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A Review of Intelligent Polymeric Coatings

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Abstract

This review deals with aspects to consider concerning intelligent polymer coatings. The expression "intelligent polymer coatings" alludes to the concept of coatings being able to sense their environment and properly react to that stimulus. Great efforts have been made to create a novel versatile coating capable of detecting corrosion, pressure, and temperature. The discussion focused on the extent and restrictions of self-healing principles in polymer coatings. Additionally, we discuss the outline of present methodologies and technologies that cover the zones of low molecular weight antibacterial agents and antibacterial polymer coatings. The concentration and spectrum distribution of the optical source can be regulated by employing optical components and filtering optical projection systems that incorporate filters, mirrors, lenses, and optical fibers.

Keywords: Intelligent polymer coatings, High performance-coatings, optical coating, Bioactive coatings; self-cleaning coatings.

1. Introduction

Researchers have been actively studying coatings for several decades. Decking requires not only the application of paint but also the capacity to endure the detrimental impact of weather conditions, such as rain and UV radiation. Currently, a wide range of natural and synthetic materials are employed in the development of numerous high-performance coatings. New coatings with remarkable sensitivity to wear, pressure, and temperature have been created. Smart coatings play a vital role in the medical industry by offering long-lasting protection against bacteria and inflammation. They are particularly useful for medical equipment such as implants and pharmaceuticals that may be delivered as needed. Furthermore, a multitude of intelligent coatings have been developed, such as hydrophobic, photocatalytic, oleophobic, and self-decontaminating coatings [1], [2]. Smart coatings are films that possess predetermined qualities enabling them to detect and react to various ambient and external stimuli.

In this review article, we give a detailed overview of the different types of polymeric coatings that can be used in different applications. In addition, we explain the advantages and disadvantages of each of these types.

2. Polymers Used in Smart Coatings

Intelligent materials, which may integrate the functions of sensors or actuators, depend on their ability to respond to physical, chemical, or mechanical stimuli by generating discernible signals. Modifications in features and structure, in response to environmental changes, are frequently reversible. Responses may often commence corrective measures, like as self-repair or healing, in addition to fundamental sensing. Smart materials are expected to work as advanced materials and integral elements of sophisticated smart structures, which encompass many components such as sensors, actuators, control algorithms, control hardware, and structural members[3], [4]. Materials that may dynamically modify their properties in reaction to environmental stimuli are termed responsive or smart materials. The term "smart coating" refers to coatings that can sense their environment and react appropriately to stimuli. The dominant belief regarding coatings is that they serve as a passive layer, insensitive to environmental influences. The dominant trend in coatings technology is to control the coating composition at the molecular level and the morphology at the nanometer scale. The regulation of sequential macromolecular layer formation and the capacity of materials to form defined structures with unique characteristics are being explored for both fundamental scientific research and industrial applications. A range of intelligent coating technologies has been developed, assessed, and is currently under investigation by various laboratories and enterprises worldwide. Intelligent coatings include stimuli-responsive, antibacterial, antifouling, conductive, self-healing, and superhydrophobic systems [5], [6].

Table 1: Polymers used in smart coatings and their stimuli.

Type of Stimuli	Type of Polymer
pH	Dendrimers, chitosan, Carbopol
Temperature	Prolactin, poloxamer
Photo-sensitive	PEG, polylactic acid
Phase-sensitive	Poly (D, L-lactide); Poly (D, L-lactide-co-glycoside)
Magnetic response	PNIPAAm hydrogel containing ferromagnetic material PNIPAAm co-acrylamide
Electric	Sodium alginate (Ca^{2+}); Chitosan (mg^{2+})
Organic Solvent	Eudragit S-100

3. Bioactive Coatings

The progress in the production of intelligent polymers presents fresh possibilities for their efficient application in medicine, particularly in the domain of drug delivery[7], [8]. Various synthetic polymers with environmentally responsive properties have the potential to serve as intelligent carriers for controlled pharmaceutical delivery [2]. Smart coatings are significantly contributed to the medical field by providing durable antibacterial and anti-inflammatory properties to medical equipment, include implants and controlled-release drugs. Antimicrobial and anti-inflammatory coatings are currently being applied to medical apparatuses (particularly drug-eluting ones), military apparel, a variety of medical equipment’s and medical devices. In general, antimicrobial coatings are created by either adding biocidal chemicals to the formulation or embedding them into polymer structures. This prevents bacteria from carrying out their usual activities, rendering them inactive. Silver and its compounds are widely used in different purposes, including medical instruments (such as tranquilizer eluting devices), military attire, and hospital equipment [1].

Five technical terms are used to describe antibacterial agents. The first word refers to the ability to effectively eradicate entire germs, although it lacks a clear objective and defined boundaries. Sterilization is the second term that has more significance than is extensive. In addition to eliminating, it is possible to integrate the ability to eradicate germs or viruses from the intended targets, independent of their harmfulness. Completely eradicating the bacterial population is a difficult task when considering probability. Thus, the SAL (sterility confirmation level) is frequently employed to evaluate the degree of sterilization. Sterilization is universally defined as the state in which the Sterility Assurance Level (SAL) is below 10-6. Reducing the population of harmful bacteria to a non-threatening level is the third step in the disinfection process. This could be accomplished by the microbiocidal impact, the principal concept. Right now, it may state that cleansing would be nearly the equivalent of a microbiocidal impact. Pathogenicity must be eliminated to achieve disinfection. The fourth technical term should be interpreted as bacterial reduction. The technique lacks both aims and extents. The purpose is to quantify the number of bacteria that could be evacuated. Furthermore, the fifth action may be characterized as one that would impede the proliferation of bacteria on the specified object. Usually, it is necessary to verify the reduction of bacteria in the range of 102[9].

The longevity of antibacterial coatings is essential in various practical applications, particularly when used on surfaces that come into touch with others. These materials can be filled with specific medications for medical purposes and then released the medicine in response to a trigger. The capacity of smart polymeric materials to respond to external or internal stimuli has allowed them to effectively deliver medications. Including pH, chemical fixation, temperature, ultrasound power, as well as light, magnetic field, redox potentials, and numerous other possible improvements [2].

Yanan Wang and colleagues suggested a practical method for producing an antibacterial coating using the in-situ polymerization of a flexible hybrid caprolactam-casein/ZnO nanocomposite (CCZ), which is based on natural polymers. The novel films exhibited excellent mechanical qualities and remarkable antibacterial effectiveness against Staphylococcus aureus and Escherichia coli. These films have been used in several industries such as textile, leather, packaging, and paper[10].

Mitra S. Ganewatta et al. utilized two effective chemical methods to fixate the surface: Copper-catalyzed azide-alkyne 1,3-dipolar cycloaddition click reaction and surface-initiated atom transfer radical polymerization. Extensive antibacterial and antibiofilm tests were conducted on Gram-positive Staphylococcus aureus and Gram-negative Escherichia coli. The biocompatibility of the modified surfaces was demonstrated through investigations of hemolysis and the evolution of human skin fibroblasts. The researchers discovered that by affixing quaternary ammonium-decorated abietic acid complexes and polymers onto surfaces, it is possible to effectively utilize renewable biomass to combat bacteria and prevent biofilm development in biomedical applications[11].

Major et al., studied the performance of graphene-based biomaterials devoted to cardiovascular treatment. Polyelectrolyte-based coatings with porous structure loaded with Reduced graphene oxide flakes. The stiffness of the resulting coating was significantly increased by the presence of graphene particles. The risk of bacteriology film generation was assessed using E-coli and Staphylococcus bacteria. An investigation was conducted on the interaction between blood and material under dynamic stream circumstances. The bacteriological examination revealed a decrease in the bacterial population upon contact with the surface containing graphene flakes. Blood dynamic analyses revealed elevated coagulation activation, significant platelet depletion, and robust immunological response. This effect is believed to originate from the acute angle created by the unique surface of the graphene[12].

4. Self-Cleaning Coatings

The potential benefits of nonstick and self-cleaning surface coatings lie in their ability to improve the resistance of the coated material against water and dust particles, making them advantageous in numerous applications[13]. Human & other mammals are significantly impacted by dust [14]. It is crucial to minimize the build-up of dust to ensure the tools used in both manned and unmanned operations operate at their best. The accumulation of dust on vehicles and sensors hinders their movement and the collection of data[15]. To overcome this issue, there has been a significant interest in the use of superhydrophobic coating substrates for self-cleaning coating applications. Because these substrates have dust-removal properties that make them easily to nonstick [16]. Various commercial items, such as protective gloves, masks, and lenses, can be employed to safeguard one's well-being against perilous environmental poisons, including those arising from dust particles[2], [14]. There have been numerous reports on the creation of superhydrophobic surfaces that imitate the lotus leaf's behavior. These surfaces have complex micro/nanostructures and are covered with wax polymers that have low surface energy, similar to those seen on the lotus plant[17], [18]. These characteristics are accountable for the significant degree of super-hydrophobicity that is seen. The level of surface roughness, in conjunction with a low surface energy, is essential in attaining this outcome (refer to Figure 1).

Figure 1: water droplets on the cabbage leaf surface (Brassica oleracea) following a rain shower[19].

A state of total non-wetting occurs when stable air pockets form within rough crevices that have low surface energy. This creates a boundary layer between a water droplet and the solid structure. Superhydrophobic surfaces are widely sought in the optical, metal, electrical, and vehicle industries because of their outstanding properties [19]–[21].

Nakajima et al. and Yamauchi et al. have shown that adding a small amount of the TiO2 photocatalyst effectively gives super-hydrophobic coatings the ability to clean themselves. In addition, this treatment maintains excellent contact angles even after extended exposure to the atmosphere[22]. In their study, S. A. Brewer and C. Willis DERA employed Oxygen plasma to enhance the water repellency of non-porous and expanded PTFE substrates by micro roughening them. However, liquids with lower surface tension, such as decane, can move through porous PTFE material due to capillary action. Applying a plasma polymer coating with low surface energy to the micro roughened surfaces of PTFE significantly improves their ability to resist liquids. The reason for this is the heightened contact angle that occurs at the boundary between the liquid and solid, which hinders the infiltration of decane into the underlying layers of the expanded PTFE substrate. This phenomenon has been noted in prior research [23].

Hyun Yoon et al. managed the duration of the spraying process to create a clear self-cleaning surface with excellent water-repellent properties. They achieved this by using electrospraying to apply an organosilane-coated alumina precursor. The coating exhibits a superhydrophobic characteristic and remarkable transparency in the visible light spectrum. The researchers determined that extending the duration of spraying can enhance the contact angle of water. However, concurrently, it diminishes the transparency of the coatings. The water droplet achieved a perfect spherical shape with a contact angle of 162° before effortlessly sliding off a surface that had been coated, at an exceptionally shallow angle of less than 3°. Self-cleaning and clear superhydrophobic coatings have the potential to be used in the optical sector[20]. Panagiotis N. Manoudis and his colleagues suggested an economical approach to produce superhydrophobic surfaces by combining PMMA and Rhodorsil (a siloxane available in the market) with SiO2 nanoparticles. The nanoparticles exhibit a hierarchical structure that imparts hydrophobic characteristics when applied to a glass surface. The study found that the concentration of particles had a significant impact on the hydrophobic characteristics of PMMA-

SiO_2 and siloxane-SiO_2 surfaces. The researchers observed a rapid increase in the static contact angles (θs) as the particle concentration increased, eventually reaching maximum values[24].

5. Optical Coatings

In recent years have seen tremendous advancements in the field of optical surface. Modern optical coatings are getting more advanced to meet the requirements of several industries, including automotive, construction, medical, electronics, solar, and defense[25], [26]. Some materials, like silver, titania, and zirconia, have the potential to significantly impact the industry. However, there has been limited advancement in optimizing these materials for optical coatings. To attain improved performance, it will be necessary to further enhance and refine these materials[27]. Additionally, it is important to explore the potential of multifunctional performance nanomaterials in advancing optical coatings[28].

Optical components and systems projectors that can use filters, mirrors, lenses, and fiber optics to change the focus and spread spectral optical sources .Often, lights are used together with optical glass filters to exclude unwanted parts of the emission spectrum. The transmission filters may experience alterations as they mature, specifically in the ultraviolet (UV) spectral region. As individuals age, they tend to absorb shorter wavelength ultraviolet radiation (UVR) more effectively. Glass filters are at risk of fracturing if they are subjected to extreme heat. This is a potential hazard as workers may be exposed to dangerous, high-frequency UVR radiation, with UV-radiation being the most potentially harmful form of energy found in exhibition halls and libraries. In general, the damage they cause is cumulative. However, light is very necessary for museums, galleries, and libraries[29].

5.1 High Refractive Index Coatings

The fundamental requirements for desirable performance optical coatings is to control the refractive index (RI)[29]. Specifically, there is a significant need to disperse high-refractive index (RI) nanoparticles into optical polymer coatings. Applying a high refractive index (RI) coating to the surface of a light-emitting device enhances its efficiency and picture quality by improving the efficiency of light transmission in and out of the device [30]. To meet the requirements of modern optoelectronic applications such as display devices, it is necessary to create polymers with high refractive index (RI), in addition, it manufactures LEDs, OLEDs, semiconductor image sensors, and other lenses[29]–[31]. Optical polymers generally exhibit refractive indices (RIs) ranging from 1.30 to 1.70, which makes them suitable for various optical applications. Currently, there is a growing interest in creating polymers that have a refractive index (RI) higher than 1.7 and provide exceptional optical characteristics[32]. To attain high refractive index (RI) values, a highly efficient method involves synthesizing an organic-inorganic hybrid material by combining metal oxide nanoparticles with organic polymers[29]–[31].

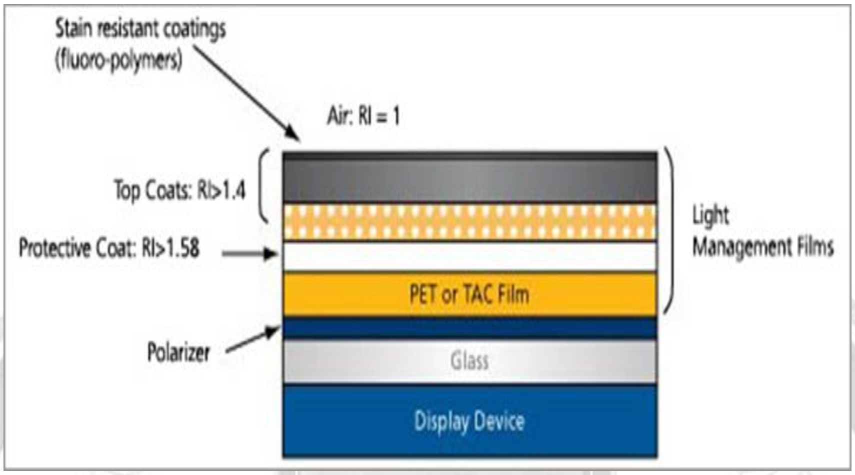

Figure 2: high refractive index coatings[30].

5.2 Anti-reflection (AR) Coatings

In order to maximize transmittance and reduce unwanted light reflections, some surfaces and technologies, such solar cells, LEDs, and LCDs, must have low absorbance [32]–[34]. An effective method for producing surfaces that minimize reflection is to apply anti-reflective coatings onto the substrate. Anti-reflection occurs when light undergoes destructive interference while passing across thin surfaces with different refractive indices (RI). For this purpose, it is required to adjust the RI tuning and thickness of an AR coating, as shown in Figure 3. Although researchers have successfully created nearly flawless anti-reflective (AR) coatings on a small scale, the manufacturing process is hindered by low resilience and contamination, which negatively affects the optical performance in industrial settings[35]. Furthermore, there is an increasing demand for surfaces that may perform many functions, as evidenced by the rising body of research[32]–[34]. Several materials have been investigated for this purpose, but two that appear to be particularly suitable are silica nanoparticles (SiO2) and titania nanoparticles (TiO2), mostly because of their contrasting refractive indices. SiO2 and TiO2 thin films can be applied onto glass substrates to enhance transmittance and reflectance. The transmittance of the glass is enhanced from 92% for the uncoated glass to 95% and above 97% for glass coated on one side and both sides, respectively. Figure 6 demonstrates the reduced reflectance of the coated samples. Additionally, this coating demonstrated multifunctional performance by effectively absorbing UV radiation, exhibiting hydrophobic and oleophobic properties, and displaying excellent scratch resistance and adhesion[33].

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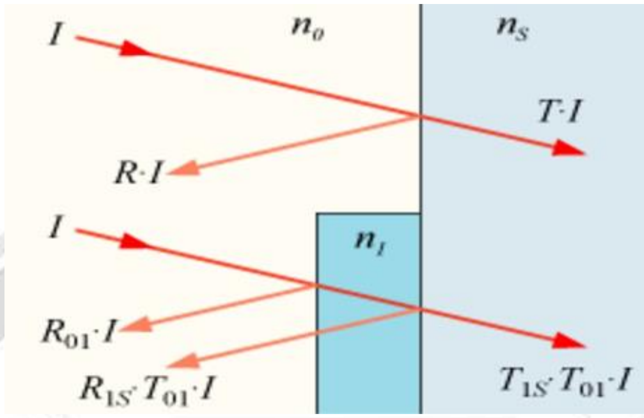

Figure 3: Anti-reflection (AR) coatings[35]

5.2.1 High Reflective Coatings

There is a significant need for highly reflective coatings that can be used in various applications, including decorative, architectural, military and defense, and telecommunication functions. This can be achieved by applying metal or metal oxide nanoparticles onto various substrates[29], [36]. Reflective surfaces are employed in various applications such as building construction, electronics for heat dissipation, and cooling of solar cells[37]. Silver-based coatings are preferred for various applications due to silver's superior reflectivity across the visible to infrared spectrum compared to other metals[38]. Silver nanoparticles, such as those found in metal mirrors, can exhibit excellent light reflection when present in small quantities within a polymer matrix, as depicted in Figure 4. Additionally, they also possess electrical conductivity. The Ag polymer coating exhibited reflectance more than 90% when measured within the range of 250 nm to 950 nm. Moreover, this material exhibited the remarkable capability to autonomously repair imperfections. This coating can be applied to various substrates, including flexible materials such as fabrics, as well as glass, wood, plastic, and steel[36].

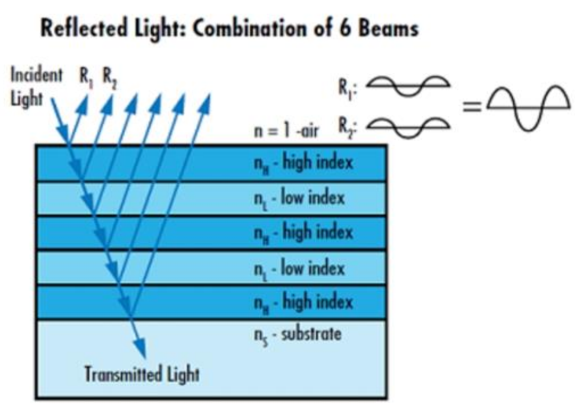

Figure 4: high reflective coatings[38]

5.2.2 Transparent Conductive Coatings

The transparent conductive coatings market has experienced significant expansion as a result of the rising demand for thin-film solar cells and light-emitting devices [27] (see Figure 5). Presently, there is an increasing trend towards the advancement of adaptable devices and larger touchscreens. Indium tin oxide (ITO) is widely utilized as a material for transparent conductive coatings. However, its expensive nature, need for high temperatures during film deposition, a tendency to be brittle, and yellow hue at specific thicknesses necessitate the search for a feasible substitute[39], [40]. Several other materials, such as carbon nanotubes, graphene, and conductive polymers, have been studied as potential replacements for ITO. However, getting comparable performance to ITO has proven to be challenging. Silver nanowires (AgNW) are a promising alternative due to their cost-effective application, excellent transparency, crack resistance, high direct current conductivity, and optical transmittance and conductivity[39]–[41]. The configuration of AgNWs is a pivotal factor in determining the performance of the resultant coating. Increased length of nanowires leads to a reduction in sheet resistance due to a decrease in the number of connections between them. Consequently, there is a strong need for the advancement of extremely long nanowires[40].

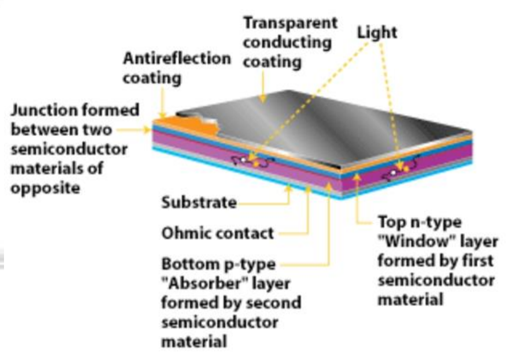

Figure 5: transparent conductive coatings [27].

5.2.3 Optical Filter Coatings

Some coating applications necessitate the selective filtration of specific wavelengths of light. For instance, specific types of plastics lack resistance to UV light, which leads to their deterioration and aging[42]. Windows can also be improved using this technique, by blocking near-infrared sun energy to enhance solar-driven cooling, as demonstrated in Figure 6[30]. There is a desire for methods that can alter surfaces such as these to enhance their ability to absorb specific wavelengths of light[42]. One contemporary method involves adjusting nanomaterials to specifically absorb harmful or undesired wavelengths while allowing favorable wavelengths to pass through. Various nanoparticles, such as titania and zinc oxide, can be exploited. When striving for optimum performance, it is crucial to consider the selection of the nanoparticle and its longevity in the coating solution[30].

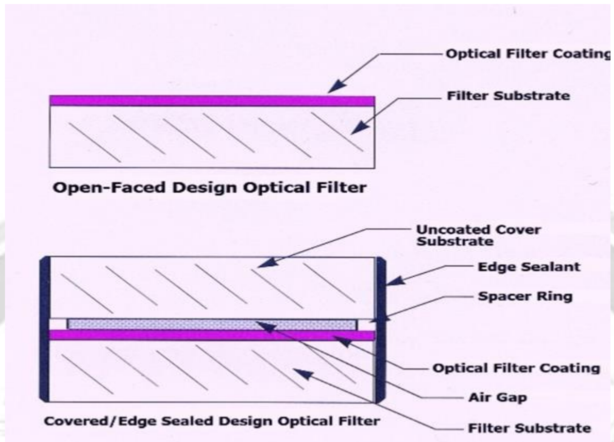

Figure 6: Optical filter coatings[30].

Conclusion

It can be concluded that there are different types of coatings with different properties according to the application they are needed for. Each type of coating has its own unique manufacturing and application process. Furthermore, the types of additives used in coatings limit their use for specific applications. Some applications need the coat to be conductive, so a conductive filler will be added; others need the coat to be hydrophobic or antibacterial, so a hydrophobic or antibacterial filler will be added.

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مراجعة للطلاءات البوليمرية الذكية

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الخلاصة

يتناول مقال المراجعة هذا جوانب ينبغي مراعاتها فيما يتعلق بالطلاءات البوليمرية الذكية. يشير تعبير "الطلاءات البوليمرية الذكية" إلى مفهوم قدرة الطلاءات على استشعار بيئتها والتفاعل بشكل صحيح مع هذا الحافز. وقد بُذلت جهود كبيرة لإنشاء طلاء متعدد الاستخدامات جديد قادر على اكتشاف التآكل والضغط ودرجة الحرارة. ركزت المناقشة على مدى وقيود مبادئ الشفاء الذاتي في الطلاءات البوليمرية. بالإضافة إلى ذلك، تم مناقشة الخطوط العريضة للمنهجيات والتقنيات الحالية التي تغطي مناطق العوامل المضادة للبكتيريا منخفضة الوزن الجزيئي والطلاءات البوليمرية المضادة للبكتيريا. يمكن تنظيم تركيز وتوزيع طيف المصدر البصري من خلال استخدام المكونات البصرية وأنظمة الإسقاط البصري المرشحة التي تتضمن المرشحات والمرايا والعدسات والألياف البصرية.

الكلمات الدالة: الطلاءات البوليمرية الذكية، الطلاءات عالية الأداء، الطلاء البصري، الطلاءات الحيوية؛ الطلاءات ذاتية التنظيف.