

Physical Vapor Deposition (PVD) is a process conducted in a high vacuum environment where solid or liquid materials are converted into a vapor phase [13]. This vapor then condenses into a metal vapor, forming a solid film. The two most commonly used PVD methods are thermal evaporation and sputtering. Given the thin nature of the coatings produced by PVD, multilayered coatings are often necessary, requiring careful selection of materials. Figure 1 shows a schematic representation of a PVD setup. In thermal evaporation, the coating growth is primarily driven by thermal energy produced from an electron beam, laser beam, heating wire, or molecular beam. This energy heats the source material to its evaporation point. The vaporized atoms then propagate in the vacuum and settle onto the substrate. In magnetron sputtering, multiple materials are applied as fine layers [14]. The raw material, or target, is placed near a magnetron in the sputtering process. An inert gas is introduced and accelerated by a high voltage between the target and the substrate, directing it towards the magnetron. This acceleration releases atomic-sized particles from the target, which are propelled by

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the kinetic energy of gas ions hitting the target, eventually forming a solid thin film on the substrate.

Sputtering is regarded as a cleaner deposition method because it enhances film densification and minimizes residual stresses on the substrate [15]. Additionally, deposition occurs at low or medium temperatures. The stress and deposition rate are controlled by adjusting the power and pressure. Using targets with larger surface areas enhances uniformity and allows for easy adjustment of process parameters and deposition time to control film thickness. However, it's important to recognize that the sputtering process can result in film contamination due to the diffusion of evaporated impurities from the source. This limitation affects the selection of materials for coatings based on their melting temperatures.

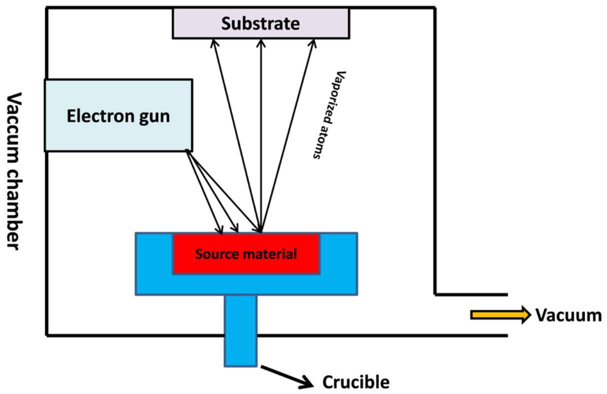

Figure 1. Schematic illustration of a PVD setup.

In conclusion, PVD coating possesses a significant advantage in terms of employing both organic and inorganic materials for deposition, resulting in coatings with exceptional hardness and corrosion resistance. Nonetheless, applying PVD processes to polymeric materials poses challenges due to polymer degradation and resultant film molecular weight reduction. Despite these obstacles, PVD has demonstrated effective application with materials like polyvinylidene fluoride (PVDF), polyethylene (PE), etc. [5].

Chemical vapor deposition (CVD)

Chemical Vapor Deposition (CVD) is utilized in the semiconductor industry to apply a durable, high-quality, and resistant coating layer on various substrates [16]. In this procedure, the substrate, often a wafer, undergoes exposure to volatile precursor materials, initiating a chemical reaction that deposits a layer onto the surface of the material. A schematic representation of the CVD setup is presented in Figure 2.

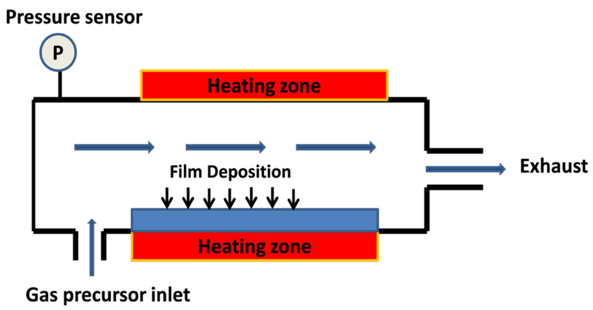

Figure 2. Schematic presentation of a CVD system.

The chemical vapor deposition (CVD) technique offers a diverse range of materials with varying compositions and structures, including nitrides, carbides, fluorocarbons, oxynitrides, diamond, polymers, graphene, fibers/nanofibers/nanotubes, titanium, and tungsten [17]. The CVD process can be classified in several ways, such as plasma-enhanced CVD, microwave-plasma-assisted CVD, aerosol-assisted CVD, direct liquid injection CVD, and photo-assisted CVD [18]. There are ongoing debates regarding the pros and cons of CVD compared to physical vapor deposition (PVD), depending on the specific applications. While CVD involves heating the substrate up to 900 °C, making it unsuitable for thermosensitive materials, PVD offers a solution for such materials. However, CVD is advantageous in terms of material efficiency as only the heated area requires coating, thereby producing high-quality films for coating applications.

Micro-arc oxidation (MAO)

The Micro-Arc Oxidation (MAO) process is recognized for its adaptable nature in coating various layers [19]. The schematics of the process is presented in Figure 3. Mouri & Oki, and Jin et al. have discussed the energy consumption and CO_2 emissions in sewage treatment processes and their associated processes [7,8].

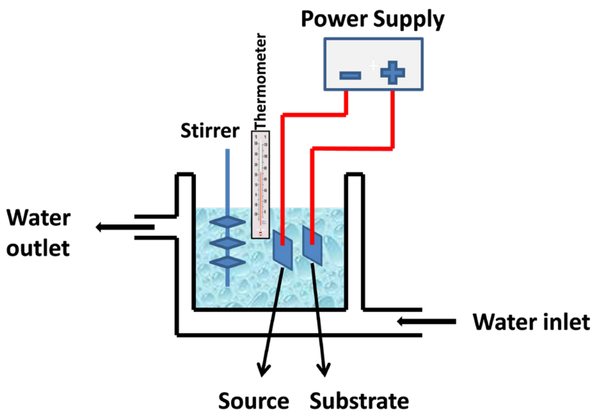

Figure 3. Schematic presentation of MAO process.

Typically, micro-arc oxidation (MAO) uses a significant voltage difference between the anode and cathode to create micro-arcs functioning as plasma channels. When these arcs contact the substrate, they induce surface melting. Simultaneously, the plasma channels apply pressure, aiding the deposition of coating materials from the working electrolyte onto the substrate surface. The electrolyte initiates a chemical oxidation reaction, leading to the formation of oxides on the substrate material. MAO is widely used to coat materials such as aluminum, magnesium, titanium, and their respective alloys. Additionally, the porous structure of the coating layer significantly enhances bone in growth when used in biomedical implants and fixations.

Sol-gel method

Sol-gel coating is a highly effective method for coating biomedical devices [20]. Extensive research has been conducted on this process, with the goal of simplifying experimental setup and execution while maintaining reliable outcomes. Moreover, sol-gel coatings have the ability to enhance existing layers by

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providing protection against corrosion and ion release. The liquid-permeable nature of sol-gel allows it to effectively seal porous structures or damaged layers. The solution, referred to as Sol, is formed by dissolving the precursors in ethanol or distilled water. By subjecting the solution to varying temperatures, the aqueous portion is removed, and the viscosity is increased to form a gel phase. The transition from liquid to gel defines the sol-gel process. Following this, the materials to be coated are submerged in the sol-gel at a uniform rate. This procedure can be repeated to apply multiple layers or a coating over the device. Moreover, coated samples can undergo accelerated drying through baking or inducing dehydration cracks for subsequent steps. Figure 4 depicts a schematic of a standard sol-gel coating process.

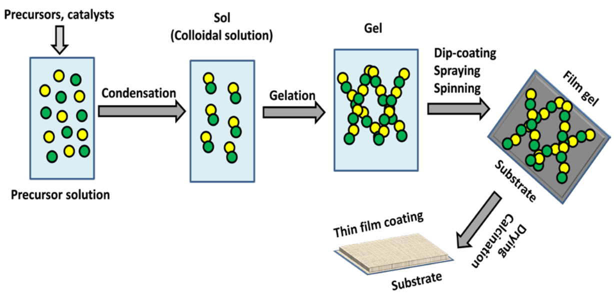

Figure 4. Schematics of the sol-gel coating

The sol-gel process offers several benefits, such as superior adhesion of the coating layer, versatility in coating compositions, and cost-effectiveness relative to other techniques. Moreover, the process does not require a conductive substrate material since there is no need for high temperatures or vacuum conditions, ensuring minimal impact on the substrate during coating. Moreover, Sol-gel coating can be applied using various techniques including dip-coating, spraying, and spinning.

Thermal spray coating

Thermal spray coating encompasses various techniques that use plasma, electric or chemical combustion heat sources to melt specific materials. These molten materials are then sprayed onto a surface to form a protective layer [21]. These coatings are highly regarded for their exceptional resistance to corrosion and wear. In the thermal spray coating process, a heat source heats the materials until they reach a molten state. These heated materials are then sprayed onto the substrate at high velocity to form a coating. Additionally, thermal spray coatings allows for precise control over coating thickness, composition, and properties to meet specific application requirements.

Graphene as a Coating Material

Graphene, a carbon allotrope, possesses unique properties largely due to its two-dimensional hexagonal lattice structure. This single-layered material exhibits outstanding thermal and electrical conductivity, along with remarkable mechanical strength, making it ideal for various coating applications [10,22]. Additionally, graphene is impermeable to gases and resistant to a range of chemicals, including acids, bases, and salts. It also possesses antibacterial properties, thermal stability, and a notably high specific surface area. The unique surface chemistry of graphene, along with its distinctive properties, offers a promising foundation for creating advanced protective surface coatings.

Functionalizing the surface of graphene is crucial for developing graphene-based functional coatings, which enables effective contact deposition and film formation on specific substrates. In the past decade, a variety of techniques have been investigated to functionalize graphene-based materials [23]. The most facile method for functionalizing graphene involves controlling the oxidation of graphite flakes to produce hydrophilic graphene oxide (GO), which possesses several functional groups on both its basal plane and edges. Additionally, the reduction of GO through chemical and thermal method can eliminate oxygen functionalities, converting hydrophilic GO into hydrophobic reduced GO (rGO). The functional groups, such as carboxyl, hydroxyl, and epoxy groups on the basal plane and edges of GO are particularly beneficial for forming covalent bonds with organic molecules [24]. This enhanced functionalization of graphene and GO plays a crucial role in enabling further modifications by immobilizing inorganic nanostructures (nanoparticles, nanocrystals, and quantum dots) and doping with heteroatoms for multifunctional applications. These various functionalization techniques for Gr offer promising prospects for developing coatings with enhanced protective properties, such as anti-corrosion and anti-microbial coatings.

Graphene for anti-corrosion coating

Recent studies suggest that graphene is being increasingly employed as an anti-corrosion coating by virtue of its unique impermeable two-dimensional structure. This structure functions as a barrier against reactive gases, liquids, acids, and salts. The barrier properties of graphene are primarily attributed to its delocalized electron cloud within the π-conjugated carbon framework. This electron cloud forms a repelling field against reactive atoms or molecules, establishing a high energy barrier that effectively prevents the diffusion of oxygen to the underlying metal surface.

Wang et al. reported a simple spin coating technique to form graphene/epoxy (OG/EP) coatings that exhibit outstanding anti-corrosion properties in challenging oxygen-rich environments, utilizing solely graphene nanosheets [25]. The findings demonstrated that the anti-corrosion capabilities of OG/EP coatings remained exceptional even when immersed in a 3.5 wt% NaCl solution for a period of 60 days. Notably, following 7 days of exposure to a harsh environment consisting of 3 MPa pure O_2 and a 3.5 wt% NaCl solution, the OG/EP coating continued to exhibit consistent and remarkable anti-corrosion performance. The protective mechanism of the OG/EP coating relies on the orientation of graphene, which enhances the impermeability of the material, thereby impeding the diffusion of corrosive substances and hindering the formation of a conductive graphene network that could accelerate corrosion. Kamil et al. developed a composite coating through the combination of Ni electrodeposition and electrophoresis of reduced graphene oxide (rGO) on low-carbon steel [26]. Initially, graphene oxide (GO) underwent a chemical reduction process to transform into rGO, enhancing its electrophoretic mobility. The simultaneous electro-co-deposition of Ni^{2+} and rGO displayed rapid growth, resulting in a well-defined and homogeneous microstructure. Consequently, the results of polarization and impedance tests in 0.5 M H_2SO_4 indicated that the Ni-rGO coating exhibited a remarkable protection efficiency of 99.5%.

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Graphene for anti-microbial coating

Graphene and its nanocomposites exhibit exceptional physicochemical properties and biocompatibility, rendering them highly favorable for antimicrobial coatings. The antimicrobial properties of graphene-based materials are attributed to the inhibition of bacterial colonization, thereby avoiding medical device-associated infections.

Agarwalla et al. examined the effects of graphene coating on Titanium and its interaction with a biofilm composed of *Pseudomonas aeruginosa*, *Enterococcus faecalis*, *Streptococcus mutants*, and *Candida albicansc* [27]. Their research demonstrated that the repeated application of graphene coating led to a decrease in biofilm formation, which was attributed to the hydrophobic properties of graphene. These findings indicate that coating titanium with graphene could be an effective strategy for preventing biofilm formation on implants. Bhattacharjee et al. investigated the antimicrobial effectiveness and cytotoxicity of cotton and silk fabrics infused with reduced graphene oxide (RGO) and silver/copper nanoparticles (Ag/Cu NPs) [28]. These fabrics were produced using a 3-glycidyloxypropyl trimethoxysilane coupling agent, followed by chemical reduction and vacuum heat treatment. The inclusion of NPs on the RGO layer led to a significant enhancement in antimicrobial activity. In particular, all RGO–Ag NPs or RGO–Cu NPs integrated into cotton or silk fabrics resulted in a 99% reduction in the viability of Gram-negative bacteria *Escherichia coli* and *Pseudomonas aeruginosa*. Furthermore, the presence of RGO–Ag NPs in cotton or silk fabrics led to a 78–99% decrease in the viability of the Gram-positive bacterium *Staphylococcus aureus*.

Conclusions

In this mini-review, we have discussed various types of coatings, with a particular focus on graphene as a coating material. The success of coating over a substrate is influenced by several factors, such as the materials used for deposition, the substrate materials, the form of the feedstock (such as powder, wire, rods, or precursors), and the deposition methods. By assessing the properties of different feedstock and substrate materials, the most suitable deposition technique can be determined. Moreover, extensive research underscores the significant potential of graphene-based materials in protective coatings. The exceptional chemical and physical properties of graphene have driven substantial advancements in developing advanced protective coating technologies. However, there remains ample opportunity for further exploration to meet the evolving needs of industries and the growing demand for sustainable solutions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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